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BIOREMEDIATION OF OIL SPILLS: CURRENT STATUS, CHALLENGES, AND FUTURE PROSPECTS

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ABSTRACT

The petrochemicals produced from refining oil have become a large part of human life, making oil a valuable and expensive commodity. As a non-renewable resource, extraction and transport efforts have intensified to keep up with the demand, increasing the occurrences of oil spills. Such accidents have devastating impacts on the environment, the health of organisms, and a country's economy like the Philippines, and thus, need to be resolved immediately. One way to deal with oil spills is through bioremediation but the process is still facing several challenges. For one, the toolbox for bioremediation is limited. About 79 genera of bacteria were observed to degrade oil but there are only a small number of bacterial species and/or strains that have been recognized as useful for bioremediation. Second is that most oil-degrading bacteria found have low oil degradation efficiencies. Another challenge is keeping the bacteria alive to carry out the process. Fortunately, progress has been made in solving these challenges. Researchers are now testing different consortia, including bacteria–bacteria, bacteria–fungi, bacteria–microalgae, that can complement each other such as biosurfactant-producing bacteria with different oil-degrading microorganisms or microalgae or fungi that enhance the growth of oil-degrading bacteria. A consortium like this improves the survivability of each microorganism and enhances the oil-degrading efficiency. Moreover, the search for additional oil-degrading and biosurfactant-producing bacteria and other microorganisms to add to the bioremediation toolbox has been improved with the emergence of high-throughput sequencing. Aside from microorganisms, seaweeds have shown potential for bioremediation. The seaweed *Caulerpa prolifera* has been demonstrated to degrade diesel up to a certain concentration with the help of the bacteria growing on its surface. Bioremediation has a long way to go, but recent developments have shown promise and it remains to be the cheapest, most environment-friendly, and most effective way of dealing with oil spills.

Keywords: bioremediation, crude oil, marine environment, oil degradation, petroleum, bacteria

INTRODUCTION

A naturally-occurring combustible mixture of hydrocarbons and organic compounds – petroleum or crude oil – is derived from mostly decayed plants and tiny marine animals exposed to the intense heat and immense pressure underneath the Earth's surface for millions of years (**Atlas and Hazen, 2011**). When refined, it yields different products that often run our modern society from gasoline, diesel, kerosene, etc. which are used for energy generation and transportation to other petrochemicals used in making plastics and other industrial products (**Favennec, 2022**). This makes petroleum a valuable and expensive commodity as it is a non-renewable resource that occurs only in select areas around the world, is often found beneath the ocean floor, and requires specialized equipment to extract (**Kaiser and Snyder, 2013; Cordes *et al*., 2016; Yang *et al*., 2022**). As a trillion-dollar industry, petroleum often impacts the economies of nations and has become part of an individual's everyday life through the years. Currently, petroleum and its derivates remain the main source of energy even after announcements of the shift to renewable energy (**Gharib *et al*., 2021; Yang *et al*., 2022**). To keep up with the demand, extraction activities have been intensified along with the increase in the transport of petroleum products from the sources to several sinks which increases the potential of leakages or spills occurring that put the immediate environment in danger (**Deng *et al*., 2014; Tian *et al*., 2018**).

The global average of oil spill occurrences in the 2010s was more than 6 (**Galierikova and Materna, 2020**). Now in the 2020s, the current average has decreased to 5.7 (**ITOPF, 2023**). Although the trend of oil spill occurrences is decreasing, the degree of damage an oil spill can deal to an area remains the same. A country that often experiences oil spills in the marine environment is the Philippines due to it being an archipelago (**Licaunan *et al*., 2019; Alea *et al*., 2022**). There are more than 7,600 islands in the Philippines and since only a few of the islands are connected by bridges, products including oil are usually distributed to the islands via maritime transport (**Salison and Vergel, 2021; Licuanan *et al*., 2019**). According to the data gathered by **Alea *et al.*** (2022), there have been 14 massive oil spills out of the total 467 oil spills that occurred from 2000 to 2021. The most recent massive oil spill was near the island of Mindoro. The tanker, MT Princess Empress which carried 800,000 liters of oil, sank near Naujan, Oriental Mindoro last February 2023. The oil spill quickly spread to different areas from Batangas in the North to Antique in the South (**Agaton *et al*., 2023**). Marine oil spills directly hinder the exchange of O_2 and CO_2 resulting in the depletion of oxygen and the alteration of the chemistry of the seawater. The anoxic environment becomes inhospitable for many organisms leading to their deaths. Aside from anoxia, some of the chemicals in the oil also poison the organisms. Oil also drenches organisms at the surface of the water which causes them to drown or experience hypothermia. Marine plants and algae also suffer due to the reduced penetration of sunlight from the surface which limits their photosynthetic activity (**Xue *et al*., 2015**). Moreover, marine oil spills pose a threat to the health of the people and the economy of the nation (**Eklund *et al*., 2019; Zhang *et al*., 2018; Alvernia *et al*., 2021**) which is why they need to be cleared as soon as possible.

One of the ways to deal with aquatic oil spills is through bioremediation. The general process employs the services of oil-degrading microorganisms which are naturally found in the seawater to breakdown the oil and convert them to other products that are less toxic and can be consumed by other microorganisms (**Das & Chandran, 2011; Chuah *et al*., 2022; Pandolfo *et al*., 2023**). In terms of microorganisms with oil-degrading capabilities, fungi are the most abundant with 103 genera followed by bacteria with 79 genera. Although less abundant, there are currently more studies regarding oil-degradation of bacteria than fungi but studies on fungi-mediated oil degradation are catching up (**Xue *et al*., 2015; Dell' Anno *et al*., 2021**). Bioremediation can be carried out in two ways: biostimulation, where needed nutrients are added to the water to encourage the growth of indigenous microbes that will breakdown the oil, and bioaugmentation, where exogenous microbes with oil-degrading capabilities are added to the water (**Rojas-Vargas *et al*., 2022**). With this, bioremediation is seen as the most environmentally-friendly method in dealing with oil spills as there are no harmful chemicals involved and the process is also cheaper to carry out (**Hii *et al*., 2009**). However, the bioremediation process is not yet fully developed. In this brief review, we explored the different bacteria involved in the bioremediation process and the current state of bioremediation as well as the challenges encountered and future prospects.

CURRENT STATUS OF BIOREMEDIATION USING BACTERIA AND OTHER ASSOCIATED ORGANISMS

Bacteria Used in Bioremediation

The ocean is home to a plethora of microorganisms such as bacteria, fungi, microalgae, and cyanobacteria. They are important components of the marine ecosystem as they perform several services like food production and carrying out the decomposition process of organic matter. They are also involved in nutrient cycling and breaking down of harmful chemicals that may have contaminated the ocean (**Pandolfo *et al*., 2023**). According to **Xue *et al.*** (2015), there are 79 genera of bacteria with oil-degrading capabilities. These include *Acinetobacter, Bacillus, Pseudomonas*, etc. The complete list compiled by **Xue *et al.*** (2015) from **Bartha & Atlas** (1977), **Giebel *et al.*** (2011), and **Singh** (2006) is shown in Table 1. The review of **Xu *et al.*** (2018) and **Dell' Anno *et al.*** (2021) have added more genera and thus were included in the list.

Table 1 List of some bacterial genera with oil degrading capabilities.

Bacterial Genus	Reference/s
Achromobacter	**Bartha & Atlas, 1977; Singh, 2006; Giebel *et al*., 2011; Ma *et al*., 2014; Xue *et al*., 2015**
Acinetobacter	**Bartha & Atlas, 1977; Singh, 2006; Giebel *et al*., 2011; Xue *et al*., 2015**
Aeribacillus	**Mnif *et al*., 2014; Xu *et al*., 2018**
Alcaligenes	**Dell' Anno *et al*., 2021; Duran *et al*., 2019**
Alcanivorax	**Dell' Anno *et al*., 2021; Yakimov *et al*., 2007; Hara *et al*., 2003**
Actinomycetes	**Xue *et al*., 2015; Bartha & Atlas, 1977; Giebel *et al*., 2011; Singh, 2006**
Archrobacter	**Xue *et al*., 2015; Bartha & Atlas, 1977; Giebel *et al*., 2011; Singh, 2006**
Bacillus	**Dell' Anno *et al*., 2021; Wang *et al*., 2019; Xu *et al*., 2018; Xu *et al*., 2018; Jahromi *et al*., 2014; Tavassoli *et al*., 2012**
Citrobacter	**Xu *et al*., 2018; Jahromi *et al*., 2014**
Coryneforms	**Xue *et al*., 2015; Bartha & Atlas, 1977; Giebel *et al*., 2011; Singh, 2006**
Chromobacterium	**Xue *et al*., 2015; Bartha & Atlas, 1977; Giebel *et al*., 2011; Singh, 2006**
Cycloclasticus	**Dell' Anno *et al*., 2021; Kasai *et al*., 2002**
Dietzia	**Xu *et al*., 2018; Wang *et al*., 2011**
Enterobacter	**Dell' Anno *et al*., 2021; Ramasamy *et al*., 2017; Xu *et al.*, 2018; Jahromi *et al*., 2014**
Flavobacterium	**Dell' Anno *et al*., 2021; Chaudhary *et al*., 2019**
Geobacillus	**Xu *et al*., 2018; Abbasian *et al*., 2015**
Gordonia	**Xu *et al*., 2018; Brown *et al*., 2016**
Klebsiella	**Rodriguez *et al*., 2023**
Lysinibacillus	**Xu *et al*., 2018; Jahromi *et al*., 2014**
Marinobacter	**Dell' Anno *et al*., 2021; Chernikova *et al*., 2020**
Micrococcus	**Xue *et al*., 2015; Bartha & Atlas, 1977; Giebel *et al*., 2011; Singh, 2006**
Microbacterium	**Xue *et al*., 2015; Bartha & Atlas, 1977; Giebel *et al*., 2011; Singh, 2006**
Mycobacterium	**Xu *et al*., 2018; Zhang *et al*., 2013**
Novosphingobium	**Xu *et al*., 2018; Ghosal *et al*., 2016**
Neptumonas	**Xu *et al*., 2018; Hedlund *et al*., 1999**
Oleispira	**Dell' Anno *et al*., 2021; Yakimov *et al*., 2003**
Pseudomonas	**Dell' Anno *et al.*, 2021; Pacwa-Plociniczak *et al*., 2014; Xu *et al*., 2018; Jahromi *et al*., 2014; Sugiura *et al*., 1997; Mukherjee *et al*., 2010; Venkateswaran *et al*., 1995; Tavassoli *et al*., 2012**
Rhodococcus	**Xu *et al*., 2018; Zhukov *et al*., 2007; Lee & Cho, 2008**
Sarcina	**Xue *et al*., 2015; Bartha & Atlas, 1977; Giebel *et al*., 2011; Singh, 2006**
Serratia	**Xue *et al*., 2015; Bartha & Atlas, 1977; Giebel *et al*., 2011; Singh, 2006**
Sphingobium	**Xu *et al*., 2018; Ghosal *et al*., 2016**
Sphingomonas	**Xu *et al*., 2018; Ghosal *et al*., 2016**
Staphyloccocus	**Xu *et al*., 2018; Jahromi *et al*., 2014**
Streptomyces	**Xue *et al*., 2015; Bartha & Atlas, 1977; Giebel *et al*., 2011; Singh, 2006**
Thallassolituus	**Dell' Anno *et al*., 2021; Mahjoubi *et al*., 2018**
Vibrio	**Xue *et al*., 2015; Bartha & Atlas, 1977; Giebel *et al*., 2011; Singh, 2006**

Note: Bacterial genus in colored boxes are those that are usually utilized in bioremediation.

The study of **Rodriguez *et al.*** (2023) also showed the potential of *Klebsiella* sp. in oil degradation. According to **Dell' Anno *et al.*** (2021), the 10 genera of bacteria that are usually involved in bioremediation efforts are *Alcaligenes, Bacillus, Enterobacter, Flavobacterium, Pseudomonas, Alcanivorax, Thallassolituus, Cycloclasticus, Oleispira*, and *Marinobacter* (**Kasai *et al*., 2002; Yakimov *et al*., 2003, 2007; Pacwa-Plociniczak *et al*., 2014; Ramasamy *et al*., 2017; Mahjoubi *et al*., 2018; Chaudhary *et al*., 2019; Duran *et al*., 2019; Wang *et al*., 2019; Chernikova *et al*., 2020; Dell' Anno *et al*., 2021; Rodriguez *et al*., 2023**). Petroleum and its derivatives are a complex mixture of hydrocarbons, and no bacterial species can degrade all of the hydrocarbon components. Bacteria exhibit hydrocarbon specificity and it depends on the enzymes they can produce to metabolize specific hydrocarbon components (**Gao *et al*., 2021; Rajasekar *et al*., 2007; Dell' Anno *et al*., 2021; Pandolfo *et al*., 2023**). For instance, an alkane is a simple hydrocarbon composed of carbon atoms singly bonded to hydrogen atoms with no functional groups attached. The bacterium *Alcanivorax* sp. strain 24 can break apart the alkane by producing enzymes such as oxygenase and dehydrogenase which convert the hydrocarbon into fatty acids which would then be metabolized by the bacterium forming carbon dioxide and water at the end (**Xue *et al*., 2015; Zadjelovic *et al*., 2020; Dell' Anno, 2021**). Another component of petroleum and its derivatives is the polycyclic aromatic hydrocarbon (PAH), which is a diverse group of organic compounds known to cause cancers and birth defects. The strain 78-ME of *Cycloclasticus* sp. can metabolize PAHs using oxygenase and hydrolase enzymes (**Xue *et al*., 2015; Messina *et al*., 2016; Dell' Anno *et al*., 2021**). **Dell' Anno *et al***. (2021) made a list of some bacterial species/strains and the type of hydrocarbon they are capable of metabolizing (Table 2).

Table 2 Selected oil-degrading bacteria and the hydrocarbons they can metabolize

Bacteria	Hydrocarbon Metabolized	Reference/s
Alcaligenes aquatilis BU33N	Crude oil and phenanthrene	**Mahjoubi *et al*., 2019; Dell' Anno *et al*., 2021**
Alcanivorax sp. IO_7	Alkanes	**Dell' Anno *et al*., 2021; Sinha *et al*., 2021**
Alcanivorax sp. 24	Alkanes	**Zadjelovic *et al*., 2020; Dell' Anno *et al*., 2021**
Cupriavidus metallidurans CH34	Toluene	**Tofalos *et al*., 2018; Dell' Anno *et al*., 2021**
Cycloclasticus sp. strain BG-2	Phenanthrene	**Gutierrez *et al*., 2015; Dell' Anno *et al*., 2021;**
Cycloclasticus sp. 78-ME	Polycyclic aromatic hydrocarbons	**Messina *et al*., 2016; Dell' Anno *et al*., 2021;**
Cycloclasticus sp. strain P1	Naphthalene, phenanthrene, pyrene	**Dell' Anno *et al*., 2021; Wang *et al*., 2018**
Halomonas sp. strain MCTG39a	Hexadecane	**Dell' Anno *et al*., 2021; Gutierrez *et al*., 2015**
Halomonas pacifica strain Cnaph3	Naphthalene	**Dell' Anno *et al*., 2021; Cheffi *et al*., 2020**
Marinobacter hydrocarbonoclasticus SdK644	Crude oil	**Dell' Anno *et al*., 2021; Zenati *et al*., 2018**
Oleispira antarctica RB-8	Aliphatic alkanes	**Dell' Anno *et al*., 2021; Gregson *et al*., 2020**
Pseudomonas aeruginosa N6P6	Phenanthrene and pyrene	**Dell' Anno *et al*., 2021; Mangwani *et al*., 2015**
Pseudomonas pseudoalcaligenes NP103	Phenanthrene and pyrene	**Dell' Anno *et al*., 2021; Mangwani *et al*., 2016**
Pseudomonas sp. sp48	Phenol, naphtalene, pentadecane	**Dell' Anno *et al*., 2021; Farag *et al*., 2018**
Pseudomonas aeruginosa GOM1	Hexadecane	**Dell' Anno *et al*., 2021; Muriel-Millan *et al*., 2019**
Ralstonia pickettii	Crude oil	**Dell' Anno *et al*., 2021; Setyo Purnomo *et al*., 2019**

Development of Various Consortia

A consortium refers to a group of different species of microorganisms that are able to coexist with each other. For instance, members of a bacterial consortium include oil-degrading bacteria as well as other bacteria that may produce biosurfactants or other nutrients (**Rojas-Vargas *et al*., 2022**). Together, these bacteria become a robust unit and can degrade oil with higher efficiency (**Patowary *et al*., 2016**). In the study by **Yu *et al.*** (2022), they used sequencing to find potential oil-degrading bacteria and eventually, they arrived at a consortium composed of *Rhodococcus* sp. OS62-1 and *Pseudomonas* sp. P35 with a high crude oil degradation efficiency of 85.75±3.21%. The consortium was found to be efficient at a pH of 5 to 11 and salinity levels from 0 to 80 g/L. Another consortium can be composed of a fungus and a bacterium. **Atakpa *et al.* (2022)** found the fungus *Scedosporium* sp. strain ZYY can be grown together with the Y2 strain of *Actinobacter* sp. The bacterium produces biosurfactants and improves the growth of the fungus. When exposed to crude oil, the consortium was able to degrade total petroleum hydrocarbons (TPH) with a degradation rate of 58.61%. Aside from fungi, microalgae can also work synergistically with bacteria in degrading crude oil (**Radice *et al*., 2023**). Different hydrocarbonoclastic bacteria belonging to different genera particularly *Alcanivorax* and *Marinobacter* spp. were found in a petroleum-enriched microalgae culture of *Pavlova lutheri* and *Nannochloropsis oculata* (**Chernikova *et al.*, 2020**). Bacterial growth, especially that of the aerobic ones, was supported by the products produced by the microalgae such as oxygen and organic materials. The bacteria, in turn, supported the growth of the microalgae by producing carbon dioxide and other nutrients aside from acting on the toxic compounds (**Mahdavi *et al.*, 2015; Chernikova *et al.*, 2020; Radice *et al*., 2023)**. However, not all combinations of microalgae and bacteria would result in hydrocarbon degradation and removal of toxic compounds. The study by **Tang *et al.* (2010)** showed that the microalga *Scenedesmus obliquus* strain GH2 had a reduced PAH removal activity when paired with hydrocarbonoclastic bacterial strains (*Shingomonas* GY2B, *Burkholderia capacia* GS3C, *Pseudomonas* GP3A and *Pandoraea pnomenusa* GP3B) (**Radice *et al*., 2023)**. As for macroalgae, the study of **Caronni *et al*.** (2023) used the seaweed, *Caulerpa prolifera*, and tested whether it can degrade the diesel in the water since seaweeds are home to various microorganisms, particularly bacteria some of which might have hydrocarbonoclastic properties. The seaweeds produce substances that favor the growth of microorganisms and the microorganisms in return produce metabolites that can influence the growth and other processes of the seaweed (**Singh and Reddy, 2014**). They reported that *C. prolifera* can degrade diesel hydrocarbons within a certain concentration. The microbial diversity on the exposed seaweed has been altered and favored the growth of *Vibrio* species some of which have oil-degrading capabilities (**Graziano *et al*., 2016; Imron *et al*., 2019; Zhou *et al*., 2021; Caronni *et al*., 2023**). Indeed, there is bioremediation potential in the various consortia but there is more work needed to be done to make them actually effective.

Search for More Oil-Degrading Bacteria

Advancements in sequencing have made it possible for more potential microorganisms with oil-degrading capabilities to be detected, classified, and eventually studied. It has enabled scientists to study microbial diversity and perhaps the functional diversity of the community (**Guerra *et al*., 2018**). Most of the current studies regarding the search for oil-degrading bacteria have included 16s rRNA gene sequencing in the protocol which uses the differences in the sequences in the regions of the highly conserved 16s rRNA gene that encodes the smaller subunit of the bacterial ribosome to identify bacteria (**Kim *et al*., 2018; Gao *et al*., 2021; Yu *et al*., 2022**). Analyzing the sequences enables scientists to link the potential oil-degrading bacterium they have found to any well-studied bacteria and gain insights into its biology (**David and Berry, 2017**). Oil-degrading microorganisms for bioremediation are still scarce (**Gao *et al*., 2021**) but the high throughput and relatively quick sequencing provided by the current sequencers now could help in significantly increasing the number of oil-degrading microorganisms detected and classified.

Through the years, the number of identified oil-degrading microorganisms has been increasing thanks to the efforts of scientists. However, discovering new oil-degrading microorganisms is one thing but using them efficiently for bioremediation opens a door full of challenges.

BIOREMEDIATION CHALLENGES

One of the challenges hounding bioremediation efforts is the low degradation efficiency exhibited by the microbes. Degradation efficiency can be seen as how efficient the microbes are in breaking down the components of petroleum into simpler, less toxic compounds. The efficiency depends on many factors given that the petroleum components are complex and that the surrounding environment is not stable and the parameters can freely change (**Xu *et al*., 2015, 2018; Galitskaya *et al*., 2021**). But generally, degradation efficiency is highest if the components have lower molecular weights or simple structures (**Xue *et al*., 2015**). Currently, scientists are still searching for bacterial strains that have high degradation efficiencies. **Gao *et al*.** (2021) tried to find novel strains in Jiaozhou Bay, which is an area in Shandong, China that can efficiently degrade diesel. They isolated a strain of *Bacillus megaterium*, which they called MJ4, that has shown promise in the controlled laboratory set-up. The *B. megaterium* MJ4 was able to achieve a degradation efficiency of almost 71%. A similar study was done in Taean, South Korea where they searched for novel strains of oil-degrading bacteria. **Kim *et al*.** (2018) found the Co17 strain of *Gordonia* sp. to have the highest efficiency owing to it producing the enzyme, alkane hydroxylase, more than the other strains. Both studies have suggested that these strains should be used for bioremediation and it should be carried out as soon as possible in order to know their true degradation efficiency. Most of the time, the environment where they will be deployed will not have the conditions or parameters similar to those in the laboratory which can possibly dampen their degradation efficiencies (**Xu *et al*. 2018**). Additionally, most of the studies done tend to focus on the degradation of specific oil components but in reality, the bacteria would be exposed to a complex concoction of hydrocarbons to which some cannot be metabolized by the specific bacteria or can even be toxic (**Varjani, 2017; Pandolfo *et al*., 2023**).

Another challenge with bioremediation is the bioavailability of the target compounds. Hydrocarbons are typically hydrophobic which makes them clump together when they are in water. This makes it harder for bacteria to facilitate the breakdown of hydrocarbons through the action of enzymes such as oxygenases as the enzymes would need to contact the substrate but the bacteria cannot access most of the hydrocarbons (**Xu *et al*., 2018**). Surfactants which are chemicals that reduce surface tension are usually added to improve the emulsification of the hydrocarbons with water and allow bacteria to access more substrate (**Mohanty *et al*., 2013**). However, surfactants can be toxic to bacteria (**Kleindienst *et al*., 2015**). The task now is finding bacterial species that can produce biosurfactants without endangering the oil-degrading bacteria in the water. Bacteria under the genera *Bacillus* and *Pseudomonas* can produce biosurfactants that are more effective, more stable, and less toxic when compared to synthetic surfactants (**Desai and Banat, 1997; Pardhi *et al*., 2022**).

Yet another challenge with bioremediation is keeping the bacteria alive for a period of time to ensure the degradation of the contaminant. Enzyme production of bacteria meant for oil degradation may take some time as bacteria are not often exposed to petroleum or they may not use it readily given the availability of other substrates they naturally use. Oil degradation depends on the activity of the bacteria which is linked to the availability of nutrients and suitable environmental conditions (**Xu *et al*., 2018**).

Lastly, the toolbox for bioremediation is still limited. Oil-degrading microorganisms with high degradation efficiency are still scarce (**Gao *et al*., 2021**).

FUTURE PROSPECTS

Nations that often experience oil spills should invest in bioremediation research. The future of oil spill bioremediation rests on improving the degradation efficiency of bacteria and other microorganisms. Improvement can be carried out by finding new or existing microorganisms with better degradation efficiencies as well as those that produce useful compounds for microbial growth and petroleum degradation such as nutrients and surfactants, respectively. Aside from searching for microorganisms, scientists should study further the different interactions of various bacteria with other bacteria and with other microorganisms. These interactions will become the basis for which microorganisms can be grouped to form a consortium that can be used for bioremediation. Currently, there are promising consortia of bacteria, bacteria-fungi, and bacteria-microalgae but there should be more in the future. Additionally, conducting bioremediation research in a country, including the Philippines that has experienced massive oil spills may lead to the discovery of a natural consortium of bacteria with hydrocarbon degradation potential. The study of **Rodriguez *et al.*** (2023) showed the hydrocarbon degradation potential of different bacterial consortia from the samples taken from Guimaras, Philippines, a small island that experienced an oil spill last 2006. One consortium was dominated by *Klebsiella* sp., a bacterium that was not listed in the different reviews regarding hydrocarbon degradation. More research should also be done on the oil degradation potential of different seaweeds that grow in each country. As previously mentioned, seaweeds are home to many bacteria and **Carroni *et al.*** (2023) have demonstrated that certain species of macroalgae can degrade hydrocarbons to some degree with the help of the epibionts. For the Philippines, seaweeds are economically important commodities and comprise most of the bulk of aquaculture production. The main seaweeds grown in the Philippines are *Kappaphycus alvarezii*, *Gracilaria* spp., *Eucheuma denticulatum*, and *Caulerpa lentilifera* (**BFAR, 2010**). Scientists could look into studying the seaweed-associated bacteria in these species and perhaps an oil-degrading bacterium with high degradation efficiency or a biosurfactant-producing bacterium may be thriving in the seaweeds which can be a lot of help in future bioremediation efforts. With this potential venture, the use of metagenomics which is the culture-independent analysis of the entire genome of all organisms in an environmental sample (**Jackson *et al*., 2015**) can help in identifying and characterizing bacteria present on seaweeds exposed to oil as well as determining the bacterial diversity. The information gathered could greatly help in developing and/ or refining bioremediation strategies (**Guerra *et al*., 2018**).

CONCLUSION

Bioremediation remains a viable choice for removing petroleum products in the water as it does not involve the use of toxic substances and is relatively cheaper. However, there are still challenges that need to be overcome particularly in the improvement of the degradation efficiency of the microbes and the search for more oil-degrading bacteria in which high throughput sequencing is a useful tool. Increasing the degradation efficiency may be achieved by establishing different consortia of microorganisms. Each microorganism involved in the consortium may produce useful compounds or may be directly involved in the degradation of petroleum products. As for the search for additional hydrocarbonoclastic bacteria, seaweeds can also be a potential source of these types of bacteria. Despite the current limitations of bioremediation, its utility during oil spills is valued and its potential for further improvement is recognized.

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