A Comparison of Candidate Bacterial Species for Potential Bioremediation of Petroleum Contaminated Soil

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Abstract

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Soil petroleum contamination is a condition that has persisted since humans have refined crude oil and petroleum. Most commonly, soil petroleum contamination is associated with the release of petroleum from storage tanks into a soil medium. The release of petroleum into the environmental can cause health and well-being issues with humans as well as with the environment. One method to remediate petroleum contaminated site is the use of bacteria with the ability to biodegrade the petroleum hydrocarbons and petroleum by-products into a more environmentally safe by-product. Only a few bacterial genus and species are known to successfully biodegrade petroleum and petroleum by-products with a significant impact to the environment. The bacterial species that have the ability to degrade petroleum and petroleum by-products do so by producing biosurfacants which alter hydrophilic and hydrophobic properties of the bacteria organism and the contaminant of concern. Four bacterial genus, *Acinetobactor, Pseudomonas, Aeromonas, and Bacillus,* were researched to determine their abilities to degrade petroleum and petroleum-by products. Biosurfacants were determined to be a major factor in assessing a bacterial species' biodegradation ability. Research has shown that biodegradation ability is relatively high in the bacterial genus *Acinetobactor* and *Pseudomonas.* Biodegradation abilities were also determined to vary between species even within the same genus. Further research and studies of individual candidate bacterial species are necessary to determine candidate bacterial species to degrade petroleum contaminated soil.

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1.0. Introduction

Soil contamination is an environmental challenge that can cause acute and chronic adverse effects humans and other organisms. One of the more ubiquitous and detrimental substances associated with soil contamination is petroleum. Although petroleum is comprised of thousands of unique chemical analytes, the total petroleum hydrocarbons (TPH) fraction, which include C_6-C_{28} and polycyclic aromatic hydrocarbons (PAH) which include the fused-ring aromatic fraction are ecologically- and toxicologically-relevant. PAH includes chemicals such as pyrene and phenanthrene. Refined petroleum also includes volatile organic compounds such as benzene, toluene, and total xylenes (o-xylene, m-xylene, p-xylene) which affect the human and environmental well-being and have been determined to be carcinogenic.

1.1: Petroleum Composition

TPH (C_6-C_{28}) includes gasoline range organics (GRO) (C_6-C_{10}) and diesel range organics (DRO) (C_{10}-C_{28}) which are the primary range of petroleum hydrocarbons associated with commercial and industrial releases (ALS Environmental 2014). Petroleum in the form of DRO and GRO contains aromatic chemicals harmful to human and environmental health including benzene, toluene, total xylenes (o-xylene, m-xylene, p-xylene), naphthalene, and fluorene and alkanes including hexane (ATSDR 1999). Petroleum degradation depends on which class of hydrocarbon is most associated with the contaminated soil. Branched alkanes and small aromatics are easily degraded while aromatics and cyclic alkanes are more difficult to remediate (Das and Chandran 2010). The ease of degradation is generally correlated to molecular weight (Das and Chandran 2010).

Generally, petroleum releases in soil are associated with commercial properties, including gasoline stations and automotive repair shops, residences with a petroleum-based heating source, and industrial buildings that house petroleum-based products (Simons, Bowen, and Sementelli 1999). Most petroleum leaks, which cause the most widespread soil contamination, can go undetected for years. The majority of undetected leaks occur from underground storage tanks (USTs), which are only discovered during the tank's abandonment or replacement (Simons, Bowen, and Sementelli 1999). Leaks occur from underground tanks because of their old age and weathered material, thus, causing a release of its contents over time. On occasion, an undiscovered tank can be punctured due to construction or investigation activities, therefore, releasing remaining contents into a medium.

Petroleum releases are a high priority issue due to two factors. First, a majority of components of petroleum possess a high storage life, and therefore the compounds degrade slowly in a soil medium. Biodegradation success is commonly measured by half-life in various studies involving bacterial biodegradation. However, differentiating half-lives exist within the components of TPH and PAH due the variations in chemical structures with the different components. VOCs including benzene and toluene typically contain shorter half-lives due to the chemicals' nature to volatize to the environment in warm temperature conditions while other components of petroleum can remain in a soil environment for a longer period of time (Chang, Chang, and Yuan 2008). Second, they can be hazardous to human health. Petroleum exposure is known to cause acute and chronic respiratory issues (Luginaah et al. 2002). Volatile organic compounds (VOCs), including n-hexane and 1-butene, are the compounds mostly responsible for these respiratory issues. Benzene, a component of petroleum, is a known carcinogen (Luginaah et al. 2002). The main exposures methods for petroleum contaminated soil would be dermally through accidental handling or respiratory due to volatilization of chemicals.

1.2: Soil Remediation Approaches

The discovery of a contaminated area of soil typically initiates remediation efforts. The most common method of soil remediation includes excavation of the contaminated soil. With this method, heavy equipment, including bulldozers and excavators, remove the contaminated soil for disposal at a waste facility specialized in treating contaminated soil. The area of excavated soil is then replaced with clean soil taken from another location and the area is sampled for remaining contaminants and compared to a contamination reference level which can vary by municipality. The method is also cost-effective, because the necessary equipment is readily available in many places and has a relatively below cost of operation. A disadvantage of this method is the fact that the entirety of the affected soil is not being decontaminated. Delineation of soil contamination is hard to accomplish, and a margin of error exist with contamination outside of the planned excavation area. The original contaminated soil is simply being replaced and some contaminated soil may still remain, unless an additional method such as bioremediation is used in conjunction with the excavation method. The possibility of contaminated soil underneath and outside of the evacuation area could exist after evacuation activities have occurred due to factors such as leaching. In addition, the process disturbs the natural pedon of soil, causing structure and fertility issues (Guerin 1999).

An alternative method is the utilization of organisms to degrade petroleum by-products into less harmful substances with minimal soil disturbance, such as soil borings. This method would require an organism that has the capacity to accept electrons from petroleum components, therefore, transforming (e.g., remineralizing) the products into substances that are less harmful to the environment over a period of time (Liu et al. 2002). This method lowers toxicity levels in the affected area, with a lower soil disturbance compared to the excavation method, preserving a majority of fertility and soil structure (Liu et al. 2002). The process of biodegradation falls under a term "natural attenuation", which is the utilization of site-specific processes to remediate a contaminated site. The processes occur naturally and can act without human intervention (Jones and Wilson 1999). The method of utilizing bacteria for site specific remediation, however, would be classified as assisted biodegradation, due to the addition of bacteria to the soil. The success rate of assisted biodegradation is not as well known. The timeframe of the biodegradation method could potentially be longer to achieve non-toxic status for the affected land. Several additional factors can speed up the biodegradation process, by facilitating the volatilization of chemicals into the atmosphere, however this can be a challenge to accomplish at higher depths where volatilization is less common as opposed to leeching (Jones and Wilson 1999). A third method would be to combine the excavation and biodegradation methods. In this approach, the area of contamination would be delineated, excavated, replaced, and the waste would be taken to a facility specialized in containing hazardous waste as detailed in the excavation method. In the combination method, however, the waste would then be treated with biodegradation organisms to break down hazardous petroleum by-products into non-hazardous materials and then the treated soil could be used for future fills. This combination method could have the potential to speed up the biodegradation aspects of the process. Additionally the natural pedon of soil would still be disturbed causing potential fertility and structural issues. The same problems arise with unknown success rate and time constraints with the biodegradation aspect of the combination method.

1.3: Petroleum Degradation

The degradation of petroleum by-products is a multi-step process. Several factors can affect the effectiveness and timeframe in which an organism can degrade the petroleum by-products including temperature, pH, and availability of nutrients (Das and Chandran 2010). Additionally, an organism that can successfully survive in a soil medium and degrade petroleum by-products into a non-hazardous substance needs to be identified. Second, the rate of degradation and time required to achieve a non-toxic threshold needs to be determined, for the identified organism as well as appropriate pH, temperature, and nutrient requirements to maximize effectiveness.

One of the properties which can be used as a proxy to determine the effectiveness of a bacterial species to degrade petroleum contaminants is its production of biosurfacants. Biosurfacants are agents that are produced by certain types of bacteria which have the ability to lower surface and interfacial tensions of liquids (Hamed et al. 2012). The biosurfacants are composed of lipids and fatty acids which cause the alteration of hydrophilic and hydrophobic properties of the bacteria and liquid (Hamed et al. 2012). The properties of the biosurfacants allow the bacteria to facilitate petroleum by-products more readily thus allow for a higher rate of biodegradation (Hamed et al. 2012). Biosurfacants also have the advantage of promoting bacterial growth and are effective in extreme pH, temperature, and saline environments (Hamed et al. 2012).

In order to study the effectiveness of the biodegradation method, organisms need to be selected based on their suitability to survive within a soil medium and their ability to degrade numerous petroleum constituents . Many microorganisms are capable of utilizing petroleum hydrocarbons as their energy (carbon) source and thus are already well-suited to surviving in contaminated soils. Survival of a microorganism in the presence of TPH influences the rate of assisted biodegradation and is a factor that can be used to determine the likelihood of long-term biodegradation success (Das and Mukherjee 2006). A literature review was conducted to provide a comparison and provide supporting information on several potential organisms, which could be utilized to provide assisted biodegradation at a petroleum contaminated site. The organisms studied will be compared based on degradation rates of petroleum by-products, survival rates within a clay-based soil medium and a sand-based soil medium, thus comparing their strengths and weaknesses to facilitating the assisted biodegradation process of petroleum contaminated soils.

2.0. Methods

This study is intended to serve as a literary review based on published, peer-reviewed studies on bacteria species and their properties in bioremediation of petroleum contaminated soils.

Four candidate bacteria genus were selected as the focus of this literary review: *Acinetobactor, Pseudomonas, Aeromonas,* and *Bacillus.* These four bacteria genus were selected based upon previous studies documenting their metabolic abilities to decompose petroleum substrates into less harmful by-products (Vasudevan and Rajaram 2001). Properties of the bacteria were studied including its physiology in the process of breaking petroleum, which chemical derivatives of petroleum yields a higher rate of decomposition for a bacterial species and what end by-products are produced as a result of each bacteria species transforming the released petroleum within a soil medium. A key factor used to compare the biodegradation rate for this study was emulsification index/percentage.

Half-life is a measurement that was compared between different contaminants arising from petroleum releases. The half-life values by different bacterial species were compared to original values to determine if the bacteria metabolic processes influenced the degradation of petroleum and petroleum by-products.

Control variables were identified within each study and recorded to determine which variable would be significant to influence a bacterial species' rate of biodegradation. These factors included location of the study, the medium in which the biodegradation of petroleum had occurred, and the optimal temperature of degradation based on the studied medium. The location of the of the study can influence the temperature of the medium, thus creating varying results of degradation.

3.0 Results

3.1. Properties of Candidate Bacteria

3.1.1: Acinetobactor:
Acinetobactor is one of the well-studied genus of bacteria for soil bioremediation. *Acinetobactor* can naturally grow on crude oil and contains a property that produces emulsifiers. The bacteria utilize the hydrocarbons in DRO-GRO as an energy source which as a result degrades the oil. The emulsifiers that the *Acinetobactor* produce as they are attached to the hydrocarbon, allows the oil to disperse, increasing the surface area for the bacteria to grow thus subsequently increasing biodegradation rate (Ron and Rosenburg 2002). This genus of bacteria was chosen as

a candidate species due to its ability to produce emulsifiers and its documented history of bioremediation of contaminated soil.

3.1.2: Pseudomonas:

Pseudomonas contains extensive properties for facilitating bioremediation by mobilizing polluted hydrocarbons and transforming them into an aqueous phase, thus allowing the expulsion of the hydrocarbons from a soil medium. The bacteria encode several hundred transporters in order to uptake substrates for bioremediation (Silby et. al 2011). *Pseudomonas* bacteria were chosen as candidate bacteria in this study due to its ability to mobilize hydrocarbons and transforming the hydrocarbons into a more soluble product.

3.1.3: Aeromonas

Aeromonas is a genus of bacteria which generally degrade different types of protein. The bacteria genus acts similar to *Acinetobactor* which transforms hydrocarbons from DRO-GRO into useable energy for the bacteria, thus degrading the oil. The bacteria genus also produces emulsifiers which promotes the facilitation of bacterial growth (Kaczorek et. al 2014). This genus of bacteria was chosen as a candidate bacteria due to its documented history of bioremediation success and its ability to produce emulsifiers.

3.1.4: Bacillus

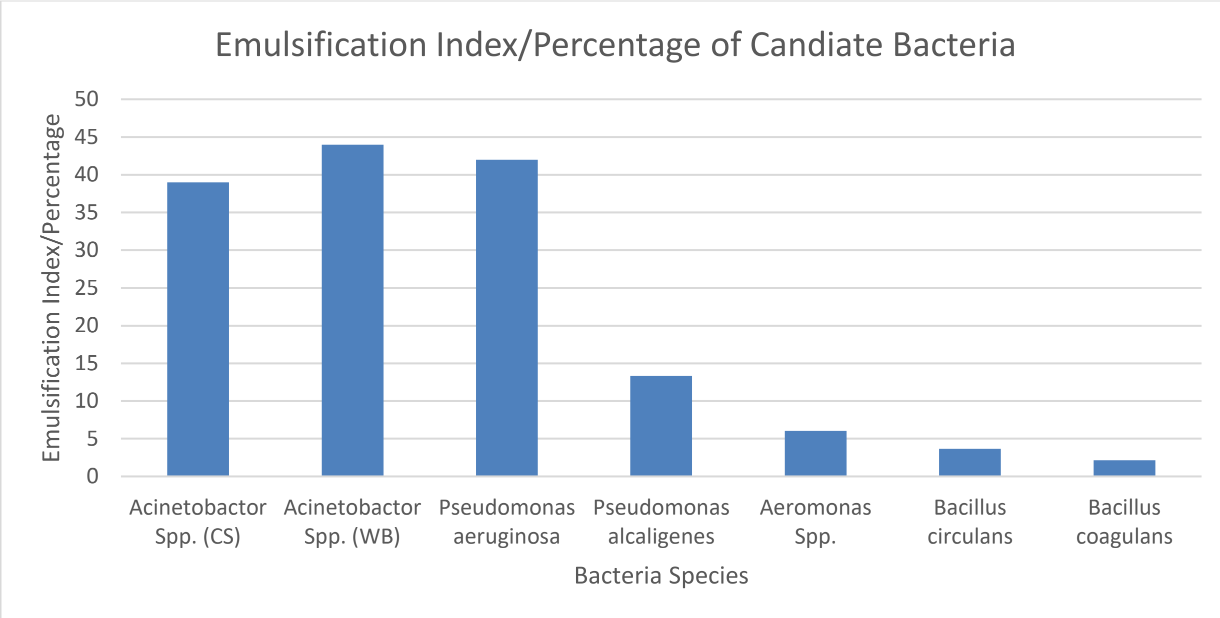
Bacillus functions similar to *Aeromonas, Pseudomonas,* and *Acinetobactor* in regards to its biodegradation properties. Bacteria strains from the *Bacillus* genus cultivate on petroleum hydrocarbon molecules and produce biosurfacants which are compounds that allow an organism to reduce its surface and interfacial tension (Fakruddin 2012). This property of certain bacteria, including strains from the *Bacillus* genus, to more readily uptake chemicals including DRO-GRO (Fakruddin 2012). The addition of bacterial species from the genus *Bacillus* have been proven in studies to enhance the process of bioremediation and assisted bioremediation in petroleum contaminated soils by facilitation of biosurfacants (Das and Mukherjee 2006). *Bacillus* bacteria were chosen as a candidate species of bacteria for their ability to produce biosurfacants and their documented history of success regarding bioremediation.

3.2. Comparison of Rates of Degradation

3.2.1: Biosurfacants and Emulsificators

Production of biosurfacants is a good reference value to assess the biodegradation properties of bacteria. Biosurfacants act as emulsifiers and thus an emulsification index can be used to determine the percentage of biosurfacants a strain of bacteria produce (Satpute et al. 2008). The production level of biosurfacants a bacterial species is assessed through its emulsification activity. This value was found in studies as an emulsification index or percentage. **Figure 1** shows the comparison of emulsification indices/percentages found through literary review regarding each candidate genus.

Figure 1:



CS: Caspian Sea
WB: West Bengal Bay
(Satpute et al. 2008)
(Hamed et al. 2012)

Figure 1 depicts the genus *Acinetobactor* as having the highest emulsification index/percentage with a maximum value of 44 percent, while the genus *Bacillus* contained the lowest index/percentage with a minimum of 2.13 percent. The genus *Aeromonas* contains relatively low emulsification index/percentage in comparison to the bacterial species with emulsification indices/percentages. The two *Pseudomonas* bacteria species emulsification data was discovered contained a wide variety of emulsification indices/percentages with 42 percent for *Pseudomonas aeruginosa* and 13.34 for *Pseudomonas alcaligenes*, suggesting that emulsification activity varies greatly in the *Pseudomonas* genus. Additional control factors including temperature, pH, and climate of the environment in which the bacteria study was conducted might also account for the differences between emulsification indices/percentages of the species studied.

3.2.2 Volatile Organic Compound Degradation: Benzene, Toluene, and Total Xylenes

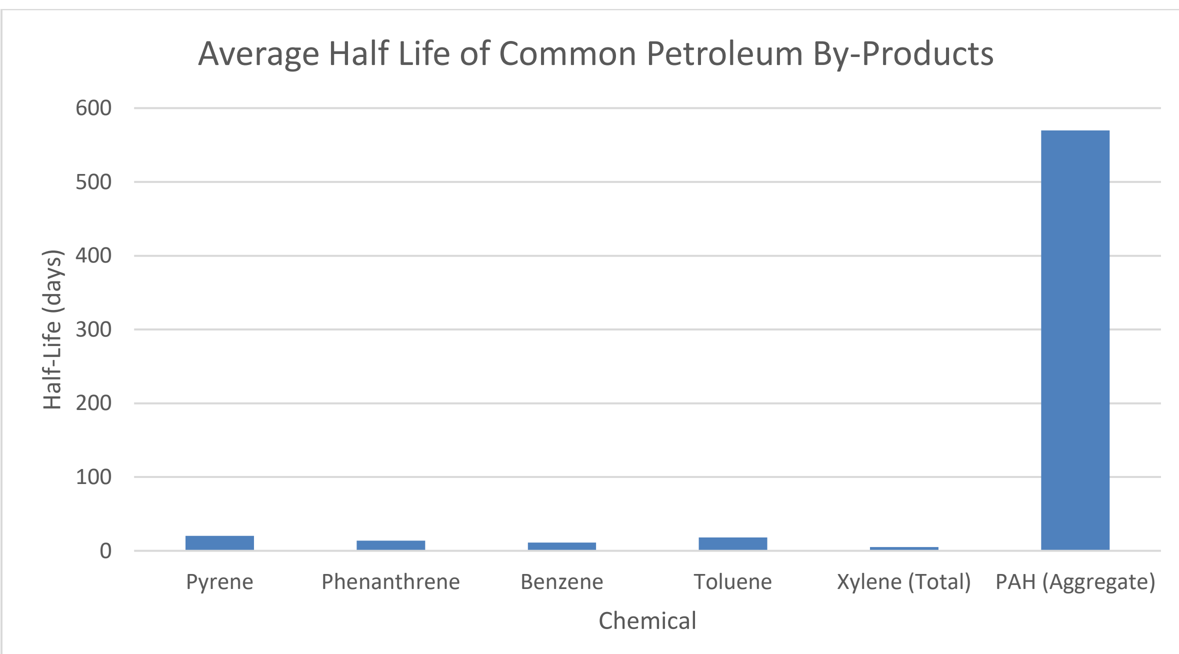
Benzene is a chemical that can be biodegraded by certain species of bacteria in soil within aerobic conditions. Previous studies confirmed that *Pseudomonas putida* can biodegrade benzene to carbon dioxide through the reduction of *cis*-1,2-dihydroxy-1,2-dihydrobenzene within 7 days of contact (ATSDR 2007). Conversely, benzene degradation by *Pseudomonas putida* can be hindered through the presence of additional substances such as toluene and total xylenes and were reported no degradation in a study with a maximum induction time of 26 hours (Otenio et al. 2005) Ultimately, only a few number of bacteria species exist in soil that have the ability to biodegrade and mineralize benzene (ATSDR 2007).

Toluene biodegradation is dependent on environmental factors including pH and temperature and the level of toluene degradation can be hindered with a highly acidic or basic pH. Optimal toluene degradation occurs in an environment with a pH ranging from five to eight (ASTDR 2017). The level of toluene contamination within a soil medium can have an effect on the level of biodegradation as toluene-degrading bacteria require a concentration of the chemical to maintain its biodegradation activity. (ASTDR 2017). Biodegradation activity of toluene can occur in anaerobic or aerobic soil environments. *Pseudomonas putida* is a bacterial species that is known to degrade toluene within a soil environment. The bacteria oxidizes the toluene, forming benzoic acid which is metabolized further into benzoic acid by-products (Shinoda et al. 2004).

Total xylene removal processes are dominated by volatilization to the atmosphere, however, biodegradation can still be a method to remediate xylene contaminated soil. Similar to the biodegradation methods of toluene and benzene, total xylene can be biodegraded through bacteria, such as *Pseudomonas putida*, through its metabolic pathways (Otenio et al. 2005). Candidate bacteria capable of biodegrading total xylene can transform the xylene into 3-methyl benzyl alcohol.

Chemical structure and properties can affect its speed of degradation. Half-lives from petroleum by-products are compared in **Figure 2**. The half-lives depicted in **Figure 2** are the result of chemicals natural processes and the breakdown depicts the difference of a chemical's half-life due to its structure.

Figure 2:



(ATSDR 1999)
(ASTDR 2007)
(Chang, Chang, and Yuan 2008)

Most of the chemicals studied have relatively low half-lives with total xylenes as the minimum at five days. PAH contains a high half-life at an average of 570 days. Half-lives in this study were conducted in a soil matrix.

The presence of certain chemicals can slow the rate of biodegradation. **Table 2** summaries results from a 2005 study comparing degradation rates of total xylenes, benzene, and toluene by *Pseudomonas putida* (Otenio et al. 2005).

Table 2: Comparison of Degradation Rates of Benzene, Toluene, and Xylene (BTX) by *Pseudomonas putida*

Chemical Substrate	Induction Time (hr.)	Volumetric Degradation Rate (mg solvent $L^{-1}h^{-1}$)
Benzene	19.0	0.00
Toluene	19.0	5.32
Xylene	19.0	2.55
Benzene and Toluene	0.0	0.00
	26.0	1.45
Benzene and Xylene	0.0	0.00
	16.5	1.20
Toluene and Xylene	19.0	3.37
	19.0	2.18
Benzene, Toluene, and Xylene	0.0	0.00
	16.5	2.31
	16.5	1.29

(Otenio et al. 2005)

Table 2 depicts how the biodegradation rate of BTX slows as benzene is introduced. Induction time represents the time the chemical takes to reach a certain state. In this study, the induction time is represented as the time the chemical takes to reach its half-life. The volumetric degradation rate is this study is the rate in which a chemical reaches the half-life within the solvent used during the study. Benzene causes *Pseudomonas putida's* ability to degrade toluene and xylene to diminish by one-half fold.

3.2.2: Limiting Factors

Various limiting factors can affect the biodegrading properties of hydrocarbons, regardless of bacteria species or properties including temperature of the matrix and nutrient availability.

As depicted in **Table 1**, the majority of candidate bacterial studies were conducted in sea water with two studies occurring in a soil matrix within a variety of locations including India, Tunisia, Taiwan, and Portugal.

Temperature can alter the solubility properties of hydrocarbon molecules, facilitating the uptake and utilization by bacterial species (Das and Chandran 2010). The optimal temperature for a maximum of degradation occurs in 30-40 degrees Celsius in a soil matrix and 15-20 degrees Celsius within a seawater matrix (Das and Chandran 2010).

Nutrient availability of nitrogen, phosphorus, and iron can improve the ability of bacteria to biodegrade petroleum hydrocarbons. Studies have shown that the anthropogenic addition of nitrogen and phosphorus can assist in the biodegradation process by stimulating bacterial growth, however there is an upper limit of nutrient levels where the bacteria's biodegradation properties decrease (Das and Chandran 2010). These studies, however, were conducted in a water matrix.

4.0 Discussion

Biosurfacants production appears to be a leading indicator to determine biodegradation success. The biosurfacants produced by bacteria allow a more diffuse pathway for the absorption of petroleum by-products by creating a more hydrophilic surface on the bacteria itself. Bacteria which are known to produce biosurfacants are correlated to higher biodegradation abilities, with a higher production rate associated with a higher biodegradation rate. The bacterial genus *Acinetobactor* and *Pseudomonas* contain relatively high levels of biosurfacant production as shown in **Figure 1**. The data shown in **Figure 1** would suggest that bacteria from the genus *Acinetobactor* and *Pseudomonas* are generally high producers of biosurfacants and thus have a high ability to degrade petroleum and petroleum by-products. **Figure 1**, however, contains a significant variety between the two *Pseudomonas* bacterial species researched in this study. *Pseudomonas aeruginosa* contained a high level of biosurfacant production (44 emulsification index) when compared to *Pseudomonas alcaligenes* (13.34 emulsification index). The resulting difference between the two *Pseudomonas* species can be attributed to species differentiation in which biosurfacant, and thus biodegradation ability, is somewhat unique to each *Pseudomonas* species. This fact can also not be ruled out for each of the bacteria species studied.

Determining the type of chemical contaminated in soil appears to be a factor in determining a remediation plan for a contaminated site. **Figure 2** displays how chemicals can have varying half-lives. Chemicals such as BTX, pyrene, and phenanthrene were determined to have relatively low half-lives while PAH contained an extremely high half-live, compared to the six chemicals involved in the study. Half-lives can differ due to the structure and physiology of a chemical. This information can factor in to how long one might expect remediation of a site to last and what resources need to be applied to the contaminated site to ensure proper remediation. The type of chemicals present in a contaminated site can also determine the rate in which biodegradation can occur as shown in **Table 2**. **Table 2** displayed how benzene, a chemical that is not degraded by *Pseudomonas putida*, can retard the bacteria's ability to degrade xylene and toluene. This phenomenon might be attributed to how benzene's chemical structure and properties hinder *Peudomonas putida's* ability to degrade xylene and toluene.

A majority of the bacterial degradation studies researched occurred in a seawater matrix in tropical climates as displayed by **Table 1**. **Table 1** also displays varying optimal degradation temperature for seawater and soil matrices. Environmental factors have been discussed in additional studies to directly affect the degradation rate of petroleum and petroleum by-products. This observation can also be applied to environments with a low or high temperature, high pH, or high salinity as some contamination site could occur in frigid climates or sites containing an extremely low or high pH. Biosurfacants have been effective at growing in extreme pH or temperature environments but the question of what the environmental limiting factor of biosurfacants is something that could be studied further.

5.0 Data Gaps/Limitations

In addition to identifying data which would determine potential bacterial species ideal for bacterial biodegradation of petroleum contaminated soil, the study also identified data limitations which further research would assist in identifying candidate bacteria. One noticeable observation with the data collected is that all of the bacterial biodegradation studies occurred in a seawater matrix with the exception of two studies as summarized in **Table 3**. Variations in the matrix have been shown to alter bacterial biodegradation properties including the temperature for optimal biodegradation. Physical properties of the matrix might alter the level of bacterial biodegradation. A soil matrix contains sorption and adhesion properties to the soil pores and clay colludes, and cation exchange capacity. This could differ from seawater properties including tidal forces, hydrophilic and hydrophobic properties altering the process of biodegradation. Further research of bacterial degradation in a soil matrix would be vital for future study. **Table 3** summarized the studies researched and their attributes for this assessment.

Table 3: Summary of Studies Researched

Author	Study Location	Bacteria Studied	Matrix Studied
N. Das and P. Chandran	Mumbai, India	*B. subtillis, B. sphaericus*	Seawater
Bea V. Chang, I. T. Chang, and Shaw Y. Yuan	Guandu and Zhuwei Mangroves, Taiwan	*B. pumilus*	Soil
S. Satpute, B. D. Bhawsar, P. Dhakephalkar, and B. A. Chopade	Caspian Sea and The Bay of Bengal	*Acinetobactor spp.,*	Seawater
S. B. Hamed, L. Smii, A. Ghram, A, Maaroufi	Bizerte, Tunisia	*P. aeruginosa, P. alcaligenes, Aeromonas spp., B. circulans, B. coagulans*	Seawater
M. H. Otenio, M. T Lopes da Sliva, M. L. Oliveria Marques, J. C. Roseiro, E. D. Bidoia	Frielas, Portugal	*P. putida*	Soil

A second data gap would be the limited studies varying species within a genus. A majority of studies involved *Pseudomonas* and *Acinetobactor* with a limited amount of studies involving *Aeromonas*. In addition, **Figure 1** shows a trend that bacterial degradation and vary between species within the same genus, notably with *Pseudomonas*. Future research needs to test a wider variety of bacterial species with known biodegradation properties.

Literary journals researched did not have many studies related to the direct observation of biodegradation of chemicals by the candidate bacteria. This potential study could directly test the effectiveness of bacteria degrading petroleum and petroleum by-products by observing how long the bacterial degradation process takes to reach the contaminants half-life.

6.0 Conclusion

Based on research, the bacterial production of biosurfacants acting as emulsifiers is a major indicator of a bacteria species' biodegradation ability. Research also shows that bacterial genus *Acinetobactor* and *Pseudomonas* have abilities to significantly facilitate biodegradation of petroleum and petroleum by-products. The bacterial genus *Aeromonas* and *Bacillus* have also displayed signs of petroleum and petroleum by-product biodegradation with degradation rates lower than those of *Acinetobactor* and *Pseudomonas*. Biodegradation abilities in bacteria are also varied between species even in species within the same genus. Data related to bacterial biodegradation of petroleum, however, is limited and further research would be required to further determine candidate species to biodegrade petroleum contaminated soil.

Attachments

Table 1: Comparison of Candidate Bacterial Properties and Studies

7.0 References

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