Resources, Environment and Sustainability 2 (2020) 100008

Contents lists available at ScienceDirect

Resources, Environment and Sustainability

journal homepage: www.elsevier.com/locate/resenv

# Bioremediation of oily sludge: A case base analysis to sustainable supply chain

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ARTICLE INFO

*Keywords:*
Sustainable reverse chain
Petrochemicals
Bioremediation
Oily sludge
Environment protection

ABSTRACT

Sustainability as an important topic has drawn considerable attention across the globe. Any business environment concentrated on maintaining a delicate balance between 3P's of *people, planet, and profit*. In today's globalized business environment, firms make every effort to keep the environment protected within their chain of operations. Petrochemicals are hazardous items creating pollution for the planet earth. A traditional solution like the banishment of unlined soak ways or evaporation of ponds is tough to implement; thus take significant time, resources, and money. Bioremediation seems to be an alternate solution of the sustainable reverse chain towards the restoration of resources over traditional methods like Incineration or Landfilling. Here, an experimental (pilot) study has been undertaken with a Middle East Oil and Gas company for evaluation of the bioremediation process for getting rid of oily sludge of unlined soak ways. In line with this, the application of Oil Spill Eater II and its successful adoption towards the successful implementation of bioremediation is discussed. The outcome of the study explores the efficacy of using OSE-II over traditional methods in line with techno-economic viability to sustainability.

## 1. Introduction

Over the decades, capitalistic philosophies move on the exploitation of physical resources of the planet earth to meet only the economic viability without the concern for the environment. With a threefold concept embracing environmental, social, and economic aspects of sustainability as known under this concern in relation to this triple-bottom-line (Cegarra-Navarro et al., 2016). The need for balancing these aspects within the business chain has become a major challenge to sustainable (green) supply chain management. Therefore, it is established long back that, there is a dire need for companies to balance ecological and social sustainability along with economic viability in line with the long term sustainability (Elkington, 1994).

The supply chain is considered as the contemporary flow through which various interconnected work systems of business operations are being driven for value creation and maintenance (Ahmad et al., 2016). With globalization, supply chains are facing greater risks and ethical dilemmas. New types of risks such as reputational and resource (sustainable) risks are becoming more critical. There is now an emerging realization that the types of businesses seen as desirable by society are those that behave responsibly towards shareholders, stakeholders, society, and the environment. Business organizations are, therefore, continuously undertaking several initiatives to plan, design, and implement sustainable practices in their work systems. The focus has been centered towards maintaining the delicate balance between 3 P's of sustainability; highlighting embraces the triad of '*profit–people–planet earth*' (Kleine and Hauff, 2009; Dubey et al., 2016).

Global economy is predominantly dependent on the Oil and Gas sector. However, this sector has a negative impact on the environment as well as society (Arscott, 2004). The Middle East is the home of liquid gold (Ali et al., 2019). During a couple of decades, it helped all these countries to prettify their Gross Domestic Products, enhancing the standard of living, and make the world notice them with awe. Though traditionally the petrochemicals are hazardous in nature, a significant resource is utilized to offset the pollution effect from those. Initially, when these Oil & Gas conglomerates started their explorations, these Middle East kingdoms were at their infancies. Off late municipalities are trying to contain pollutions and discharges through local laws and orders, but first explorations and subsequent productions were the bottom line during those initial years (Berman and Bui, 2001).

Economic growth and prosperity are fundamental imperatives in today's competitive and globalized marketplace for any humankind. However, the '*science of sustainability*' has taken on a sense of urgency in recent years as mounting evidence suggests that adverse change of environment effects drastic reduction in agricultural yields as well as the depletion of energy, loss of natural resources and water to affect the quality of human existence and its own sustainability. Data

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https://doi.org/10.1016/j.resenv.2020.100008
Received 9 August 2020; Received in revised form 26 November 2020; Accepted 26 November 2020
Available online 30 November 2020

pertains to the growth of global primary *energy demand* in response to industrialization, urbanization, and societal affluence has led to a greater than 35 percent increase in total consumption from all sources of just under 10,000 million tonnes of oil equivalent (Mtoe) in 2000 to about 13,500 Mtoe in 2015 (Enerdata, 2016).

Reverse supply chain plays the role of chains in product returns, source reduction, re-use of materials, materials substitution, waste disposal, recycling, refurbishing, repair, and re-manufacturing. Essentially, the systems required to take care of waste in a responsible, effective and sustainable way that as it concerns mainly the reverse direction of a typical supply chain. This is synonymous with material recycling and waste management in an effort to minimize cost, retrieve the value from reverse flows, and fulfills legislative and environmental requirements in a more sustainable way (Fathollahi-Fard et al., 2020a; Yu et al., 2021; Fathollahi-Fard et al., 2020b and Eftekhari et al., 2020d).

In recent years, due to increasing regulatory and competitive pressures, industries have started looking into alternatives to simply allowing end-of-life products to be land-filled. More companies are now building the *reverse chain* infrastructures and practices required to reduce, reuse, recycle, and recover the products they produce. Some companies' even embracing environmental leadership have demonstrated that it is possible to create a truly closed-loop supply chain without becoming more expensive than their competitors. The regulation of extended producer responsibility will further drive investment in reverse chaining and recycling, which will in turn drive further innovation and investment.

Research published in *Nature* in 2013 predicted that the rate of global solid-waste generation will exceed 11 million tonnes per day by 2100 if we continue to create waste following a *'business-as-usual'* attitude (Hoornweg et al., 2013). This rate is more than three times the rate in 2013. Such gigantic amounts of waste can cause significant public health and environmental problems, and if our waste continues to end up being landfilled and incinerated this will speed up pollution, global warming, and the depletion of natural resources (Abdi et al., 2019). This is a complicated issue as waste is generated by a long line of supply chain members, from material extraction to consumer consumption and disposal of end-of-life products (Liu et al., 2020).

With the rise of new enterprises making reuse, refurbishing, remanufacturing, upcycling, recycling and energy-from-waste commercially viable, researchers now try to explore many more possibilities for creating a 'green circular economy'. It aims to regenerate biological nutrients and restore technical nutrients. Resource efficiency is the key; which means the emphasis on working hard to manage waste created by industries and people, so-called 'waste management', has to be replaced by a 'waste and resource management' perspective. This problem is created by a 'linear economy' model that relies on simply the 'taking, making and disposing' of natural materials. Instead, a 'circular economy' approach that produces no waste and no pollution is required.

Recently, the researchers try to explore several interdisciplinary optimization approaches under different stochastic and fuzzy environment to address the green issues in concerned to the following multidisciplinary area(s) of application. Research relates to green supply chain network for production–inventory problem refers to Karampoura et al. (2020), Artificially intelligence based meta heuristics for scheduling in cross docking and fuzzy environment (Fathollahi-Fard et al., 2019a,b, 2020c), possibilistic–stochastic programming to address resilient green logistics (Nezhadroshan et al., 2020), greening in healthcare supply chain under fuzzy environment (Fathollahi-Fard et al., 2020a), sustainable closed loop supply chain (Fathollahi-Fard et al., 2020b), multi-objective strategic sourcing under fuzzy environment (Safaeiana et al., 2019), Lagrangian based algorithm for natural resource management (Fathollahi-Fard et al., 2020d), and many more. Rationale, context and significance of the present problem of bioremediation of oily sludge is thus established in line with a problem of sustainable reverse chain and its optimization; and accordingly highlight the following issues as a major concern for further research:

- Sustainable reverse chain to bring back the originality of natural resources while in operation in terms to economic, social, and environmental balance(s) highlighting embraces the triad of *'profit–people–planet earth'* (Baumgartner and Ebner, 2010).
- There is a mismatch of occurrences in the Petrochemical sector (especially for Oil and Gas sector) where reverse chaining of waste hazard materials into a usable form is of serious concern.
- Companies are searching for better techniques over the traditional ones in order to reverse chaining of hazard elements into a reusable form Liu et al. (2020).

Remainder of the paper is as follows: Section 2 discusses the bioremediation as an efficient reverse technique towards natural balance that may adopt as managing sustainability in their supply chain operation. Section 3 establishes the research statement with a close view of use of OSE-II as an experimental way. Section 4 is the development of a case study. Managerial implications are discussed in Section 5. Conclusion with limitation and future direction is discussed in Section 6.

## 2. Bioremediation with oil spill Eater II - a sustainable chain

In the refinery, the process flow of the supply chain in Oil and Gas generates oily sludge as waste end products. Out of the wastes, Oily sludge is treated as one of the most voluminous solid wastes generated in the refinery. In a production floor, it is generated and extracted while periodic cleaning of crude oil and refinery products storage tanks (Dotson et al., 1972). Oily sludge is basically a complex emulsion of several petroleum hydrocarbons (PHCs); mixed with some solid particles and heavy metals (Genouw et al., 1994). These wastes are poorly biodegradable constituting an environmental hazard to human health. The major challenge is its safe disposal without affecting the environment. Many of the constituents of oily sludge are carcinogenic and potent immune-toxicants (Ivshina et al., 2015). Disposal of oily sludge is treated as hazardous wastes. Again, the discharging process wastes at unlined soak ways are a serious concern to any environment. As a commitment to municipal local regulations and showing environmental leadership, some Oil & Gas companies employed Waste Water Treatment Plants (WWTP). Effluent Treatment Plant (ETP) is not now a new concept to these O&G corporations, which are mainly controlled by the royal families of the gulf region. Review of Middle East Environment Protection Regulations are highlighted in Appendix A (Dubai Municipality Local Order 61 of 1991: Environment Protection Regulations and Federal Law of 24 of 1999: Protection and Development of the Environment)

Some persisting problems still remain, like the existence of the unlined soak ways, some of which are not in use though. Hazardous wastes which are remained in these unlined soak ways still extremely very high in quantity and continue polluting the surrounding land and the groundwater. Banishment of these unlined soak ways or evaporation ponds is not easy and can take significant time, resource, and energy (Christopher et al., 2004).

The Table 1 shows the level of contaminations of surrounded boreholes of a particular evaporation pit. Some of the numbers (in an Italic form) are way significantly very high from the local municipality environmental standards.

Oil-contaminated soil has known to be a polluted resource that directly degrades the environment (NRC/NAS report, 2005). Again, high concentrations of Total Petroleum Hydrocarbons (TPH) in soil cause a significant degradation in farming thus affect the environment. Due to its hazardous nature, the safe disposal of oily sludge has attracted serious attention to floor managers as well as academic researchers. Refineries use a number of traditional method(s) to decontaminate the shop floor in a more sustainable way. Conventional disposal methods involve storing in sludge pits, incineration, land-filling which are expensive to construct, having land restricted issues, and with problems in relate to environment.

**Table 1**
The oil & grease-free oil maximum allowable limit for discharge to land as for irrigation is 5 mg/l and for sewage system 50 mg/l. Test method: APHA 5520 B.

| *Borehole* | *Dec., '08* | *Oct., '09* | *April, '10* | *Oct.,'10* | *April, '11* | *May,'12* |
|---|---|---|---|---|---|---|
| BH1 | 17 | *531* | <5 | 05 | N/A | <5 |
| BH2 | 36 | 34 | <5 | 15 | N/A | <5 |
| BH3 | 17 | 09 | <5 | 05 | 06 | 05 |
| 7A | 49 | *2980* | *3926* | *535* | *430* | *1168* |
| 7D | 01 | *7063* | 23 | 66 | 12 | 20 |
| 7E | *260* | 18 | 25 | 56 | 06 | 27 |
| 7F | 16 | <5 | <5 | <5 | <5 | <5 |
| 7G | 31 | – | <5 | 48 | 08 | 07 |
| 7H | 38 | *2847* | *3870* | *393* | *449* | 659 |

Recently, researchers try to explore an alternate method over the traditional ones that use microorganisms for *in situ* degradation in the soil. Using enzymes and biomaterials, these eco-friendly approaches may be used in order to reduce the concentrations of hazardous wastes at a contaminated site and in parallel revert back the natural environment. In search of these, most refineries presently adopt the technique of bioremediation (Prado-Jatar et al., 1993). As a state-of-the-art technique, the process of bioremediation employs natural ecological evolution to complete elimination of toxic contaminants (Naughton et al., 2003). During operation, the process of bioremediation can include different fertilizers, bulking agents, and also some chemicals that are used for oil dispersants. Bioremediation makes use of living organisms to eliminate toxic pollutants. These organisms may be naturally occurring and they either eat up the contaminant (and/or assimilate) within all hazardous compounds; thereby make the area contaminant-free (Rosenberg et al., 1992). One of the significant benefits is that: *this process is cost-effective with less technological complexities and can be operated out on-site (in-situ) or off-site (ex-situ)* (Erdogan and Karaca, 2011). Below in Table 2, we highlight the different in-situ and ex-situ bioremediation techniques with their merits as well as demerits in support with literatures.

In any contaminated site, bioremediation typically works in any one of two directions: *growth of whatever pollution-eating microbes might already be living at the contaminated site, and adding specialized microbes to degrade the contaminants.* Once started operational by this bioremediation processes, the following significant changes will have to monitor: *sufficient bio-surfactants to start emulsification and solubilization processes; fire hazard and toxicity started declining with no odor (smell), and oil or spill started adheres to anything.*

There are several ways to treat this unlined evaporation ponds — chemical, biological, and the like. Even for the chemical processes, there are organic and inorganic ways. All remediation is costly exercises. To start with this experimental (pilot) study, an American firm named BESCO Ltd. was finally shortlisted. BESCO is one of the leading firms worldwide who is the expert in the field of successful implementation of Oil Spill Eater II.

Oil Spill Eater II popularly known as OSE II is the world's one of the most environmentally safe and cost-effective bioremediation products. It is known for its efficacy in optimizing hazardous waste, spills, and waste contamination. Being cataloged to the US Environmental Protection Agency's National Contingency Plan for Oil Spills, it has a chemically developed efficient nutrient system which is activated once mix the product with natural water; following *'water native to the spill environment'*. OSE II contains a chemical composition of enzymes, bio-surfactants, nutrients in a perfect measured ratio used for bioremediation. Significant benefits of using OSE-II over traditional approaches can be summarized. They are: *reduction of clean-up costs with optimizing hazardous waste and with no need for secondary clean-up; workability and efficiency of OSE II that converts the waste into a natural food source for the native bacteria found in the environment, and most importantly, addition to a hydrocarbon spill need not necessary to wait on the proximal bacteria to release enough enzymes or bio-surfactants.*

Summarizing, all the above discussion, the following issues are significant and need serious attention:

- Bioremediation of oily sludge may be viewed as a problem of sustainable (supply) reverse chain.
- OSE-II technique may be, thus, handy for any environmental decision-makers to bring back natural resources by the process of a reverse chain.

## 3. Problem statement

Sustainable operation with Oil and Gas sector keeping the environment protected led to serious concern for all stakeholders (Ahmad et al., 2016). Removing petrochemicals and toxic substances through the reverse process from the soil is both time and cost-constrained issue. Significant delays to reuse contaminated sites directly affect economic viability. Applying Bioremediation, companies sustain a reversing process in the supply chain by targeting specific soil contaminants.

Under the backdrop, this pilot study is an attempt to fulfill the following gaps as find it imperative to study further:

- Bioremediation of oily wastes research with the application of microbes, bacteria, fungi, algae, water hyacinth, or even cow dung or poultry droppings were quite common and frequently available.
- To some extent the research was also carried out on bioremediation of oily wastes through bio-surfactants. EPA approved Oil Spill Eater II (OSE II) is primarily used to control and contain the oil spills biologically.
- OSE II was never considered to be utilized for bioremediation of unlined soak ways or pits in oil and gas plants.

The novelty of this study was to experience the utility of enzymes, bio surfactants, nutrients together in the form of Oil Spill Eater II for the oily sludge bioremediation.

Considering all the above, significance and context of the study thus boils down to answer the following questions (Benessia and Funtowicz, 2015):

- *Whether the fire hazard has diminished?*
- *Whether the toxicity due to the presence of several contaminants of the evaporation pit is rapidly diminished?*
- *Whether the odor (smell) is almost non-existent after OSE II employment?*
- *Whether the contamination will no longer hazardous?*
- *Whether OSE II will prevent the oil from sinking?*

To answer the above 5 W questions, we critically discussed a resource-based view and analyze a case base study with a pilot project as developed by BESCO and monitored by the Oil and Gas Company. The nature of this pilot study is experimental and case-based. With OSE II pilot project as successfully adopted, the outcome of this study can be generalized to be applicable in other related sites as well. Detailed diagram for workflow and its implicational area are depicted in *Appendix B (Work Flow Diagram: OSE II; As Developed By BESCO Ltd.-USA) and Appendix C respectively.*

## 4. Bioremediation - a case base analysis

### 4.1. History and development of bioremediation

The industry, where we accomplished this case, was a medium-sized gas refinery based in the United Arab Emirates. It is running its operations for more than four decades. As in the beginning, municipality requirements were not in vogue, the liquid waste streams were sent to the unlined soak ways. Later when environmental protection rules and regulations came into operation; this refinery constructed *Waste Water Treatment Plant* (WWTP) to treat the hazardous liquid wastes

**Table 2**
In-situ and ex-situ bioremediation techniques with literature support.

| *In-situ bioremediation techniques with literature support* | | | | |
|---|---|---|---|---|
| In situ - types | Technique details | Merits | Demerits | Lit. support |
| Biosparging | Involves injection of air under pressure to enhance biological activity of microbes. | Non invasive | Environment constraints | Sharma (2012) |
| Bioventing | It involves supplying air and nutrients through well | Relatively passive | Extended treatment time | Atlas and Philip (2005) |
| Bioaugmentation | It involves supplying specialized microbes or genetically engineered microbes to target specific Pollutants | Natural attenuation processes | Monitoring difficulties | Thapa et al. (2012) |
| Biostimulation | It involves the management of the natural environment to optimize the growth and activity of the natural microbial population | Natural attenuation process | Extended treatment time | Crivelaro et al. (2010) |
| *Ex-situ bioremediation techniques with literature support* | | | | |
| Ex situ - types | Technique details | Merits | Demerits | Literature support |
| Land farming | Involve tilling of top soil and adding water and nutrients. (Work with low ground water contamination) | Cost efficient | Space requirements | Besalatpour et al. (2011) |
| Composting | Anaerobic, convert's solid organic wastes into humus-like material (Requires nitrogen supplementation) | Rapid rate of reaction, Low cost | Extended treatment time | Nataraj et al. (2007) |
| Biopiles | It is a hybrid of land farming and composting | Env. friendly | Need to control abiotic loss | Wu and Crapper (2009) |
| Bioreactors | These are basically tanks in which living organisms carry out biological reactions | Better extent of degradation | Highly expensive | Chikere et al. (2012) and Sonawdekar (2012) |

and converted into irrigable water. This WWTP is almost going to be a decade old. At present, though there is no environmental threat from the liquid waste streams, but the existing liquid waste in the previous unlined soak ways still remained a significant concern.

A pilot case study was undertaken by the Environment Management Department of this refinery to mitigate the existing hazard of the liquid wastes present. In the Management Review Meeting, it was decided to search for firms who can accomplish this project. Accordingly, *Scope of Work* (SOW) was prepared and the *Request for Quote* (RFQ) was asked from the enlisted and other specialist firms. During the interaction processes with the firms, BESCO, an American company came up with an idea of doing a pilot study to demonstrate the efficacy of the product, which was well received by the Management. Accordingly, BESCO LTD. was allowed to conduct the pilot study as re-processors.

Re-processors are companies or individuals who disassemble, repair, remanufacture, refurbish, recycle and reprocess products and materials from the 'disposal' market and transform them into (re-)usable forms. Unless the products can be reused without the need for reprocessing, most recovered products need to go through the re-processors. These businesses have to be commercially viable and therefore require a constant supply of recovered/recycled products and materials, as well as a constant and profitable demand from the markets.

There was no requirement of changing any process as the soak ways were disconnected/blinded from the existing liquid waste streams. Only the pilot study area was marked and secured to prevent any unauthorized entry. Precautions like *Personal Protective Equipment (PPEs)* were required to carry on the job like a collection of the sludge, mixing with OSE II, overturning the mixture from time to time, etc.

The undergoing project was a joint exercise between BESCO technical staff, refinery technicians, and the environment management division officials. A significant amount of data was collected and BESCO was able to scrutinize and validate the data and put conclusive outcome. Management got a better idea of the scale of the operation, timeline, and the expected budget.

Overall the pilot study was successful by reducing the petroleum hazard of the liquid wastes.

### *4.2. Procedure to perform a pilot remediate*

The procedure of the attempted remediation can be summarized as under:

#### *4.2.1. Identification and selection of the infected site*

In the premises of the Middle East Oil & Gas, the facility was identified. The infected area contained sludge pits and contamination was measured for TPH. For experimental convenience a volume of 25 x $10^4$ $cm^3$ infected soil was provided with OSE II.

#### *4.2.2. Methodology*

There are two procedures to address the soil. In first procedure soil from the pit was excavated and spread on the plastic of 100 cm by 100 cm keeping the height as 250 cm. In the other method, the soil of the pit was directly treated in situ. In the first method, a solution of 57 L of clean water and 0.575 L of OSE II was prepared and it was applied to the above volume of soil in 50:1 ratio and complete saturation was ensured.

#### *4.2.3. Materials required*

*Tools/Equipments*

1. Pumps — Sprinkling a solution to the soil.
2. Small hand shovels/soil extraction device — Extracting soil for testing.
3. Soil excavating unit — To mix soil in the pit.
4. Moisture Meter Sensor — To check the moisture content.

*Chemicals*

1. 0.5751OSE II.
2. 3.25g OX powder.

*Facility*

1. Reservoir 1 - To have 57 Lt. of clean water.
2. Reservoir 2 - For storing and discharging OSE II mixed water (with a capacity of at least 57 Lt.).

*Glassware and others*

1. Laboratory glass beakers (3 Nos.) with airtight cover.
2. Markers.
3. Ice Chest — For transportation of the samples from the site to the laboratory.

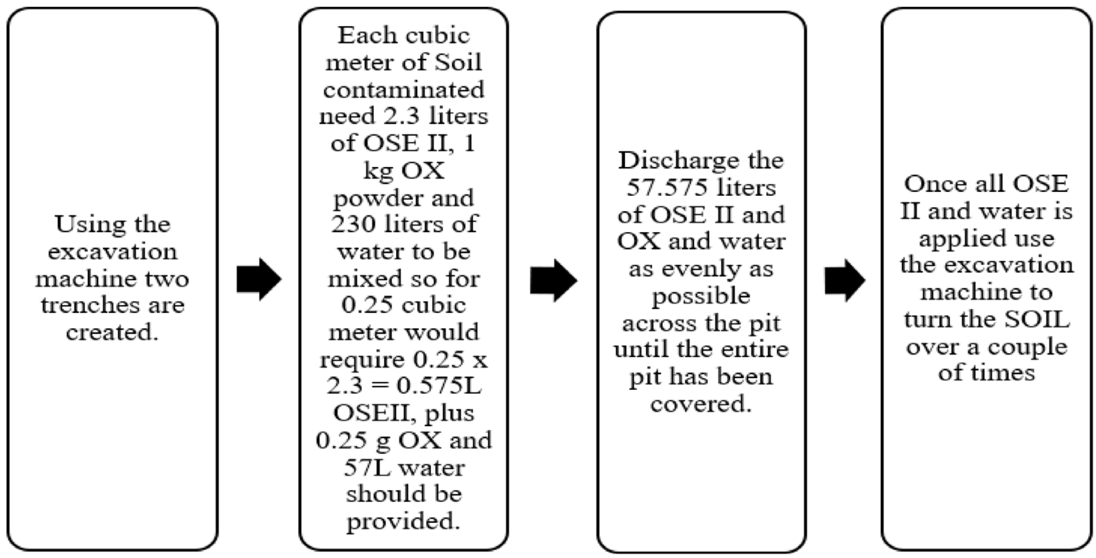



**Fig. 1.** Experimentation Procedure.

#### 4.2.4. Experimentation

The total experimentation procedure can be depicted as provided in figure *(Fig. 1)*.

#### 4.2.5. Site maintenance

48 h after treating the soil with the solution, moisture level is checked using the moisture sensor. In case the level falls below 30%, enough clean water is sprinkled to bring the level to 30%. It must be ensured that the source of the clean water should be same that has been used to prepare the solution. If the work is done in rainy season things would be better. Moreover once a fortnight, using the excavating machine, the entire soil should be remixed.

#### 4.2.6. Sample collection for testing

The observation for evaluation and sample collection can be followed as shown in figure *(Fig. 2)*.

### 4.3. Collection of data

After the successful joint exercise between BSECO technical staff, refinery technicians, and environment management division officials, a huge amount of data was collected starting from week 0 to week 5 for all test sites. In total six sites were selected around the existing boreholes' locations surrounding the soak ways to get the normalized data as much as possible. Data were collected for gasoline, diesel, and heavy fractions residue before and after use of OSE II. The results were analyzed by an accredited laboratory.

We followed two procedures A and B. In A, we excavated the contaminated soil from the pit and did spread it on a plastic sheet measuring 1 m × 1 m. We kept the thickness of soil 0.25 m. We applied OSE II with this excavated soil and mixed it uniformly and turned over periodically. With the procedure B, we applied OSE II in situ inside the contaminated pit and thoroughly mixed with the contaminated soil and turned periodically.

#### 4.3.1. Bioremediation test report zone: A1–A2–A3 (ex-situ)

With the literature review and various iterations and depending on the type and quantity of contamination can be assumed that by a months' time the levels of hydrocarbon remaining would be in or around the acceptable limit in the soil. The soil is expected to be like rich garden compost upon completion of the cleanup and the water is likely to be clean non-potable water. The bioremediation reports are provided in Appendix D, E, and F for zones A1, A2, and A3 respectively. For plotting the graphs, $X$-axis was kept as per the weeks and the $Y$-axis was kept as per the PPM values of gasoline, diesel, and heavy fractions residue. We took the weekly residual data as it was the prevalent practice in oil and gas to monitor process data on a regular frequency. As it was expected that the level of hydrocarbon to come down to an acceptable level by a month's time, we kept a frequency of weekly monitoring.

*Bioremediation Test Report Zone: A1*

In all the figures as extracted, X axis is taken as an observation for weeks (week 1 to week 4) after the application of OSE II and the Y axis is taken for the Oily residues measured in ppm.

As depicted in Fig. 3, the Gasoline seemed to start at 2.9 and ended up at 0.0 which was very significant. The diesel range started at 70.1 and ended up at 25.8 which again were feasible. Based on the initial data of 70.1, it was a 74% reduction in a short time which shows a steady reduction. For the heavy fraction, OSE II took a longer time to partition the hydrocarbons from the soil. We could see the trend going up to 31.9, however, there was an anomaly with the 165; the next sample should show the trend going down. Heavy ends generally do not produce much toxicity to the environment and even at this level might still be acceptable.

*Bioremediation Test Report Zone: A2*

In A2/W4 (Fig. 3), there seemed to be an error since we have seen two samplings going up exponentially. The gasoline tests showed zero at A2/W3, then went up. There are supposed to be an error at A2/W3 or more likely at A2/W4. It was virtually impossible to start at 3.3 then climb to 229.9. Probably some sampling or mixing error. The expected endpoint should be zero. The diesel range once again, the partitioning should have been complete at 65.5 and the trend should have continued down. The result is not possible at 549.3 when we started at 58.4. The heavy fraction would have ended at 0. On A2/W2, however, the endpoint was 8.8 which were still good as well.

*Bioremediation Test Report Zone: A3*

The gasoline ending at zero was good. The diesel ending at 21 was also good. The heavy fraction should have been stopped at zero. The endpoint is actually 10.3 at the A3/W4 and A3/W3 was out of order. The endpoint was actually 10.3, once again showing great reduction. Sampling collection, mixing, and testing should have been properly regulated.

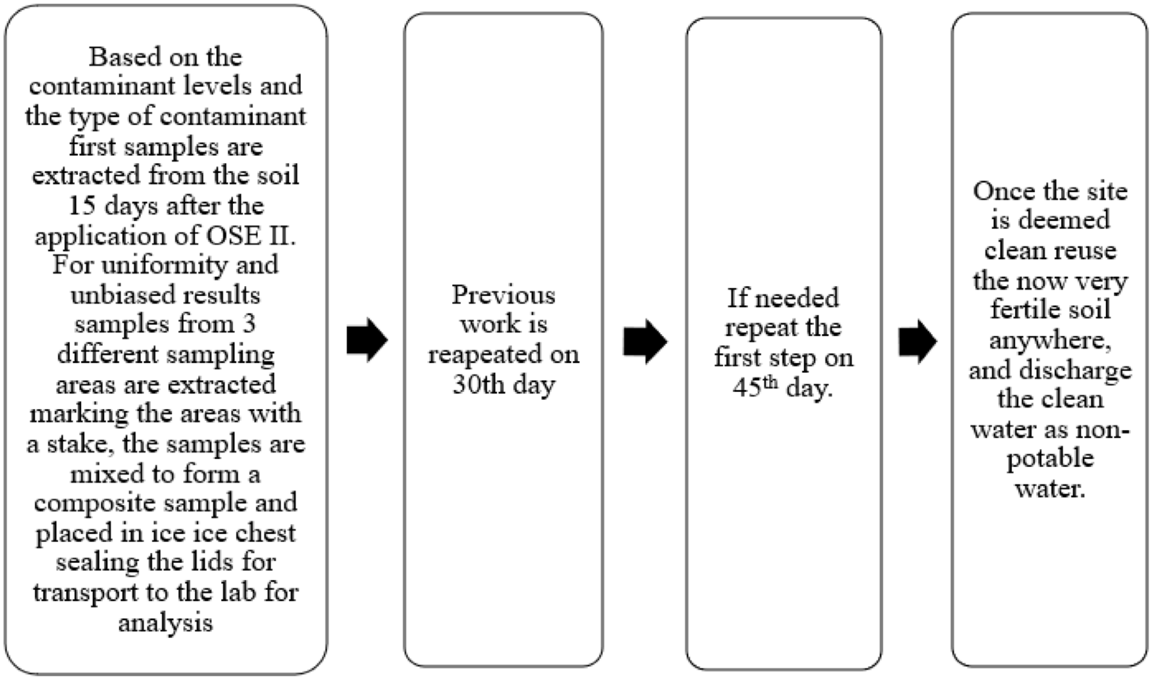



**Fig. 2.** Procedure for Sample Collection for Testing.

**Table 3**
*Bioremediation reduction test analysis report*.

| Gasoline reduction test analysis report (A) | | | | Gasoline reduction test analysis report (B) | | | |
|---|---|---|---|---|---|---|---|
| Gasoline | Highest point | End point | Remark | Gasoline | Highest point | End point | Remark |
| A1 | 496.7 | 0 | 100% reduction | B1 | 528.1 | 395.1 | 25% reduction |
| A2 | 40.3 | 229.9 | Anomaly | B2 | 3.3 | 55.3 | Anomaly |
| A3 | 309.5 | 0 | 100% reduction | B3 | 586.7 | 77.7 | Anomaly |
| Overall (A) | 845.5 | 229.9 | 73% reduction | Overall (B) | 1118.1 | 528.1 | 52.7% reduction |
| Average | 281.83 | 76.63 | 73% reduction | Average | 372.7 | 176.0 | 52.7% reduction |
| Diesel reduction test analysis report (A) | | | | Diesel reduction test analysis report (B) | | | |
| Diesel | Highest point | End point | Remark | Diesel | Highest point | End point | Remark |
| A1 | 2454 | 25.8 | 99% reduction | B1 | 2711.7 | 1315.5 | 51.49% reduction |
| A2 | 191.8 | 549.3 | Anomaly | B2 | 2991.1 | 721 | 75.9% reduction |
| A3 | 2291.1 | 21 | 99% reduction | B3 | 3153.7 | 1611.1 | 48.9% reduction |
| Overall (A) | 4936.9 | 596.1 | 87.93% reduction | Overall (B) | 8856.5 | 3647.6 | 58.8% reduction |
| Average | 281.83 | 198.7 | 29.5% reduction | Average | 2952.17 | 1215.87 | 58.8% reduction |
| Heavy fraction reduction test analysis report (A) | | | | Heavy fraction reduction test analysis report (B) | | | |
| Heavy fraction | Highest point | End point | Remark | Heavy fraction | Highest point | End point | Remark |
| A1 | 31.9 | 165 | Anomaly | B1 | 42.3 | 90.9 | Anomaly |
| A2 | 134.1 | 8.8 | 93.43% reduction | B2 | 73.8 | 92.2 | Anomaly |
| A3 | 35.2 | 443.4 | Anomaly | B3 | 49.8 | 1.6 | 96.8% reduction |
| Overall (A) | 201.2 | 617.2 | Anomaly | Overall (B) | 165.9 | 184.7 | Anomaly |
| Average | 67–07 | 205.73 | Anomaly | Average | 55.3 | 61.57 | Anomaly |

#### *4.3.2. Bioremediation test report zone: B1–B2–B3 (in situ)*

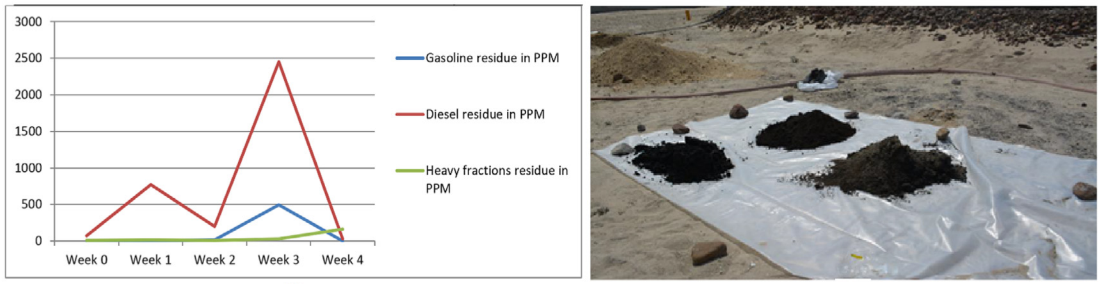
Bioremediation reports are provided in Appendix G, H, and I for the zones B1, B2, and B3 respectively.

*Bioremediation Test Report Zone: B1*

The lab results here were absolute anomalies, when we saw an increasing trend of all the samples, even though we saw a general trend down from B3 to B4 (Fig. 4) for gasoline and diesel. The heavy end showed a huge anomaly. This chart showed the soil dried out or there was something amiss in the collection process. The gasoline showed a trend up until the B1/W4 then it showed the level dropping. This was still very high from where it started. The diesel showed levels not really seen in the A charts with levels up to 2711.7 and 1315.5.

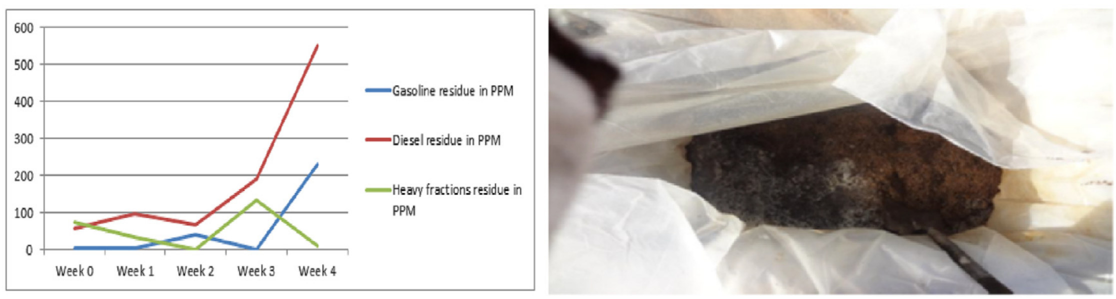
OSE II was very good a partitioning hydrocarbons from the soil, however, it was generally much faster, especially with the diesel range. The trend was down in the end. This was a 50% drop in a matter of days. The heavy fraction showed an absolute anomaly at the end since the trend was up and doubled, the 12 and 10.6 were more of where historically trends fall with the starting point of 9.2 to 90. It is virtually impossible to have a 100% or higher increase at this time of the testing.

*Bioremediation Test Report Zone: B2*



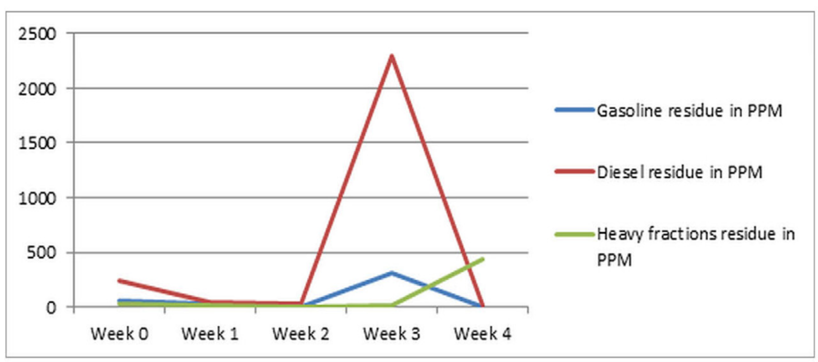

(a) (b)

**Zone A1**




(a) (b)

**Zone A2**




**Zone A3**

**Fig. 3.** Report Zone (A1, A2, A3) (a) Graph for Bioremediation Test (b) Experimentation Procedure.

The gasoline range showed zero twice then a huge anomaly on the B2/W4 (Fig. 4). From the table, result zero appears twice; indicates good performance. The diesel range also showed a high point of 2991.3 which might be somewhat of an anomaly however the endpoint of 721 from the high point is a great reduction. If we were calculating the amount of drop from B2/W3 to B2/W4, it was easy to see a total reduction in only a few days. The heavy fractions, once again showed anomaly may be due to the extraction process or any other reasons. We could expect the result to behalf of or lower than the 15.9.

*Bioremediation Test Report Zone: B3*

The gasoline range showed a great increase and then the trend was down (Fig. 4). The diesel range also showed a high point of 3153.7; however, the endpoint of 1611.1 from the high point was a great reduction. If we were calculating the amount of drop from B3/W3 to B3/W4, it was easy to see the total reduction in only a few days. This was the only heavy fraction test in the B chart that did not show an anomaly.

*4.3.3. Bioremediation reduction report*

Now is the time to look at the hard data (Table 3) to find out whether the exercise is worth doing. We shall gradually look into gasoline, diesel, and heavy fraction residues in the remedied contaminated soil before and after the use of OSE II.

If we discard the anomaly, gasoline reduction was in the range of 73%–100% in a thirty days times period (A), which justifies our pilot study. Still, all parties should be more coordinated and be error-free for sampling, mixing, turning, and analytical sample testing. If we discard the anomaly, gasoline reduction was in the average range of 52.7% in a thirty days times period (B), which justifies our pilot study. Still, all parties should be more coordinated and be error-free for sampling, mixing, turning, and analytical sample testing.

If we discard the anomaly, diesel reduction was in the range of 88%–99% (A) and the average reduction of 29.5% in a thirty days times period, which justifies our pilot study. Still, all parties should be more coordinated and be error-free for sampling, mixing, turning, and analytical sample testing. Diesel reduction was in the range of 48%–75% (B) and the average reduction of 58.8% in a thirty days

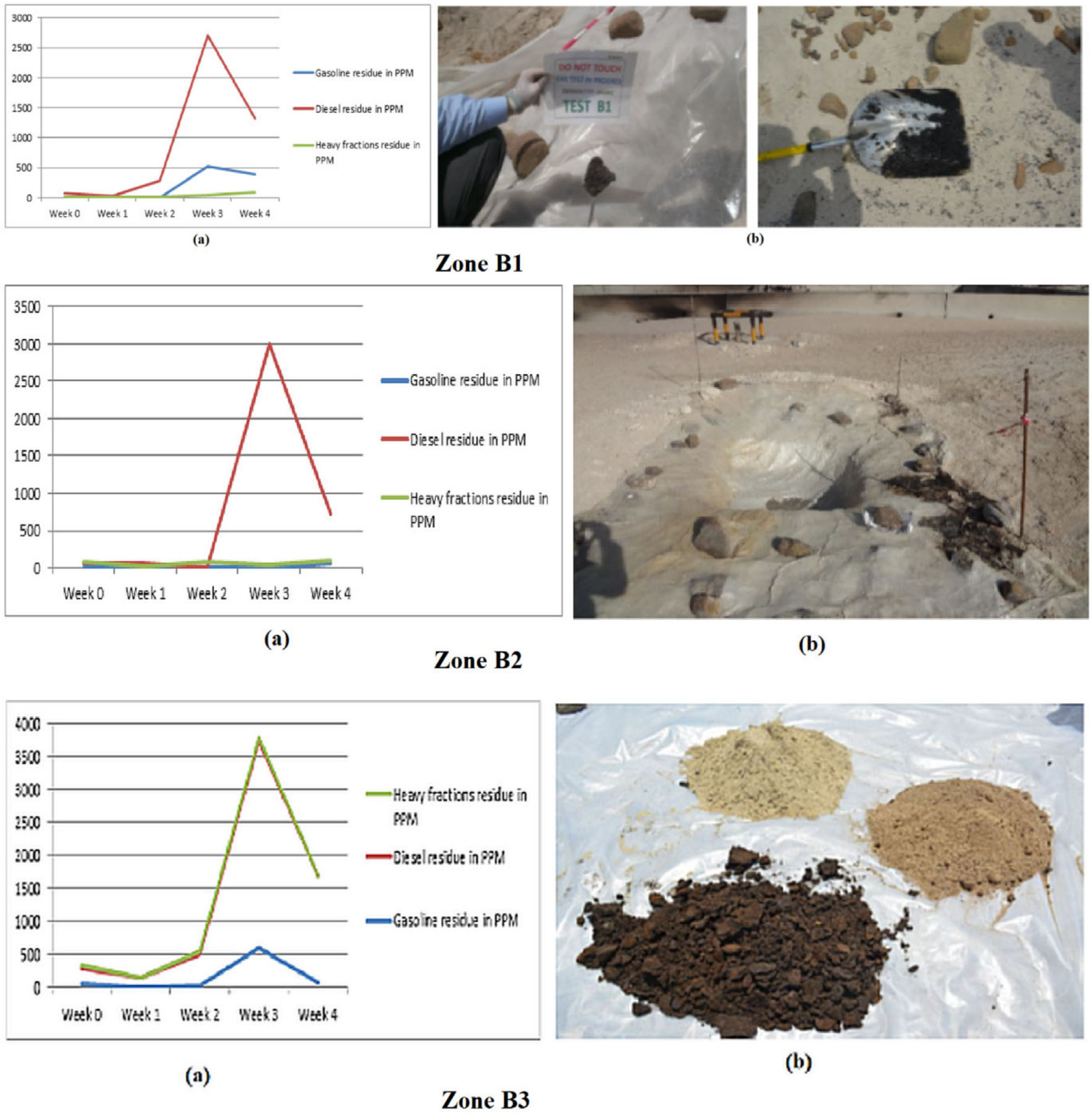



**Fig. 4.** Report Zone (B1, B2, B3) (a) Graph for Bioremediation Test (b) Experimentation Procedure.

times period, which justifies our pilot study. Still all parties should be more coordinated and be error-free for sampling, mixing, turning and analytical sample collection and testing.

If we discard the anomaly, only one sample showed the reduction of 93.43% in a thirty days times period (A), which justifies our pilot study. Still, all parties should be more coordinated and be error-free for sampling, mixing, turning, and analytical sample testing. If we discard the anomaly, only one sample showed the reduction of 96.8% in a thirty days times period (B), which justifies our pilot study. Still all parties should be more coordinated and be error free for sampling, mixing, turning and analytical sample collection and testing.

Discarding anomalies, overall good reduction is seen in gasoline, diesel and heavy fraction samples for a period of thirty days experimental (pilot) study samples.

Overall keeping our objective, OSE II worked marvelously to reduce the gasoline and diesel contents of the contaminated soil samples. Test A sites showed a relatively better performance than test B sites. So some digging and excavations are envisaged while using the OSE II in contaminated pits rather than applying OSE II in situ.

When we designed this experiment we kept 5Ws, out of which we accomplished straight forward 3Ws, like: diminished fire hazard, almost nil odor and OSE II reduced the further penetration of oil through the soil. For other 2Ws, like: diminished toxicity or no more presence of hazardous contaminations, we did received only a single set of data from the both A and B sites which were supporting our objective, but other two sets of results showed anomalous. We needed to be more cautious in future for collecting and testing samples.

From the result it can be highlighted that:

- This experimental (pilot) study gave a good input to management decision making process show the efficacy of reverse chaining of wastes in order to balance the planet earth.
- Bio remediation could definitely be undertaken as an efficient process of reverse chain of restoration of natural resources; particularly in the domain of Oil and Gas.

**Table 4**
*ANOVA-single factor analysis ANOVA TABLE.*

| Source of variation | SS | d.f | MS | $F_{(Cal)}$ | P Value | F(Tab) |
|---|---|---|---|---|---|---|
| Between groups | 2657.10 | 2 | 1328.55 | – | – | – |
| Within groups | 641.07 | 3 | 213.69 | 6.217 | 0.0856 | 9.552 |
| TOTAL | 3298.17 | 5 | – | – | – | – |

**Analysis of variance (ANOVA) on the hazardous wastes' removal**

The impact of noise is insignificant. As the site (soak away pit) was far off from the production area, which almost one and half miles away. The area was undisturbed by any operational or any other needs, so variance due to noise was not considered. When checked by a portable dB meter the ambient noise was found in the range of 40–50 dB. For gasoline and diesel we took the average reduction figures and by that way anomalies were normalized. For the heavy fraction reduction, we had to discard the anomalies and only took the relevant data to run ANOVA (shown in Graphical Abstract). The results were collected in every week as set up as a standard practice to have regular monitoring and better management.

The ANOVA results as depicted in Table 4 show the Model F value of 6.21 implies the model is significant. Our sample data provide strong enough evidence to conclude that three population means are not equal.

From a circular economy perspective, the different reverse and recycling systems that enable reuse, refurbishment, re-manufacturing and up-cycling are crucial for keeping products, materials and components at highest utilization and value at all times (Hart, 1995). Instead, by switching to a 'circular economy' model, supply chain entities will take more responsibility for a product's life after its 'death' (Hart and Dowell, 2011). Summarizing, this pilot study with the case analyses gives a meaningful insight about the statement of the problem as framed.

## 5. Management implications

Increased demand for liquid petroleum forces the manufacturer to search for reliable and efficient oil spill clean-up techniques in order to restore natural resources. Bioremediation has been treated by the researcher as successful attenuation of polluting (or contaminating) substances using biological evolution processes. Reversing natural waste in a sustainable way occurs by this process has the obvious advantage of treating the contamination in place; thereby a large amount of soil, sediment, or water does not have to be dug up from the ground (Silvestre et al., 2017). In the contrast, bioremediation, though, is considered one of the most sustainable clean-up techniques, but the potential has not been fully exploited in this domain as it is too slow to meet the immediate demands of the environment. Again, though bioremediation is a workable solution for treating oily sludge, but process perfection and real time monitoring is a must to achieve desired results.

From a practical perspective, this study has significant managerial contributions:

- Implementation of sustainability standards are controlled by external auditors thereby needs serious attention to optimizing hazardous waste.
- Referring to identified impact, stakeholders may convince companies' sustainability engagements and foster sustainability pervasion (Yawar and Seuring, 2015).
- With a proper evaluation of the expected sustainability benefits, companies may strategize a holistic consideration of economic, green, and social benefits to mankind (Verguts et al., 2016).
- Finally, companies have to analyze business opportunities by using more and more environmental benefit processes, tools, and techniques in order to keep sustenance in their business.

## 6. Conclusions

Sustainability is a hot topic for researchers globally. In the case of operational wastes that are coming from the production process, reversing the same is a serious concern towards natural restoration. Traditional engineering approaches, though, extensively used in remediation technology, concern for sustainability forced companies to adopt biological methods keeping planet earth more safe and secure. Thus, increasing awareness of the energy–environment nexus is compelling new technologies to reduce both environmental impacts (during energy production) and energy consumption (during environmental remediation). With stringent regulations coming into operation towards saving the planet earth, these oil and gas companies now started adopting reverse chain projects with newer technologies in order to keep balance in between economic, social, and environmental consequences.

Successful analysis of this experimental (pilot) study, it may be highlighted that:

- Bioremediation can be one of the preferred reverse chain solutions to these oil and gas companies towards sustaining waste optimization due to its cost-effectiveness and environment-friendly approach.
- Though time-consuming, Bioremediation is successfully proved to be less expensive than alternative traditional methods of Incineration or Landfilling. Landfills, without proper containment, can pollute groundwaters and create methane, which is a form of greenhouse gas (GHS). Incinerations, though, generate energy from waste and produce lots of toxic gases and ashes.
- Most importantly, the successful application of pilot study via Bioremediation proves long-term benefit in a more sustainable manner to all the stakeholders, and ultimately the planet earth.

The limitation of this study is obviously the case-based experimental (pilot) approach which is lacks of analytic or quantitative approach towards data-based inference. The inference here may thus not be made as generalization and more application is required to conclude and generalize its efficacy. For future study, decision-makers as well as researchers should focus on improving the existing technologies under better standardization of environmental rules and regulations. Again, this pilot study may outperform in a better manner by the development of new hybrid technologies (like combining bio-engineered evolution techniques) under the Artificially Intelligence platform. Further study is awaited in those directions.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

The authors sincerely acknowledge the comments and suggestions of the reviewers that have been instrumental for improving and upgrading the paper in its final form.

**Appendix A. Middle east statutory regulations**

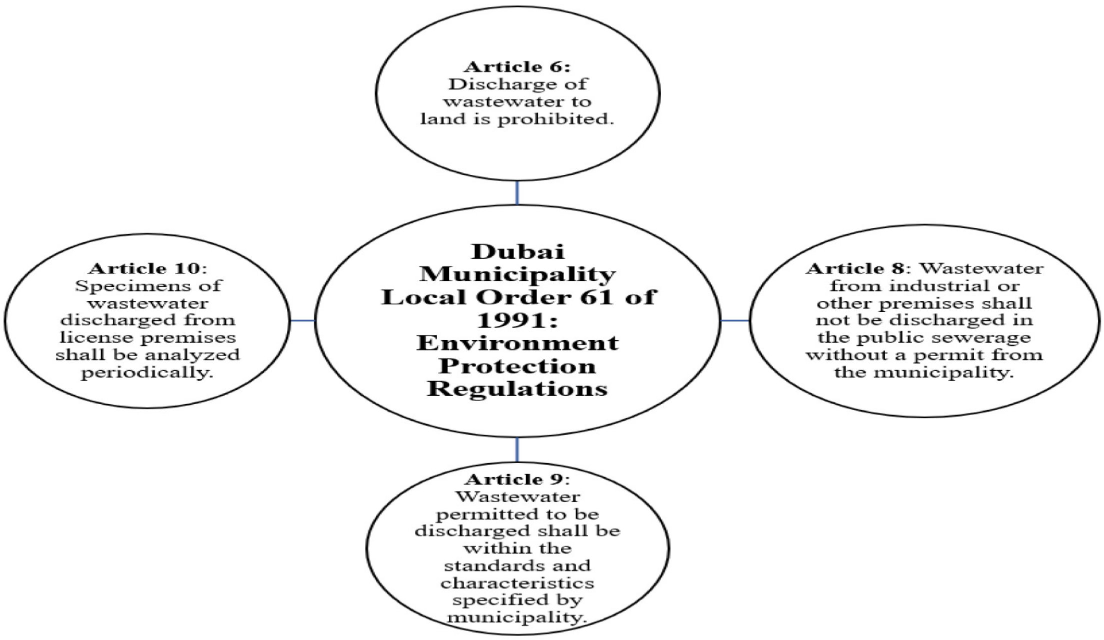



Exhibit 1: Dubai Municipality Local Order 61 of 1991

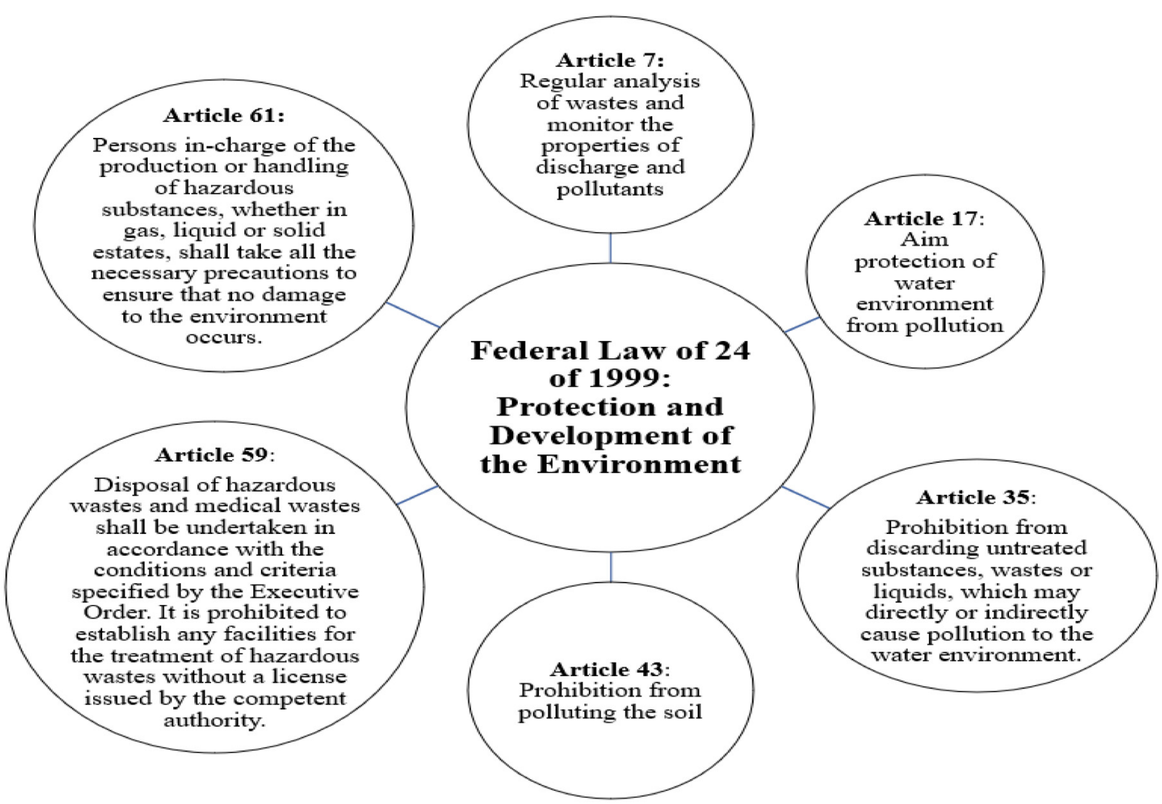
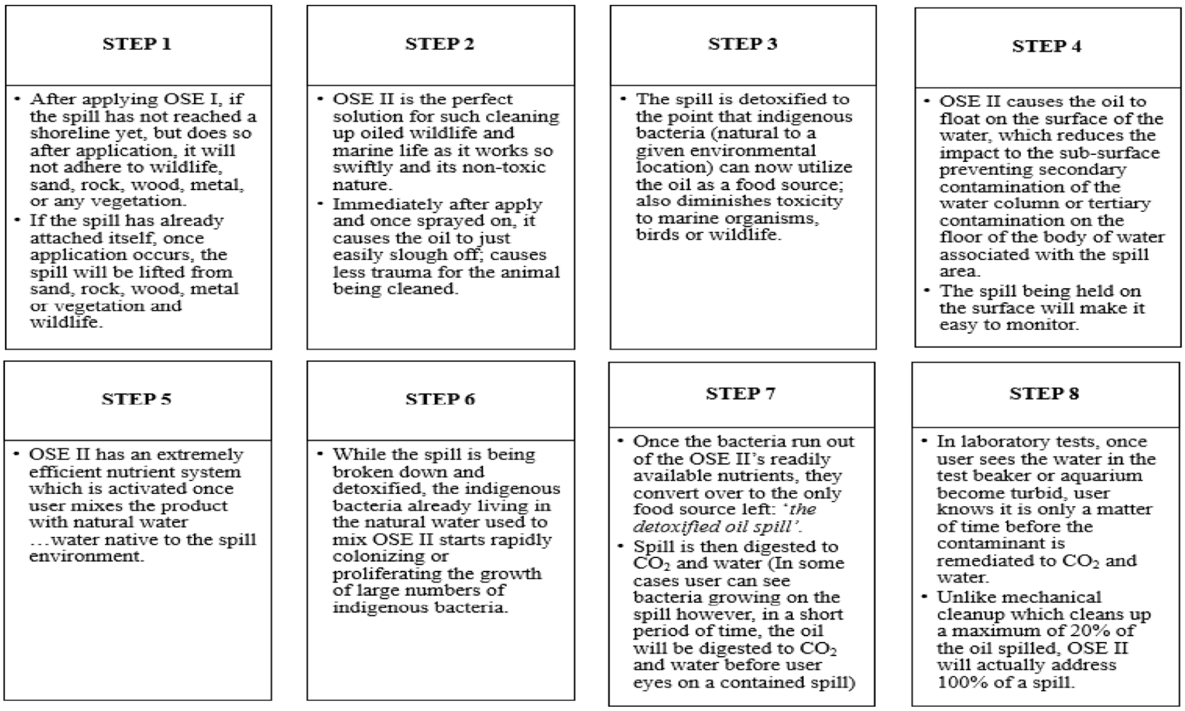



Exhibit 2: Federal Law of 24 of 1999

**Appendix B. Work flow diagram: OSE II (as developed by Besco Ltd. USA)**




**Appendix C**

*OSE II: APPLICATIONAL AREAS (WHERE)*

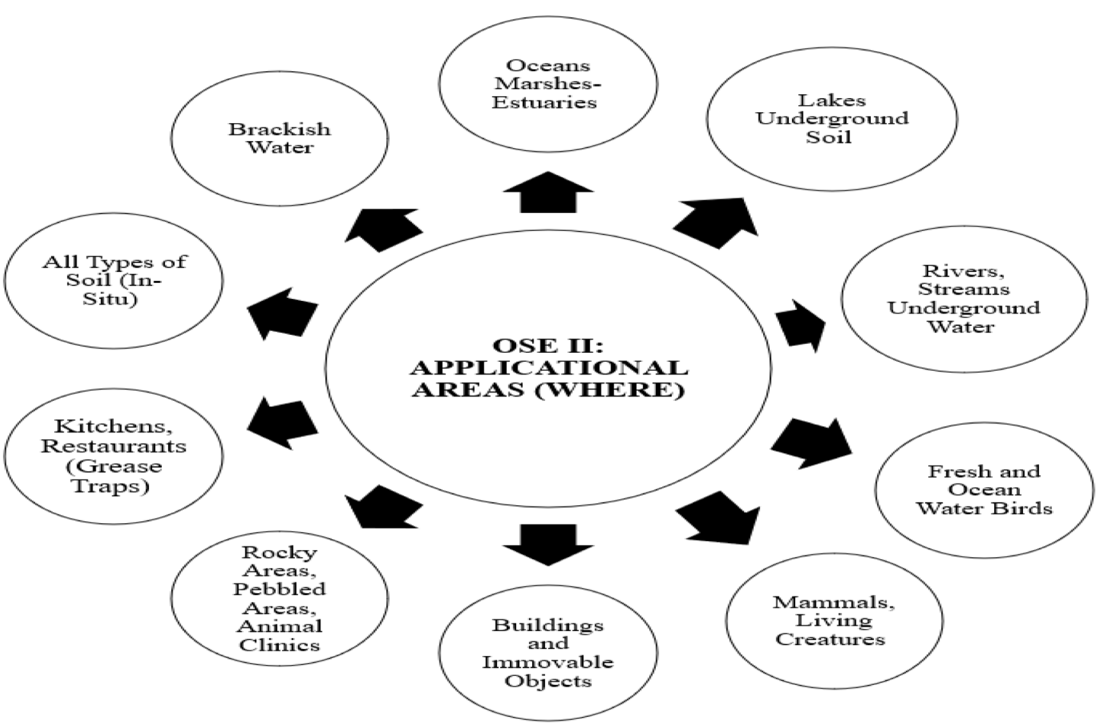


**Table D.1**
*Bioremediation test report zone: A1.*

| Residue/Week | Week 0 | Week 1 | Week 2 | Week 3 | Week 4 |
|---|---|---|---|---|---|
| Gasoline residue in PPM | 2.9 | 0 | 18.3 | 496.7 | 0 |
| Diesel residue in PPM | 70.1 | 773.9 | 199 | 2454 | 25.8 |
| Heavy fractions residue in PPM | 9.2 | 11.8 | 9.1 | 31.9 | 165 |

**Table E.1**
*Bioremediation test report zone: A2.*

| Residue/Week | Week 0 | Week 1 | Week 2 | Week 3 | Week 4 |
|---|---|---|---|---|---|
| Gasoline residue in PPM | 3.3 | 5.2 | 40.3 | 0 | 229.9 |
| Diesel residue in PPM | 58.4 | 96.5 | 65.5 | 191.8 | 549.3 |
| Heavy fractions residue in PPM | 73.8 | 32.8 | 0 | 134.1 | 8.8 |

**Table F.1**
*Bioremediation test report zone: A3.*

| Residue/Week | Week 0 | Week 1 | Week 2 | Week 3 | Week 4 |
|---|---|---|---|---|---|
| Gasoline residue in PPM | 51.9 | 31.4 | 0 | 309.5 | 0 |
| Diesel residue in PPM | 239.2 | 42.4 | 26 | 2291.1 | 21 |
| Heavy fractions residue in PPM | 35.2 | 19.7 | 0 | 10.3 | 443.4 |

**Table G.1**
*Bioremediation test report zone: B1.*

| Residue/Week | Week 0 | Week 1 | Week 2 | Week 3 | Week 4 |
|---|---|---|---|---|---|
| Gasoline residue in PPM | 2.9 | 0 | 6.5 | 528.1 | 395.1 |
| Diesel residue in PPM | 70.1 | 27.1 | 293.5 | 2711.7 | 1315.5 |
| Heavy fractions residue in PPM | 9.2 | 12.4 | 10.6 | 42.3 | 90.9 |

**Table H.1**
*Bioremediation test report zone: B2.*

| Residue/Week | Week 0 | Week 1 | Week 2 | Week 3 | Week 4 |
|---|---|---|---|---|---|
| Gasoline residue in PPM | 3.3 | 1.6 | 0 | 0 | 55.3 |
| Diesel residue in PPM | 58.4 | 60.1 | 3.2 | 2991.1 | 721 |
| Heavy fractions residue in PPM | 73.8 | 15.9 | 71.6 | 37.7 | 92.2 |

*OSE II: APPLICATIONAL AREAS (WHO)*

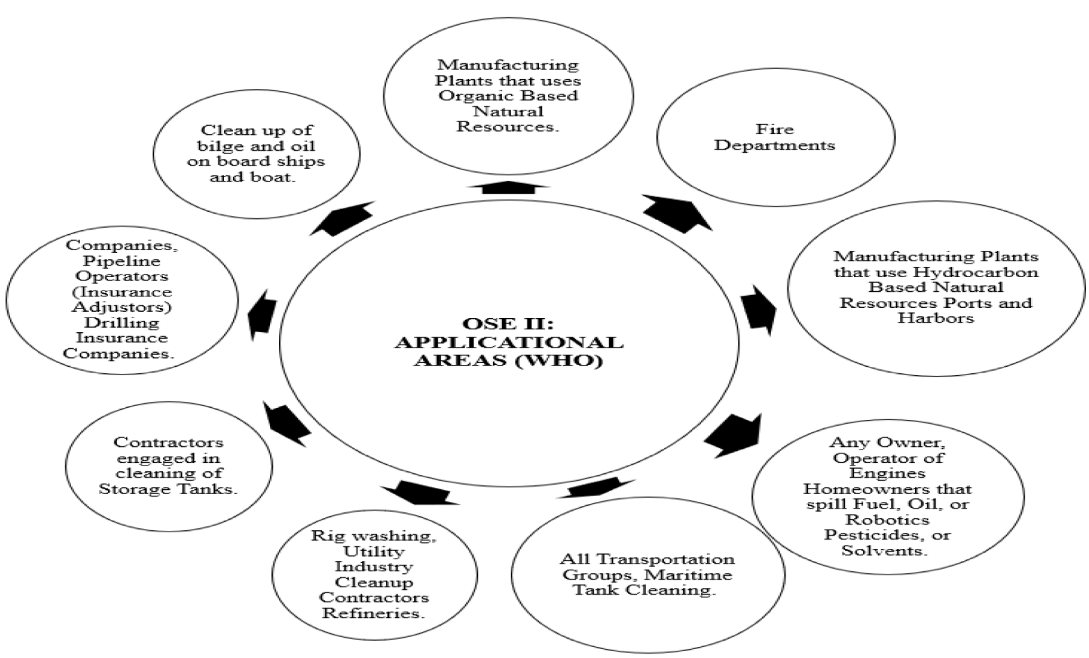


**Table I.1**
*Bioremediation test report zone: B3.*

| Residue/Week | Week 0 | Week 1 | Week 2 | Week 3 | Week 4 |
|---|---|---|---|---|---|
| Gasoline residue in PPM | 51.9 | 0 | 34.5 | 586.7 | 77.7 |
| Diesel residue in PPM | 239.2 | 137.1 | 465.4 | 3153.7 | 1611.1 |
| Heavy fractions residue in PPM | 35.2 | 19.2 | 49.8 | 46.2 | 1.6 |

## Appendix D

See Table D.1.

## Appendix E

See Table E.1.

## Appendix F

See Table F.1.

## Appendix G

See Table G.1.

## Appendix H

See Table H.1.

## Appendix I

See Table I.1.

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