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Bioremediation Technology Potential for Management of Soil and Water Pollution from Anticipated Rapid Industrialization and Planned Oil and Gas Sector in Uganda: A Review

Isa Kabenge[1*], Abia Katimbo[1], Nicholas Kiggundu[1], Noble Banadda[1,2]

[1]Department of Agricultural and Bio-Systems Engineering, College of Agricultural and Environmental Sciences, Makerere University, Kampala, Uganda
[2]Department of Agricultural and Biosystems Engineering, Ames, USA
Email: *isakabenge@gmail.com

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Abstract

Oil exploitation in many African countries is associated with litigation and conflicts to water and soil pollution. It is because of inadequate planning for management of oil spills and industrial effluents in environmentally sustainable manner. Uganda's natural resources such as soils and water bodies are threatened by contamination due to rapid industrialization and rural-urban migration in established Industrial Business Parks and planned oil and gas production at Albertine Graben Region. The low level of compliance to industrial effluents discharge standards relevant to specific environmental receptors and activities within oil and gas sector development pose a big question of how to sustain the biodiversity and natural resource management. Experiences from elsewhere have shown bioremediation as a viable and proven option to provide potentially manageable solutions to resulting pollution as a substitute to modern well-known remediation methods, for it is relatively cheaper, more efficient and minimal toxic byproducts after treatment. The most used bioremediation agents in different studies reviewed are bacterial species especially *Pseudomonas* and *Bacillus*, followed by *Aspergillus* a fungi species, microalgae and aquatic plants such as *duckweed*, *macrophytes* and *pteridophytes*. Regardless of the waste produced in either oil and gas sector or industries, these agents have shown greater biodegradation rates. *Pseudomonas sp.* has a degradation efficiency of oil compounds ranging from 90% - 100%, and *Aspergillus sp.* 75% - 95%. Some aquatic plants can thrive in created wetlands with relatively still water such as *Phragmites australis* which can degrade hydrocarbons especially Aromatic compounds with benzene ring up to 95%. It can thrive in salty water with high pH range of 4.8 - 8.2. With industrial wastewater, algae is the most dominant with the degradation rates varying from 65% -100% and bacteria at 70% - 90%. Most of the reported results are in the developed country context. In developing countries, duckweed is reported as the commonest aquatic plant in wastewater treatment for removal of heavy metals because it is more tolerant to a wide range of environmental conditions and produce biomass faster. It has a removal rate of heavy metals between 90% and 100%. Basing on literature data analysis, bacteria are more suitable for treating water from oil pollution using *Pseudomonas sp. Phragmites australis* is suited for cleaning up oil in both water and soil. Duckweed is the best in treating water polluted with industrial effluents. This paper presents the different bioremediation methods that Uganda can potentially apply to mitigate the increased risk of environmental pollutions from planned industrialization and oil and gas development in the Albertine Graben Region.

Keywords

Bioremediation Potential, Industrialization, Oil and Gas, Biodiversity, Pollution Management

1. Introduction

Uganda is endowed with fertile soils and enough water resources known as wealth creating resources but threatened by contamination. Because of constantly growing agricultural production in the country, many investors have set up industries for value addition to generate more revenues. Too much volume of partially treated or untreated wastewater is being frequently discharged by processing industries into the environment [1]. Similarly, so many manufacturing industries are now widely spread to serve markets created by increasing populations [2]. Examples of manufacturing industries include that for textiles, building materials, beverages, packaging materials and plastics, etc. Hazardous wastes containing toxic compounds are produced by such industries along their processing stages. It is estimated that about 7.62 million m^3/year of industrial wastewater is generated with nearly half coming from Kampala City [3]. For that reason, proper management and treatment are required to prevent pollution within lakes and open agricultural lands which might cause loss of biodiversity [4]. However, the poor quality of effluents into water bodies by the industries which are the biggest dischargers, who don't meet the required standards, indicates low compliance to the laws [5]. Wastewater treatment systems that are constructed to prevent pollution in environment, primarily reduce COD and suspended solids but nutrient removal is still a big challenge [6]. It is also reported that large quantities of industrial pollutants have mainly entered Lake Victoria through Napoleon Gulf at Jinja in Eastern Uganda which has escalated eutrophication levels due to high nutrient inputs for the past 50 years [7]. This is acknowledged due to observed increase of alga biomass that has occurred within successive years and almost half of bottom lake water is anoxic.

In the year 2006, commercially viable oil, a precious product was discovered in Albertine Graben region [8], and this has placed Uganda on the global energy map. Different human activities within oil industry such as exploration, production, transport, refining and storage cause pollution from toxic hydrocarbon compounds [9]. Diesel oil is one of the products of crude oil which can have detrimental effects when exposed to the environment, because it has got long-chained hydrocarbons which make it less soluble and less degradable [10]. Diesel oil is also of a low molecular weight, and according to [11], light oils are more toxic because it has got high concentrations of saturated hydrocarbons. Common incidences of oil contaminations is attributable to oil well blow outs, leaks and spills from underground tank, pipelines and illegal disposals all of which threatens the ecosystem [12] [13]. The heavy oil with carcinogenic compounds most times is attached to the sediments which are easily transported by the surface runoff into water bodies if poorly managed and disposed to the environment [14]. Therefore, the discovered petroleum deposits calls for preparation to safeguard the environment [15]. According to the Government's estimations, there is 6.5 billion barrels of oil in place, and only 1.8 - 2.2 billion barrels is recoverable oil [16]. Because Uganda is a land locked country, oil will only flow to the international markets with construction of a regional pipeline through either Tanzania or Kenya which is regarded economically viable [16]. Nonetheless, the country should be prepared to prevent oil spills from the constructed oil refinery or used pipelines to transport crude oil either to a refinery or markets. The moment oil is exposed to a water body, it undergoes a complex and concurrently physical, chemical and biological transformations including spreading, drifting, dispersion, stranding and weathering. There is always mutations and deaths when hydrocarbons accumulate the animals and plant tissues through soil contamination [9]. For any country conducting oil exploration and refining, a pollutant-free soil ecosystem should be strengthened with remediation of contaminated soil with petroleum [12].

Most environmental oil pollutants such as polycyclic aromatic hydrocarbons (PHAs), petroleum hydrocarbons, heavy metals and nutrient-rich organics cause deleterious effects due to their inertness and toxicity [6]. To address these draw backs, the best method which suits the complete removal of pollutants is using bioremediation approach which uses natural biological activities to destroy various contaminants. This is a safer, clean, cost effective and environmentally friendly technology with a high public acceptance and easily done at any site [15]. Industrial and crude oil contaminants can be degraded with use of microorganisms and plants in bioremediation processes. Commonly used modern technologies are very expensive and often time there is incomplete degradation of contaminants [9].

Bioremediation process uses various agents such as bacteria, yeast, fungi, algae and higher plants to treat oil spills and heavy metals identified in the environment. It is very important to use biological sources because of their ability to multiply and expand in terms of initial inoculum as compared to physical and chemical treatment means [4]. The inoculums can be a mixture of nonindigenous microbes from various polluted environments specifically selected and cultivated for their various pollutant degrading characteristics, or mixture of microbes picked from a site in need of cleaning or can be mass cultured in the laboratory [4]. Two or more remediation techniques can be used to improve the efficiency of bioremediation in a harshly contaminated environment [12]. Addition of nutrients along with seeding process has shown improved results for bioremediation [17] [15]. Different researchers have developed diverse technologies to treat contamination from the lessons learnt from successive practices of bioremediation process. The best example is research done by [18], which based on the earlier limitations of using direct application of nutrients to the oil spills to fertilize hydrocarbon oxidizing bacteria where nutrients could rapidly dissolve in open marine waters. Thereafter, researchers designed nutrient amendments to oil spill using film minerals comprised of Fuller Earth clay. The adsorbed N and P fertilizers, filming additives, and organoclay, clay flakes was engineered and floated on sea water to attach to the oil, and slowly release contained nutrients. The found results were that after treatment, 98% of the total alkane concentration was removed compared to 82.5% in the sample lacking the additives. The application of P and N based fertilizer is one of the realistic approach to simulate the oil breakdown [18].

Sustainable bioremediation research and development is required in developing countries where the average standard of living is much lower as compared to the developed countries [19]. The major concern in most of the developing countries is contamination due to heavy metals and aromatic hydrocarbons [20]. The terms "developing" and "developed" countries are used for statistical convenience but not to express the level of development [21]. The development of the country is measured with statistical indices such as life expectancy, rate of literacy and Gross National Income (GNI). GNI is the sum of value added by all nation's resident producers, any product taxes (minus subsidies) not included in output, income received from abroad such as employee compensation and property income [20]. In relation to GNI per capita, countries are grouped as low income, \$1,005 or less; lower middle income, \$1,006 - 3,955; upper middle income, \$3,956 - 12,235; and high income, \$12,236 or more [22]. The developing countries can also be determined using the Human Development Index (HDI) where in general such countries have not achieved a significant degree of industrialization as compared to the population and most of the people have low standard of living. Common developing countries are found in Sub-Saharan Africa (SSA) where people are still facing socio-economic challenges, and many of the citizens live below the poverty line. [23] defined poverty as a pronounced deprivation of well-being due to lack of material and income, low levels of education and health, vulnerability and exposure to risk, lack of opportunity to be heard, powerlessness and lack of information, etc. Africa is the poorest region in the world where half of the populations live on less than USD 1 per day and most countries come from Sub-Saharan Africa [24]. The problem of environmental pollution is expected to be exacerbated by failure of governing institutions to address present and future demographic and socio-economic conditions on a priority basis [19].

A global survey carried out by [19], showed that there is an association between the per capita income of the country to the environmental concerns, remediation techniques and research. [19] proved the hypothesis that increase in per capita income gradually increases the environmental deterioration /decay until when at the turning point where it begins to decrease. More increase in GDP creates both environmental improvement by raising demands for improved quality in environmental protection and available resources for ensuring the desired improvement. Improved environment comes with favorable policies and institutional interventions. The hypothesis agrees with existence of relationship between nation's wealth status and their environmental pollution experience. Successful stories of use of plant and bacteria species as bioremediation agents have been reported, but knowledge relating to possible drivers in use of different techniques is lacking. There is lack of information about the demography of the relative acceptance and global use of bioremediation, adoption factors and challenges for implementation and also to what extent is the application of advances of biotechnology in bioremediation [19]. Economic barriers may restrict research and development institutions to develop remediation information because of low funding opportunities to conduct research in use of microorganisms/plant species in remediation processes as compared to physical remediation techniques such as landfilling. Different information such as use of molecular tools technologies and decision support software for selection of appropriate remediation approaches to model anticipated environmental factors which could affect the process either positively or negatively. The same survey found out that most countries with low developed economies have focused mainly on using more expensive *ex-situ* remediation technologies such as land filling. Excavation and transport of materials always significantly increase remediation costs thus leading to a preference for *in-situ* techniques. However, bioremediation is currently hindered by little knowledge base to understand the genetics and genome-level characteristics of the organisms to be used, the metabolic pathways and kinetics of the processes [25]. The findings still in the survey showed that the most barriers for bioremediation developments included socioeconomic, health and safety, management, regulatory and policy issues, cost considerations and information access and developments in developing countries. The country policies and bio-safety legislation on environmental medium such as soil and water still have to be strengthened and as well the knowledge and perceptions on the extent of contamination. Lack of centralized information on remediation activities have to be improved by the Government by funding or supporting research and development in bioremediation research.

Developing countries could be at risk of major environmental problem which may arise due to pollution of groundwater resources. In the global survey by [26], a bigger percentage of respondents who were Bioremediation Researchers all over the world were very concerned about soil contamination since there is a close relationship between soil and groundwater pollution. However, respondents from developing countries were more concerned about pollution of surface-water bodies an indication that such economies focus more on contamination which is immediately visible. On the other hand, developed countries always deal with hidden issues whose effect might only happen after a long period. Routine monitoring of groundwater resources has not been practiced to the same extent in developing countries as compared to developed countries. Similarly, there is lack of remediation technologies as well as legislation yet to be fully implemented in the area of groundwater pollution management in countries like Uganda. Therefore, this review paper addresses different bioremediation methods which can be used by both manufacturing and petroleum industries in Uganda to protect soil and water bodies. In addition, a summary of available research reporting microbial utilization and plant derived biomass for bioremediation is highlighted.

2. Study Area

Uganda is located in the eastern region of Africa (UTM Easting: 421,045.88, UTM Northing: 151,806.57) with a spatial extent of about 241,500 km^2 of which 15.3% is open water, 3% permanent wetlands, and 9.4% seasonal wetlands. Uganda's perimeter is about 16,630 km long shared with the Republic of Kenya in the east, Tanzania and Rwanda in the south, Democratic Republic of Congo in the west and Republic of South Sudan in the north.

2.1. Discovered Oil Reserves in Uganda

According to [27], oil and gas industry will fetch billions of dollars in investment since the Government of Uganda is transitioning from exploration to development or production. The discovered oil reserves have been estimated to be as low as 3.5 million barrels to as high as approximately 2.5 billion barrels [28]. From the study done by Tullow Oil Pty Ltd. as reported by [27], Tullow Oil estimates a gross of 1.1 billion barrels of oil in the Lake Albert Rift Basin, therefore, there is potential of processing oil in so many years to come and this pose a question of the possibilities of the environmental pollution and how cheap can the wastes produced be treated. More so, Tullow still believe that there is additional 1.4 billion barrels of oil which are yet to be discovered in the basin. Tullow Oil and Heritage Oil Ltd. have so far successfully drilled reserves in Albertine Rift area beside and under Lake Albert, which lies in the uppermost part of the western arm of the Great Rift Valley [27]. However, this region also hosts sensitive ecosystems with most species thriving on the water bodies and nature reserves which are receptors for possible pollution by the oil compounds spilled along the processing chain of oil development (exploration, extraction, pipeline transportation and refining). The famous Murchison Falls National Park (MFNP) found in the Exploration Area 1, has many already drilled wells (including Mpyo 1, 2 and 3 in the south section of the park, Rii and Jobi-East 1 in the north side of the park). Other well sites in the south side and the north section of the MFNP are planned. Plans to exploit the country's oil and gas will base on the confirmed reserve sizes. However, there will be a need to safeguard the established oil and gas reserved by avoiding poor extraction practices such as excessive production from wells which may lead to loss of integrity of the reservoirs. Protection of the host environment from pollution is a vital goal for the Oil Companies, Government of Uganda and the Public. Efficient production, therefore, will contribute to better extraction practices [29]. **Table 1** presents the exploration areas and their status found in the Albert Graben region (**Figure 1**).

2.2. Established and Planned Industrial Business Parks in Uganda

It is estimated that at least twenty two (22) Industrial and Business Parks (IBPs)

Table 1. Exploration Areas in the Albertine Graben Region.

Exploration Areas	License year	Company with License	Status
Pakwach Basin—Exploration Area 1	2004	Heritage Oil and Gas Ltd in partnership with Tullow Oil	Area has potential prospects of drilling oil
Northern Lake Albert Basin—Exploration Area 2	2001	Hardman Petroleum Africa Pty in partnership with Tullow Oil. Later Tullow Oil bought Hardman Petroleum Africa Pty and became the sole licensee	There is drilling prospects both onshore and offshore. Two of these onshore prospects having oil are Waraga and Mputa. A third onshore prospect having natural gas is Nzizi. Plans to develop an Early Production Scheme from these discoveries are underway—Currently under production license for a joint venture between Total EP, CNOOC and Tullow.
Southern Lake Albert Basin—Exploration Area 3A	2003	Heritage Oil and Gas Ltd and re-licensed to heritage Oil and Gas Ltd with Tullow Oil	There is Kingfisher prospect on the shores of Lake Albert—Currently under production license for a joint venture between Total EP, CNOOC and Tullow.
Semiliki Basin—Exploration Area 3B	Not Captured	Not Licensed	Three wells were drilled on the Turaco prospect, one of the prospects mapped in the area. Wells have oil and natural gas. But natural gas is contaminated with carbon dioxide. Some zones were identified with a lot of hydrocarbons and their potential was not tested.
Northern lakes Edward and George Basin—Exploration Area 4A	Not Captured	Not Licensed. Several oil companies expressed interest in acquiring exploration rights but their applications are awaiting a new licensing policy	Area has structures with potential for petroleum accumulation.
Southern Lakes Edward and George Basin—Exploration Area 4B	2007	Dominion (U) Ltd	The company is yet to be given permission to conduct exploration studies of oil potential in this area
Rhino Camp Basin—Exploration Area 5	2007	Neptune Petroleum (U) Ltd now called Tower Resources	There are 10 deep wells which were recently drilled on Turaco, Waraga, Mputa, Nzizi and Kingfisher prospects. There is confirmed working petroleum system without risks in exploration

Source: MEMD (2008).

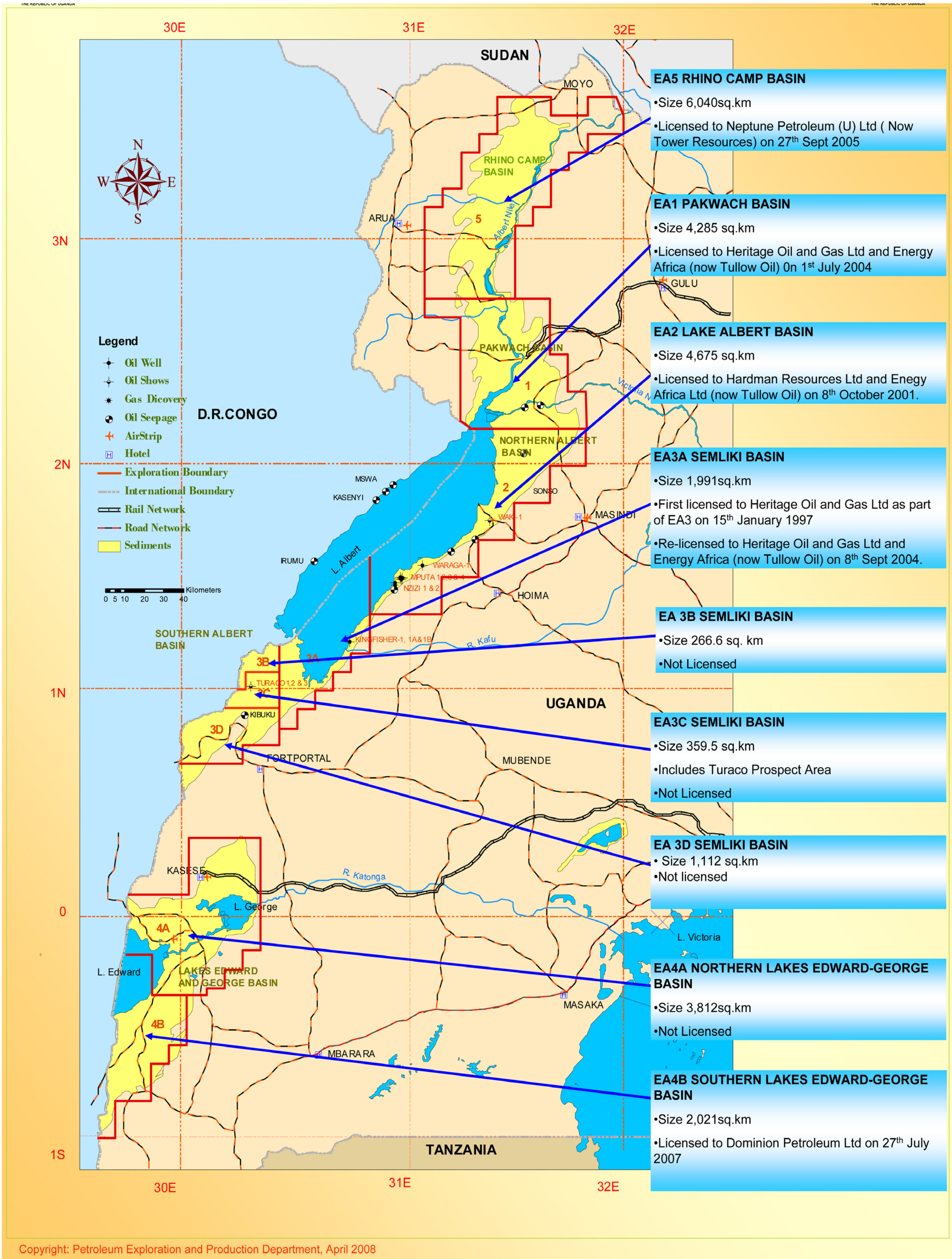


Figure 1. Exploration Areas in the Albertine Graben and status of Licensing (Source: MEMD, 2008).

are to be established by Government of Uganda in spread areas some shown in **Figure 2** (http://gov.ug/content/industrial-and-business-parks). The main purpose of this initiative is that the Government wants to create jobs to the youthful population and as well collect more money from products by value addition. By the plan designed by the Uganda Investment Authority (UIA), the main IBP is in Kampala located 11 km East of Kampala, the Capital City. This is a 2200 acre facility and will include a number of Industrial clusters and large projects. More than two hundred investors have been allocated land in the Park. Luzira and Bweyogerere parks are near Lake Victoria and incase of high accumulation of contaminants may end up into this water body.

Given the spatial distribution of water resources in Uganda (**Figure 2**), the footprint of Industrial Business Parks as shown in **Table 2**, overlap with catchment areas of the main water resources. Any pollutants within the IBPs would thus follow natural drainage patterns in the catchments as pollution paths into the water resources. The main water bodies include Lakes; Victoria, Kyoga, Albert, Edward and George, as well, Rivers; Victoria Nile, Albert Nile, Murchison Nile and Katonga. Therefore, it is very important to be cautious of the contami-

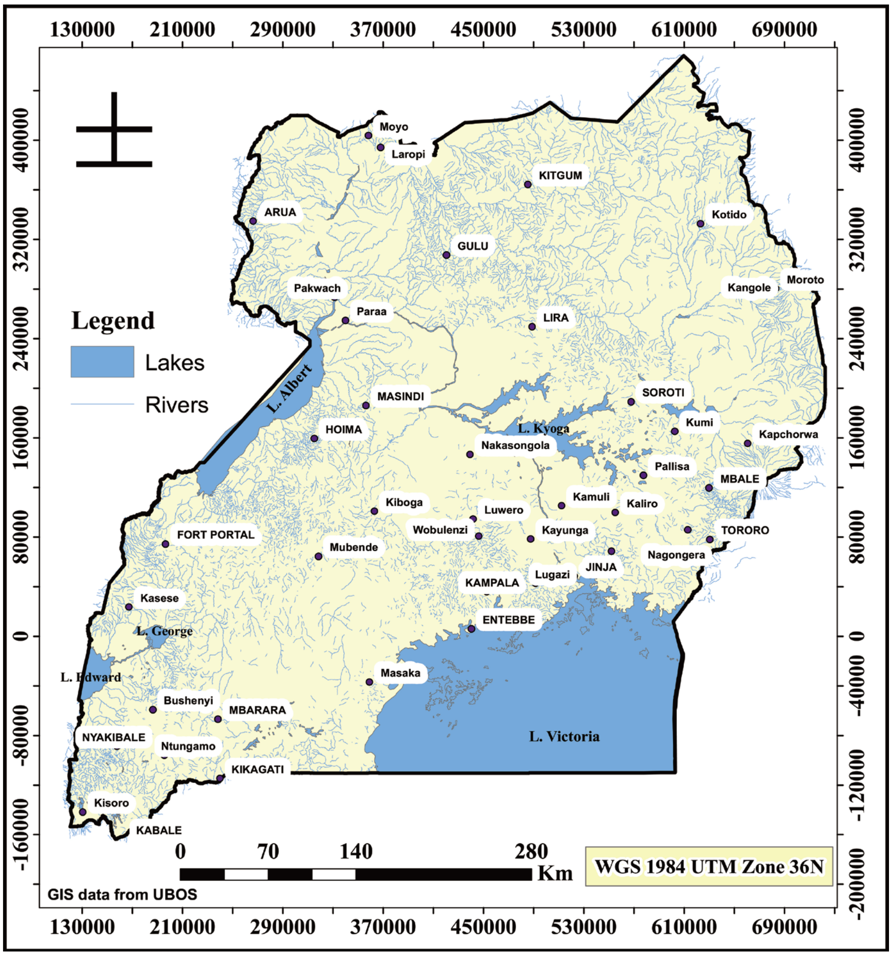


Figure 2. Water Resources and Towns where Industrial Business Parks are and/or planned to be established.

Table 2. Planned Industrial Business Parks in Major cities of Uganda.

Location in Uganda	Planned Industrial Business parks	Size	Status
Kampala (Capital city)	Luzira Industrial Park is located 5 km East of Kampala	70 acres	Facility is operational with functional infrastructure (road, water, power). Currently, power is being upgraded to investor's requirements, and the government is targeting more investors to occupy in this park to establish their projects
	Bweyogerere Industrial Estate is located 10 km north east of Kampala	45 acres	The land has been also allocated to different investors. This was largely a wetland that was reclaimed to give way to industrial development.
Upcountry	Soroti IBP is 350 km North East of Kampala	219 acres	Five acres of land in the IBP have been allocated to the Teso Fruit farmers Association to tap the large fruit potential in the region
	Kasese IBP is located 430 km from Kampala in Western Uganda near the border with the Democratic Republic of the Congo (DRC)	217 acres	Intended to stimulate agricultural products value addition and mineral benefaction in the region
	Mbarara SME Park	12 acres	To cater for small scale enterprises adjacent to Mbarara Municipality 280 km southwest of Kampala. This lies in the heart of Mbarara town with little effluent treatment capability and class-room style blocks. Since its launch, it has failed to attract serious industrialists because their different production areas needs were never addressed during construction.
	Jinja IBP is located 80 km east of Kampala	182 acres	Jinja is being re-activated as a major industrial town that it was once in early years. This IBP largely lies in a wetland in a sugarcane growing belt.
	Moroto	417 acres	Mineral beneficiation activities are being targeted for employment generation
	Gulu IBP is 350 km north of Kampala	Not Captured	Negotiations to acquire 500 acres of land were started
	Kabarole and Kyenjojo IBPs	150 acres	Not Captured
	Masindi IBP	Not Captured	Planned as an oil park and Government is in the process of procuring land in the Masindi/Hoima area
	Masaka, Bushenyi, Lira, Iganga and Mubende	Not Captured	Are yet to bid for IBP and received by the Uganda Investment Authority (UIA)

Source: http://gov.ug/content/industrial-and-business-parks

nations that might be produced from the human activities mainly from industrialization, which end up in the water sources utilized by inhabitants for irrigation and domestic use. These pollutants may also affect the agricultural lands whereby the soil characteristics are altered and soil no longer viable enough for farmers to produce high yields. To address this challenge, we suggest the use of bioremediation processes to help in cleaning them up from the environment and left safe for human use.

3. Waste Production in Oil Processing and Manufacturing Industries

3.1. Waste Production in Oil and Gas Production and Their Effect to the Environment

Oil pollution has been poorly regulated in developing countries where oil exploration and drilling has been taking place for example in Nigeria where they are referring it as an "oil curse" because it is associated with high environmental pollution. Oil spills are common on both on-shores and off-shores. The majority of spills are caused by corrosion of pipelines, neglected equipment and citizen sabotage [30]. For the case of Uganda, oil was discovered in the Albertine region comprising of water resources and national parks [31]. Water pollution is a primary environmental, social and economic concern wherever oil and gas drilling procedures are done near primary water sources. Oil spill in Lake Albert doesn't only affect the health of the lake and biodiversity, but also the local livelihoods and human health in that region [30]. Oil pollution can occur in different ways: water runoff established at well pads or from storms to water ways; runoff introducing sediment and toxic chemicals into waterways and water becomes unsafe for drinking for humans, wildlife and livestock; uptake of contaminated water by plants and food sources and produced water during oil drilling procedures may contain arsenic, cadmium, mercury, lead, zinc and copper which are all heavy metals thus affect human and environmental health. Mud cuttings and wastewater remaining after oil drilling pollute the aquifers and ground sources [30]. Poor management of oil waste can lead to severe environmental degradation from effluent from sewage treatment, drill fluids, drill and mud cuttings from well construction and other solid and hazardous waste materials. It is reported by [30], that the major concern will be the storage of waste particles after treatment and how safe they will be transported.

Crude oil petroleum hydrocarbons (PHs) are anticipated to be the main pollutants on Lake Albert [31]. PHs are pollutants since they can dissolve in lipids in aquatic animals and thereafter bioaccumulate in the food chain and can be delivered to other trophic levels of the food chain [32]. The toxicity levels of crude oil or petroleum products depend on the compositions, environmental factors and the biological state of soil organisms at the time of contamination [33]. In each refinery starting from primary distillation to final treatment, there is production of various fractions of oils and other hydrocarbon compounds in their wastewaters such as polycyclic and aromatic hydrocarbons, phenols, metal derivatives, surface-active substances, sulfides, naphthylenic acids and other chemicals [34]. Oil pollution from compounds such as TPH (Total Petroleum Hydrocarbon), TOC, C/N and C/P changes soil chemical properties [12]. Phenol and its derivatives is also a contaminant from the refinery wastewater. Phenol is highly toxic and hazardous to living organisms. Low molecular-weight aromatics such as benzene, toluene and xylene are the most toxic petroleum compounds which are easily degraded by the marine microorganisms. The hydrocarbons with high complexity structures such as those with high number of methyl-branched substituents or condensed aromatic rings, experience slow degradation rates and thus high accumulation of partially-oxidized intermediary metabolites. There is always incomplete biodegradation of crude oil producing complex residue inform of black tar which contains a high proportion of asphaltic compounds. This residue can coat on both the earth and water body surfaces which may suffocate the living microorganisms, unless it doesn't coat, then it becomes an inert environmental contaminant with no toxic ecological effects.

3.2. Waste Production at Manufacturing Industries and Their Effect to the Environment

Whenever industrial effluents are not properly treated, when discharged into open water streams, there is always nutrient enrichment, accumulation of toxic compounds and reduced levels of dissolved oxygen in water [35]. Common compounds within wastewater that affect the ecosystem within water bodies include the organic substances which consume dissolved oxygen required by aquatic animals during degradation, nutrients and also inorganic toxic substances. Much accumulation of Total Suspended Solids (TSS) attracts foreign pathogens into water which accelerates microbial pollution. High Total Dissolved Solids (TDS) indicates the presence of heavy ions such as Sodium, Chloride, Magnesium and Calcium. Such ions have negative effects to aquatic life, poor quality of water for drinking and domestic purposes, accumulation of ions when water is used for irrigation thus reduction in crop yields, and intensify corrosion in water networks [36]. Heavy metals mainly Lead, Copper and Cadmium from industries pose serious environmental risks. Cadmium affects the metabolic processes in plants and can as well bio-accumulate in aquatic organisms and in the entire food chain. Acute effects of Lead are inattention, hallucinations; delusions, poor memory, and irritability which are symptoms of acute intoxication. There is retardation in growth among children due to Lead absorption and its storage in bones. Phenol is produced from chemical and pharmaceutical industries when substituted compounds are being formed in oxidation and disinfection processes [37]. Even at very low concentrations, Phenol is seriously toxic. Phenols cause depletion of ozone layer and thus increase in heat on earth, reduced visibility and accumulation of acidic air pollutants in the atmosphere. Industrial wastewater and solid waste are common sources of xenobiotics especially from industries such as chemical and pharma, plastic, paper and pulp mills, and textile mills. The characteristics of industrial waste can differ considerably both within and among different industries [1], and this is shown in **Table 3**.

4. Bioremediation Technologies Applications during Cleanup of Polluted Environment

Bioremediation technology is classified as *ex-situ* or *in-situ* whereby *in-situ* bioremediation involves direct application of the bioremediating agents (microorganisms or plants) on pollutants at the site of pollution. *Ex-situ* bioremediation is where a toxic material (pollutant) is collected from a polluted site and the selected range of microorganisms carry out the biodegradation at the designated place. This is an improved method over *in-situ* since the bioremediating agents which cleanup contaminated sites are tested for their natural capability to effi-

Table 3. Characteristics of industrial wastewater in Uganda.

Industry Type	Wastewater characteristics
Mining	Metals
Abattoir	BOD, COD, TSS, N & P
Brewery	BOD, COD, Detergents
Fish processing	BOD, COD, N & P, Oils
Meat processing	BOD, COD, TSS, N & P
Oil and Soap	BOD, COD
Battery production	Heavy metals, oils, acids, lubricants
Galvanizing	Metals, lubricants, acids
Paints	Heavy metals, Xenobiotics
Pharmaceuticals	BOD, COD, Xenobiotics
Soft drinks	BOD, COD, N&P, detergent

Source: UNCST, 2009 (BOD is the Biological Oxygen Demand which is the amount of dissolved oxygen required by aerobic microorganisms to breakdown organic matter/material present in industrial wastewater at certain temperature over a specific time. **COD** is the Chemical Oxygen Demand which is the amount of dissolved oxygen required for decomposing of organic matter and the oxidation of inorganic chemicals such as heavy metals, ammonia and nitrite. **TSS** is the Total Suspended Solids which are solid materials including organic and inorganic that are suspended in water, for example, silt, sediments and oils. Nitrates (**N**) and Phosphates (**P**) are nutrients when exposed to water promote algae growth which might result into Eutrophication.)

ciently biodegrade compounds. Different types of microorganisms can be used for bioremediation including bacteria, archaebacteria, yeasts, fungi and algae and plants (**Table 4** & **Table 5**). Microorganism is able to clean the oil polluted environment because of their capability to degrade and such active microorganisms can be selected in high numbers for treatment [38]. Use of bioremediation to clean oil pollutants was started after realization of its success with oil tanker Exxon Valdez oil spill which occurred in Gulf Alaska in 1998 [39]. Oil spill bioremediation can be done with use of microorganisms with high metabolic rates and easily adapt to the exposed environment to ensure high oil biodegradation rates. Important environmental factors are adequate nutrient concentration for example nitrogen is one of the biodegradation inhibitor of hydrocarbons in soil, presence of oxygen and optimum pH. There are different methods of practicing oil spill bioremediation, which includes, Bioaugmentation is a process where microbial population is supplemented by the oil degrading bacteria whereas Biostimulation is where nutrients or other growing stimulating substances are added when growing the indigenous degraders [40] [41]. Bioaugmentation reduces on the adaptation time of microorganism but importantly increases the biodegradation rates [42]. Phytoremediation is also an important method in bioremediation processes where rhizospheric microorganisms are used mostly the hyper-accumulating plants. A microalga has an advantage that it contains higher biomass production than terrestrial plants. Still compared to terrestrial plants, micro algae need a lower rate of water removal and can be cultivated in

Table 4. Recent Studies with use of Microorganisms (Bacteria, Fungi, Algae) to treat oil contaminated environments (Publications from 2006-2016).

Studies to Clean Oil Contaminated Water					
Oil waste type	**Microorganisms type**	**Species**	**Research Objective**	**Conclusion**	**Reference**
Crude Oil	Bacteria	*Enterrobacteria cloacae*	Study the ability of the bacteria in oil degradation	• After 30 days of incubation, E. cloacae degraded 70.00% ± 0.4% of the crude oil and degrading aromatic compounds	[76]
Oil wastewater effluent	Bacteria	*Pseudomonas aeruginosa*	Effectiveness of biodegradation of bacterial species with or without nutrients	• There was percentage degradation of 96.43%, 99.94%, 99.80% and 90.38% for Lead (Pb), Selenium (Se), Arsenic (As), and Cadmium (Cd) respectively	[34]
Crude oil	Fungi (Mushroom)	*Pleurotus tuber regium, Pleurotus pulmonarius, Lentinus squarrosulus*	To assess the possibility of fungi to degrade different crude oil concentrations in liquid medium	• Three indigenous mushroom degraded crude oil at different rates, however the mixture of the 3 fungi was the most effective in oil degradation • The mushroom species can be used in management of oil spills	[77]
Crude oil	Fungi	*Fusarium, Penicillium, Aspergillus*	Biodegradation of crude oil using fungi isolated from sea water contaminated by oil spill	• The Highest drop of 83.12% in total hydrocarbon concentration was detected for *Aspergillus* followed by 75.43% for *Penicllium sp.* and 69.89% for *Fusarium sp.* • *Aspergillus sp.* was found to have a high capacity to thrive on hydrocarbons present in crude oil • *Aspergillus sp.* showed the highest drop of 49.99%. *Penicillium sp.* showed a drop of 44.43%. whereas *Fusarium sp.* showed a drop of 41.64%	[78]
Raw Crude Oil polluted water and Treated Crude oil polluted water	Bacteria and Fungi	*Aspergillus niger* (*fungi*) *and Pseudomonas aeruginosa* (*bacteria*)	Investigation of biodegradation activities of fungi and algae on two crude types. BOD and THC (Total hydrocarbon Content) were monitored	• Treated crude oil polluted water was easily bio-remediated than raw crude oil polluted water and this was high when only bacteria was used • In raw crude oil polluted water with use of bacteria BOD was 97.9%, THC was 91.3% • In raw crude oil polluted water with use of fungi, BOD was 89.3% and THC 76.4% • In raw crude oil polluted water with use of both bacteria and fungi, BOD was 93.8% and THC 84.5% • In treated crude oil polluted water with use of bacteria, BOD was 99.8% and THC 95.3% • In treated crude oil polluted water with use of fungi, BOD was 95.4% and THC 86.5% • In treated crude oil polluted water with use of bacteria and fungi, BOD was 97.9% and THC 90%	[79]
Crude Oil	Bacteria	*Pseudomonas aeruginosa, Bacillus subtilis, Acinetobacter lwoffi*	Biodegradation rates with different bacterial species	• Removal rate of 88.5% with mixture, 77.8% for *Pseudomonas aeruginosa*, 76.7% for *Bacillus subtilis*, 74.3% for *Acinetobacter lwoffi*	[80]
Crude oil	Bacteria	*Bacillus and Geobacillus*	Study the biodegradation of thermophilic bacteria isolated from a volcano island	• The isolated species had their sole carbon source as hydrocarbons and degraded long chain alkanes between 46.64% and 87.68%	[81]

Continued

Studies to Clean Oil Contaminated Soils					
Crude oil	Fungi	*Aspergillus niger, Fusarium oxysporum, Drechslera spicifera, Penicillium chrysogenum, Penicillium documbens, Aspergillus flavus, Aspergillus candidus, Verticillium dahliae*	Isolation and identification of soil fungi from oil polluted samples. Applying a safe method as biodegradation of oil spill by those isolated fungi to control environmental pollution in crude oil contaminated soils and screen their ability in crude oil bioremediation	• *Aspergillus niger* and *Fusarium oxysporum* showed the highest frequency represented by (9.8%) for each, followed by *Drechslera spicifera*, *P.chrysogenum*, which represented by 7.8% and 7.5% respectively • *Penicillium documbens* and *Aspergillus flavus* were represented by 7.2% for each, followed by *Aspergillus candidus* and *Verticillium dahliae* represented by 6.2%, 6.5% respectively • The biodegradability of isolated fungi was measured and the results showed that *Aspergillus niger* and *Lichtheimia ramosa* were the most efficient fungi in reducing of oil spill from the environment	[53]
Crude oil	Fungi	*Aspergillus niger, Candida glabrata, Candida krusei and Saccharomyces cerevisiae*	Investigation of the abilities of four fungi species isolated indigenously contaminated soil for crude oil biodegradation	• *Aspergillus niger* recorded the highest biodegradation of 94%, then *Candida krusei* 61% and *Candida glabrata* 60% whereas the lowest biodegradation rate was demonstrated by *Saccharomyces cerevisiae* 58 after 7 days of incubation. Fungi utilized petroleum hydrocarbon as a carbon and energy source	[82]
Crude oil	Bacteria	*Ochrobactrum cytisi, Ochrobactrum anthropic, Sinorhizobium meliloti*	Assessment of the capability of the bacterial strains to degrade oil in culture medium and soil	• The strains have potential to degrade more than 84% and 54% of total petroleum hydrocarbons (TPHs) in basal salt medium and soil amended with 4% crude oil after 30 day incubation	[83]
Crude and Diesel oil, Gasoline	Fungi	*Aspergillus*	Evaluate removal ability of oil compounds from contaminated soils	• The isolated strains were able to degrade petroleum by-products in percentages ranging over a wide range between 32.46% and 78.42% after 40 days	[84]
Crude oil	Protozoa	*Aspidisca, Trachelophyllum and Peranema*	Biodegration ability in different oily wastewater concetrations	• High amount of COD released and over 80% DO were removed • The protozoan was able to degrade crude oil (initial concentration: <50 mg/L) from 10.41% to 55.5%, from 11.0% to 64.5%, from 11.66% to 44.21% and from 21.2% to 61.1% for *Aspidisca sp.*, *Trachelophyllum sp.*, *Peranema sp.*, and a consortium of the three isolates, respectively.	[85]
Oil Mining industrial wastewater	Bacteria and Protozoa	*Pseudomonas putida, Bacillus licheniformis and Peranema*	Assessment of resistance to heavy metals by selected protozoan and bacterial species	• Living *Pseudomonas putida* demonstrated the highest removal rates of heavy metals (Co 71%, Ni-51%, Mn-45%, V-83%, Pb-96%, Ti-100% and Cu-49%) followed by *Bacillus licheniformis* (Al-23% and Zn-53%) and *Peranema sp.* (Cd-42%). • The study advocates for the use of all the species as a potential candidate for the bioremediation of heavy-metals in wastewater treatment	[67]
Crude oil	Bacteria	*Bacillus subtilis, Pseudomonas aeruginosa*	Biodegradation ability in oil contaminated soils	• An increase in cell number indicated the oil degradation	[86]

Continued

Kerosene	Fungi	*Aspergillus niger, Aspergillus terreus, Rhizopus sp and Penicillium sp isolated from soil and tarball*	Assessment of degradation capability of petroleum hydrocarbons for different concentrations of kerosene (5%- 20% (v/v))	• *Rhizopus sp* showed the highest growth diameter in 5% kerosene and *Aspergillus niger* showed the highest growth diameter in 20% kerosene while, *Penicillium sp* showed the lowest growth diameter at all the concentrations of kerosene as compared to other three strains. • Mix culture consisting of *Penicillium sp*, *Rhizopus sp* and *Aspergillus terreus* showed highest degradation rates	[87]
Crude oil	Fungi	*Polyporus sp. S*133 *pre-grown in wood meal*	Degradation of crude oil in soil was significantly increased with an addition of oxygen flow and some absorbent (kapok and pulp)	• The highest degradation rate of crude oil was 93% in the soil with an addition of 10% kapok. The present study clearly demonstrates that, if suitably developed, *Polyporus sp. S*133 could be used to remediate soil contaminated with crude oil	[52]
Crude oil	Fungi and Yeast	*Aspergillus sp.*; *Cephalosporium sp., Cladosporium sp.*; *Fusarium sp.*; *Geotrichum sp.*; *Mucor sp.*; *Penicillium sp. and Trichoderma sp* (*Fungi*) & *Candida sp. And Rhodotolura sp.* (*Yeast*)	Investigation of effect of crude oil concentrations on fungal population in soil	• This study showed that there is a large increase in both heterotrophic and hydrocarbon-degrading fungal populations after the introduction of oil into the soil	[88]
Crude oil	Bacteria	*Pseudomonas putida*	Evaluation of biodegradation of crude oil in an open environment using naturally adapted bacteria species adapted from oil contaminated sites	• There was an increase in microbial count and rate of degradation in oil plus bacteria and fertilizer plot • It also revealed that fertilizer stimulated the rapid multiplication of microbes which simultaneously increased the rate of degradation.	[44]

Table 5. Phytoremediation studies for petroleum hydrocarbon removal in water using constructed wetlands (Publications from 2012 to 2001).

Type of Contaminant	Plants Used	Configuration of plantation	Results	Reference
Runoff waters with hydrocarbons from vehicle exhaust pipes and heavy metals	*Phragmites australis*	Wetland of Vertical Flow	• Removal efficiencies of 90% - 95%. Widely satisfied the Dutch, European, and American standards for surface waters and shallow subsurface waters	[89]
Waster waters contaminated with benzene	*Phragmites australis*	Wetland of Vertical Flow	• Benzene removal of 85%; in wetlands with biomass, the removal took half of the time to that of the wetlands without biomass; the predominant removal mechanism was Phytovolatilization	[90]
Subsurface waters with hydrocarbons and cyanide	*Ceratophyllum demersum and Potamageton sp.*	Wetland of Superficial flow	• Removal of 67% of gasoline and diesel.	[91]
Wastewaters contaminated with diesel	*Typha latifolia*; *Lemna minor* (*Control*)	Wetland of Subsurface Flow	• Removal efficiencies between 80%, 78% and 72% on the surface, medium and bottom sections of the planted wetland.	[92]
Subsurface water contaminated with gasoline-ethanol	*Salix babylonica*	Wetland of Superficial flow	• Reduction of ethanol and benzene >90%. Toxic compounds for macrophytes in concentrations over 2000 mg/L.	[93]

brackish water, micro algae require only sunlight and few simple nutrients such as nitrogen, phosphorous and carbon [43].

4.1. Bioremediation of Oil Compounds Using Microorganisms

4.1.1. Using Bacteria to Treat Oil Compounds

Biological degradation of hydrocarbons is only done by microorganisms [44]. Different microorganisms contain enzymes which actively degrade the petroleum hydrocarbons. Some microorganisms are capable of degrading alkanes (normal, branched and cyclic paraffin), others degrade aromatics—paraffinic and aromatic hydrocarbons. Aerobic microorganisms degrade oil through oxidation and this is the leading and effective approach [45]. Oil compounds are used as food substrates by bacteria to carry out metabolism. Hydrocarbon degrading microorganisms feed on oil contaminants and use carbon compounds as energy source for growth and reproduction [45]. The degradation was reported to be simulated with fertilizer in laboratory [46]. Different bacterial species have shown potential in degrading hydrocarbons which include *Bacillus* [47], *Pseudomonas* [48], and *Streptomyces* [49] and all have potential to remove heavy metals. The biodegradation of petroleum in the marine environment is performed by different bacterial populations including various *Pseudomonas* species. *Pseudomonas* is a strong bacterium effective in degrading a wide range of aliphatic, aromatic and polynuclear aromatic hydrocarbon compounds into simpler compounds [50]. *Pseudomonas Alcaligenes* is capable of breaking down polycyclic aromatic hydrocarbons while *Pseudomonas Mendocina* and *Pseudomonas Putida* can remove toluene. *Pseudomonas Veronii* can degrade large number of aromatic organic compounds [51]. *P. australis* can remove compounds derived from petroleum since its roots can excrete enzymes which stimulate the degradation of petroleum compounds. And the interaction with microorganisms such as *Mycobacterium sp and* this accelerates degradation of compounds with high molecular weight [52]. Different studies have been done to test the effectiveness of using microorganisms in cleaning of oil polluted environments (**Table 4**). Most researchers reported positive results which support the ability of microorganism to breakdown the oil compounds, therefore, they are very essential in cleaning the environment and worthy to be considered.

4.1.2. Using Fungi/Algae to Treat Oil Compounds

Most common plants used for treating oil compounds are fungi and algae. Fungi remove hazardous compounds from water and sediment particles contaminated with crude oil which an ecological niche for fungi since there is substrate and carbon source from hydrocarbons. Fungi in a process help in biodegrading the crude oil from sediments [33]. According to [53], fungi is the best degrader as compared to bacteria since it almost breakdown all alkanes of particular chain lengths. Fungal growth cannot be inhibited by environmentally stressed conditions (pH and poor nutrient status) unlike bacteria. Fungi can also be easily be transported, genetically engineered and produced in large quantities. Most used fungi are of genera: *Alternaria, Aspergillus, Candida, Cephalosporium, Cladosporium, Fusarium, Geotrichum, Gliocladium, Mucor, Paecilomyces, Penicillium, Pleurotus, Polyporus, Rhizopus, Rhodotolura, Saccharomyces, Talaromyces and Torulopsis* [33]. Most capable fungi is white-rot fungus (*Phanerochaete chrysosporium*) which is efficient in degrading toxic and insoluble compounds as compared to microorganisms [54]. White-rot fungi secret extracellular enzymes which help in oxidation of complex aromatic compounds and other hazardous pollutants [52]. The white-rot fungi *P. pulmonarius* secrete lignolytic enzymes such as lignin peroxidase, manganese peroxidase and laccases which aid the degradation process [55]. Different studies have been done to check the viability of fungi to treat oil contaminated sites. Fungi stains are used to breakdown crude oil and several polycyclic aromatic hydrocarbons as shown in **Table 4**. Suitable bioremediation conditions such as oxygen, nutrient, pH, temperature and water enhances high biodegradation rates. Algae controls and bio-monitors the accumulation of organic pollutants in an aquatic ecosystem. Microalgae also produce enzymes which degrade harmful organic compounds within petroleum hydrocarbons into less toxic compounds. [56] reported that water hyacinth (*Eichhornia crassipes*) can accumulate petroleum hydrocarbons since it has got a fibrous root system and floats on water where it absorbs the crude oil while on the water surface.

4.1.3. Using Plants to Treat Oil Compounds

Different terrestrial plants such as legumes and grasses are also suitable in remediating harmful hydrocarbons in soil environments [57]. Several grass species degrade PAHs such as *Agropyron smithii*, *Bouteloua gracilis*, *Cyanodon dactylon*, *Elymus Canadensis*, *Festuca arundinacea*, *Festuca rubra*, and *Melilotus officinalis* [58]. Total Petroleum Hydrocarbons (TPHs) in crude oil were broken down by 2 plants—*Arctared red fescue* and *annual ryegrass* [59]. This bioremediation process is referred to as Phytoremediation. Such plants remove pollutants by either storing them in plant roots or foliage. Legumes have microorganisms within the rhizosphere such as the genera *Pseudomonas*, *Arthobacter*, and *Micrococcus* which degrade a variety of hydrocarbons [60].

Most recent studies have used terrestrial plants to remove oil compounds by setting up constructed wetlands (see **Table 5**) [61]. The constructed wetlands are engineering systems that have been designed and built with aim of having a controlled environment similar to the natural wetlands, taking advantages of the interactions between the vegetation, soils and microbial communities to treat wastewaters [62]. The constructed wetland is classified depending on the type of growth or life form of the predominant macrophytes and the flow regime [63]. The first classification is divided in systems based on macrophytes that are either free floating, submerged or emerging roots. The second classification is characterised as a function of the incoming water flow into the system, for example horizontal, surface, subsurface or vertical flow [61]. With use of the wetlands, the principle steps for the removal of hydrocarbons are volatilization, biological or microbial degradation, photochemical oxidation, sedimentation, absorption and chemical filtration and precipitation. **Table 5** presents a summary of phytoremediation process in treatment of contaminated water with petroleum hydrocarbons.

4.2. Bioremediation for Treatment of Industrial Wastewater

4.2.1. Use of Microorganisms to Treat Industrial Pollutants

Industrial effluents are the most important sources of toxic contaminants in any environment. The level of organic pollutants in the environment has been exacerbated by the rapid industrialization and urbanization. Use of cyanobacteria has shown a great potential in treatment of wastewater and industrial effluents. Bioremediation of aquatic and terrestrial habitats help in detoxifying effluents from chemical, bio-fertilizer, food, feed and fuel industries. Most predominant microbes used in activated sludge to treat municipal sewage include *Pseudomonas, Flavobacterium, Alcaligenes, Acinetobacter, and Zooglea* sp. *Pseudomonas sp* are responsible for efficient removal of COD in activated sludge [64]. *Pseudomonas* is important in aerobic decomposition and biodegradation, and hence they play a key role in the carbon cycle. [65] realized that *Pseudomonas sp*. were efficient in breaking down the compounds in the tannery effluent and later were nontoxic and safe for disposal. Naturally occurring consortia of microorganisms like *Bacillus, Pseudomonas, Arthrobacter, and Micrococcus* species reduced 95% of COD and BOD in steel industrial effluents [66]. Most used microbes in textile industries for bioremediation processes are *Bacillus subtilus*, *B. cereus, B. mycoides*, *Pseudomonas sp. and Micrococcus sp*. [63]. To remove heavy metals from industrial wastewater, microorganisms such as *Pseudomonas putida* and *Bacillus cheniformes* can be of great importance [67]. **Table 6** summary research about use of microorganisms during bioremediation of industrial effluents.

4.2.2. Using Fungi/Algae to Treat Industrial Pollutants

Fungi are also important in treatment of industrial effluents since they produce enzyme known as peroxidass which convert toxic compounds into nutrients. Common fungal enzymes are manganese peroxidase and fungal laccases which remove phenolic compounds from industrial wastewater [68]. Algae controls and bio-monitors the accumulation of organic pollutants in an aquatic ecosystem. Heavy metal can be effectively hyper-accumulated by algae and also degradation of xenobiotics [69]. The microalgae has potential for wastewater treatment and can be used to remove the chemical and organic contaminants, heavy metals and pathogens due to presence of CO_2 in wastewater which provides a conducive growth environment within the medium for microalgae to assimilate such contaminants [70]. Different studies have used fungi and algae for effluent treatments in different types of industries (**Table 6**).

4.2.3. Using Plants to Treat Industrial Pollutants

A term used to refer to use of plants in treating industrial effluents with both

Table 6. Studies with use of microorganisms and plants to treat industrial waste contaminated environments (Publications from 2015 to 2011).

Treated wastewater type	Microorganisms /Plants	Species	Research Objective	Conclusion	Reference
Greywater and Dairy	Algae	*Botryococcus sp.* (1000 *cell/mL as initial concentration*)	Physiochemical parameters removal	• Reduction of BOD up to 73.3% in dairy wastewater; removal of 88% COD in grey water	[94] [95]
Metal plating effluents	Bacteria	*Shewanella xiamenensis,*	Utilization of the bacterial species in removal of heavy metals (Zn, Fe^{2+})	• Its growth was maximum at 150 ppm (0.67), minimum at 500 ppm (0.07), no growth beyond 500 ppm of Iron and it was 0.41 in the control setup. It exhibited 97.09% iron removal in the 150 ppm setup and around 89.71% of the available iron in the 400 ppm setup. Thus the overall results clearly indicate that the bacterium *Shewanella xiamenensis* scavenges heavy metal after achieving osmotic tolerance in the sweet water environment, which being a marine bacteria	[96]
Refinery and petrochemical	Algae	*Lemna minor L.*	physiochemical characteristics of the waste water removal	• The highest rate of mean reduction were for heavy metals accounting 99.6%, 93.3%, 99.3%, 94.3%, 100% and 95.4% of Cd, Hg, Zn, Mn, Pb and Ag respectively • Other physiochemical parameters include Total Dissolved Solids (TDS) 81.3%, Chemical Oxygen Demand (COD) 91.6%, Nitrate 93.3%, Biochemical Oxygen demand (BOD) 68%, Conductivity 50.3%, Total suspended Solids (TSS) 77.3%, Turbidity 85%, 81% Total Solids (TS) and the pH were increase from 6.29 to 7.7. Lemna minor L. is a suitable candidate for effective phytoremediation of water	[74]
Mining industrial	Algae	*Spirogyra, Diatoms, Ossilaoria, Chara*	Testing the efficiency of algal species to improve water quality	• Algal species can improve the quality of mine water by reduction in pH, Temperature, Nitrate, Iron, Chloride, Fluoride, Total Hardness, Sulphate, Calcium and Manganese	[97]
Sewage	Algae	*Chlorella vulgaris*	Organic and inorganic pollutant removal	• Reduction by 70% BOD, 66% COD, 71% TN, 67% P, 54% VS, 67 % of phosphorus and 51% DS	[98]
Ground water	Algae	*Synechocystis salina*	To reduce heavy metals and total hardness within 15 days of treatment	• Removed Cr 60%, Fe 66%, ni 70%, Hg 77%, Ca^{2+} 65%, Mg^{2+} and total hardness 78%	[99]
Primary treated sewage water	Algae	*Chlorella minutissima, BGA Nostoc and Scenedesmus*	Physiochemical parameters removal	• They were efficient in reduction of parameters	[100]
Domestic	Algae	*Chlorella Vulgaris, Scenedesmus quadricauda*	Physiochemical reduction	• *Chlorella vulgaris* effectively removed COD by 80.04%, BOD 70.91%, nitrate 78.08% and phosphate 62.73% • *Scenedsmus* removed COD by 70.97%, BOD 89.21%, nitrate 70.32% and phosphate 81.34% on 15^{th} days of cultivation	[101]

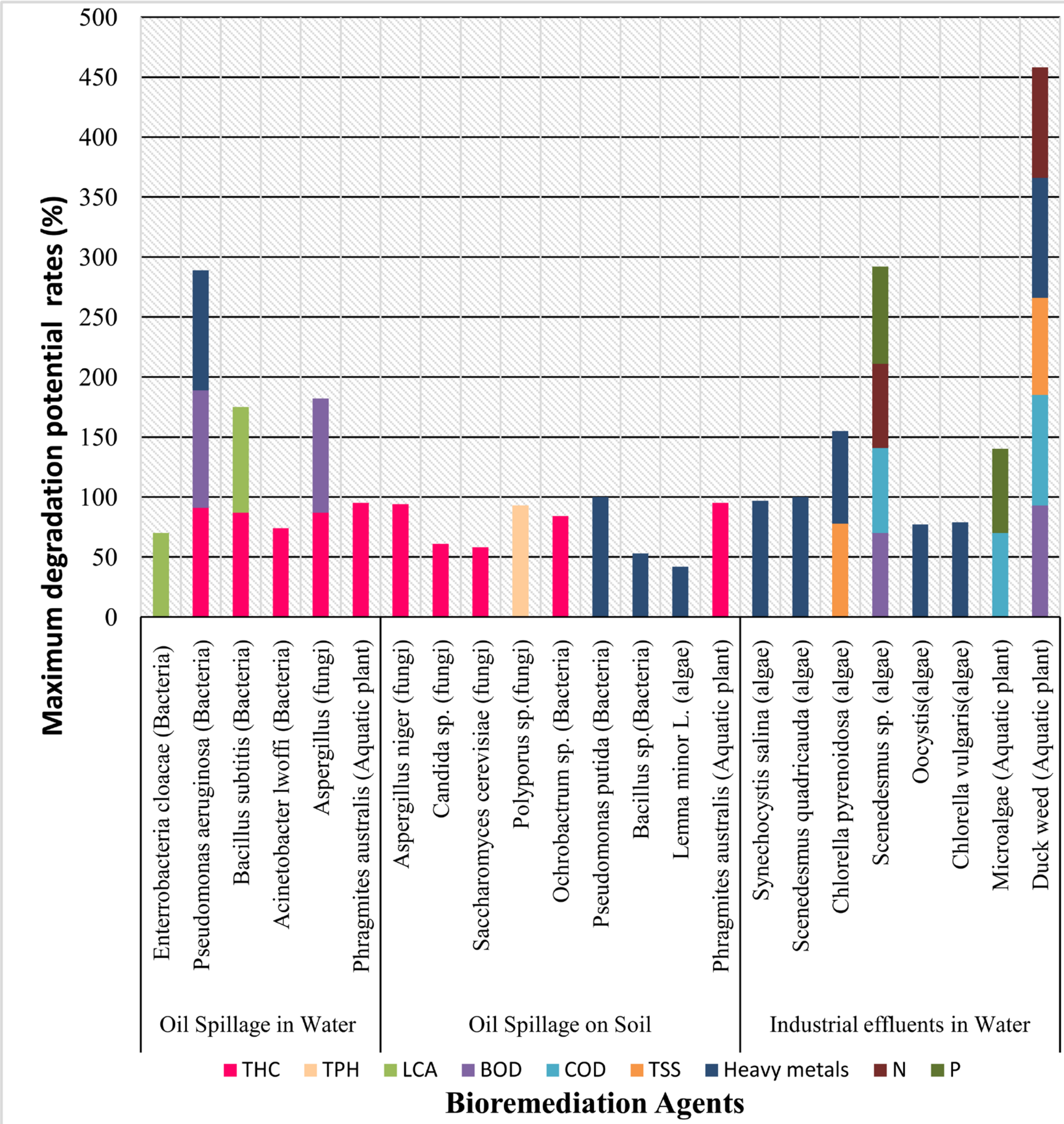
Continued

Tannery effluent	Algae	*Two strains of microalgae—Chlorella pyrenoidosa and Scenedesmus sp.*	Comparing removal rates of Cu with 2 strains	• Highest removal of Copper with 77% for Chlorella pyrenoidosa and 79.2% for Scenedesmus sp.	[102]
WWTP wastewater	Algae	*Indigenous microalgae*	Effective removal of heavy metals using microalgae	• Microalga was very effective in removing of Barium(Ba) 91.2% and Iron(Fe) 94.6%	[103]
Fish processing	Algae	*Oocystis species from* 2 *photobioreactor inoculated at* 23˚C *and* 31˚C	Chemical parameters removal	• COD and Phosphate removed by 70%	[104]

organic and inorganic compounds is referred to as Phytoremediation. Plants can be used in removal of nutrients and heavy metals from industrial effluents, transformation and degradation of xenobiotics. Ideal plants for phytoremediation should have the ability to tolerate and accumulate high levels of heavy metals and capable pf producing high biomass. Several studies have used different species of aquatic plants to treat industrial wastewater. Aquatic macrophytes such as *aquatic spermatophytes* (flowering plants), *pteridophytes* (ferns), and *bryophytes* (mosses, hornworts, and liverworts) [71]. Macrophytes hyperaccumulate heavy metals [72]. Common plants for hyperaccumulation of different toxic effluent compounds include Water hyacinth (*Eichhornia crassipes sp.*), Pennywort (*Hydrocotyle umbrellata sp.*), Cattail (*Typha latifolia sp.*), Duckweed (*Lemna minor sp.*). Duckweed is considered as the best plant to treat wastewater because they are more tolerant to cold water than water hyacinth, easily harvested than algae, capable of rapid growth on wide range of pH and produce biomass faster. All these properties help duckweed to accumulate large amount of heavy metals. Duckweeds are aquatic plants which form dense floating mats in eutrophic ditches and ponds [73]. Studies which has used duck weed include that for [74] who found out the efficiency of removal of heavy plant by this plant to be 99.6%, 93.3%, 99.3%, 94.3%, 100% and 95.4% of Cd, Hg, Zn, Mn, Pb and Ag respectively. Other physiochemical parameters include Total Dissolved Solids (TDS) 81.3%, Chemical Oxygen Demand (COD) 91.6%, Nitrate 93.3%, Biochemical Oxygen demand (BOD) 68%, Conductivity 50.3%, Total suspended Solids (TSS) 77.3%, Turbidity 85%, 81% Total Solids (TS) and the pH increased from 6.29 to 7.7. [75] provided the result under experimental conditions that duckweed found to be a good accumulator of Cd, Se, and Cu, a moderate accumulator of Cr, and a poor accumulator of Ni and Pb.

4.3. Literature Data Analysis for Table 4 to Table 6 for Periods from 2016 to 2001

As shown in **Figure 3**, there are so many bioremediation agents that can treat environments polluted with oil and industrial wastewater. These include bacteria, fungi, algae and aquatic plants. However, the most successful bioremediation



THC _ Total Hydrocarbon Concentration, **LCA**_ Long Chain Aromatics, **TPH**_ Total Petroleum Hydrocarbons, **BOD**_ Biological Oxygen Demand, **COD**_ Chemical Oxygen Demand, **HM**_ Heavy metals (Fe^{3+}, Cu, Zn, Pb, Cd, Hg, etc), **TSS**_ Total Suspended Solids and **N, P**_ Nitrates and Phosphates respectively.

Figure 3. Comparisons between biodegradation rates and different Bioremediation agents used in cleaning up oil and industrial effluents in both water and soil.

agents for treatment of oil polluted environments are bacteria and fungi since they have a greater potential in breaking down the Total hydrocarbons. Bacterial species *Pseudomonas* have a degradation efficiency of oil compounds ranging from 90% - 100%, and fungal species *Aspergillus have its range as* 75% - 95%. *Pseudomonas sp.* have a degradation rate of 91% for Total Hydrocarbon, 98% for organic matter and achieves 100% in removal of heavy metals. With *Aspergillus sp.* there is 87% degradation of Total Hydrocarbons and similarly it achieves 95% when breaking down the organic matter. *Enterobacteria* and *Bacillus* bacterial species can work well in regard to degrading the long chained aromatic hydrocarbons with maximum degradation rates reported so far as 70% and 88% respectively. Aquatic plants such as *Phragmites australis* have the capability in degrading the Total Hydrocarbons especially Aromatic compounds with benzene ring. It has the degradation efficiency of 95% when used in created wetlands with still water and can tolerate high salinity and a wide pH range of 4.8 - 8.2. In comparison to industrial wastewater treatment, there are also a number of bioremediation agents but the most commonly reported by different researchers as most efficient include algae and aquatic plants. The most efficient agents are algal species of *Scenedesmus* and aquatic plants known as the duckweed (*Lemna minor L.*). The *Scenedesmus sp*. has the removal rates of 70%, 71%, 70% and 81% for organic matter (BOD), inorganic and organic matter (COD), nitrates, and phosphates respectively. But, duckweed is more superior in treating the industrial effluents as it almost cleans it removal of all constituted heavy metals, organic and inorganic matter, total solids and nutrients. The removal rates are 100%, 93%, 92%, 81% and 92% respectively. Interestingly, duckweed has potential to remove all the heavy metals within the polluted environment basing on the results of other researchers. In conclusion, from the analysis it shows that bacteria are most suitable for treating oil pollution in water body using *Pseudomonas sp.* which can biodegrade organic matter, hydrocarbons and also remove heavy metals. *Phragmites australis* is suited for cleaning up oil pollution in both water and soil. Duckweed is the best in treating water polluted with industrial effluents.

4.4. Best Suited Bioremediation Applications in Uganda

Researchers from developing countries prefer use of traditional methods where assayed samples are picked from the polluted areas to find microorganisms which are surviving in toxic environment and degrading contaminants. An example is the research by [31] where samples of *Pseudomonas aeruginosa* were picked from oil polluted water in Lake Albert in Uganda and the findings showed that there was significant breakdown of Petroleum Hydrocarbons (PHs) after 3 days. Microbial detoxification of metals and use of plants for metal-contaminated areas has been popular and this has shown the usefulness of Phytoremediation [26]. For researchers who have used Phytoremediation method to treat polluted sites use plants including various Legumes (cowpea), Fern, eucalyptus, Water hyacinth, Bamboo, Alfalfa, sunflower [26]. Phytoremediation has also been used in combination with microbial method where in most cases it is used as a second treatment for the remediation of contaminated environment such as in wastewater treatment in Uganda. In the context of Uganda, removal of heavy metals can be done with use of phytoremediation, and organic and inorganic compounds with use of only microbial biodegradation or combination of phytoremediation and biodegradation. There has been a growing trend in use of biotechnology in Uganda through developing genetically modified foods (GMOs) and the Government has supported programs with provision of enough funds to facilitate more research, but still, our wastewater treatment body in Uganda referred to as National Water and Sewerage Cooperation (NWSC) use biological treatment with use of microorganism in stabilization ponds and phytoremediation in natural wetlands. Therefore, Bioremediation as process will not be new in the context of Uganda and Government will always support new technologies which focus at maintaining a pollutant free environment which always good for citizens utilizing the natural resources.

5. Conclusion

Bioremediation is a proven alternative treatment technique which is sustainable and ecofriendly for removal of petroleum and industrial waste compounds from the contaminated sites. It is a very efficient and cost effective method in comparison to other methods used commercially for pollutant removal. Different plants and microorganisms can be used to treat any polluted site. Bacteria species most suited to the removal of toxic oil pollutants are *pseudomonas* and *bacillus* since they use these compounds as the source of carbon to generate energy for cell development. *Aspergillus species* is the major fungi used in treatment of contaminated sites from the petroleum hydrocarbons or untreated industrial effluents. Fungi species are more adaptable as compared to bacterial species since they can thrive in environmentally stressed conditions. Other advantages with fungi include ease of production in large quantities, transportation and genetic engineering. White rot fungi (*Phanerochaete chrysosporium*) are the most efficient in biodegradation of toxic and insoluble compounds as compared to microorganisms. They secrete extracellular enzymes which help in oxidation of complex aromatic compounds and other hazardous pollutants. Aquatic plants such as the *macrophytes* and *pteridophytes* as well as other different grass species can also be used as bioremediation agents, but duckweed is more recommended. The most used aquatic plant in wastewater treatment is duckweed, importantly in removal of heavy metals because it is more tolerant to environmental conditions and produce biomass faster. Interestingly, the water hyacinth can also be used in removal of heavy metals and petroleum hydrocarbons which has been one of the plants that has populated Lake Victoria due to high eutrophication levels. From literature data analysis, bacteria are most suitable for treating oil pollution in a water body. *Pseudomonas sp.* can biodegrade organic matter, hydrocarbons and also remove heavy metals. *Phragmites australis* which is an aquatic plant is also suited for cleaning up oil pollution in both water and soil. Duckweed is the best in treating water polluted with industrial effluents. Thus phytoremediation is more applicable for heavy metals removal whereas biodegradation with use of bacteria species can be used for breakdown of organic and inorganic compounds from industries or oil and gas production.

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