Kennedy University

Provisional research proposal leading to PhD degree in

Environmental Management.

Candidate Name: Ahmed ElIdrisy

Research title:

Decontamination and Disposal of Produced Water from Oil Exploration in Sudan: An Analysis of Characteristics and Biotechnologies

Table of Contents

Chapter 1. Introduction

1.1 Background

1.1.1 ***Overview of Oil Exploration in Sudan:***

As the history of oil exploration in Sudan demonstrates, the recognition of the potential oil reserves occurred in the early nineteenth century, and quite a long history has been associated with the oil industry. However, the serious commercial exploration did not start until the period after the mid-20th century. Sudan's oil industry, a leading player in the region's energy sector, has experienced considerable growth and encountered many obstacles over the passing years (Osman and Ali, 2021). The modern oil exploration era in Sudan is started in the seventies through the creation of the Sudan Petroleum Corporation (SPC) and subsequent exploration activities by international oil companies (IOCs) (McGregor and Yeung, 2022). In 1974, Chevron made a discovery of oil in the Muglad Basin that opened the door for oil production in Sudan (Omer, 2017). Conversely, the uprising and political instability, triggered a subsequent of years for scientific and industrial activities.

The game changer happened in the late 1990s when, after long talks, the government of Sudan signed Oil permits with foreign companies, including Greater Nile Petroleum Operating Company (GNPOC), to increase drilling speed and oil production (Witchell-Chibber, 2020). This attracted other companies who established another oilfield in the area and by early 2000s the production was steadily ramping up (Longxin et al., 2020). Sudan's oil production exploits the mid of 20^{th} century, reaching over 500,000bpd at the zenith of the exploitation. Although Sudan has been renowned for its oil industry, the sector has hurdles in the wake of the rebellion in oil producing regions such as South Sudan which made a declaration of independence in 2011 (Mathelemusa, 2021). This division of a single oil bank account into two different accounts divides oil reserves between Sudan and South Sudan. This leads to conflicts about revenue sharing and oil infrastructure. Furthermore, economic sanctions imposed on Sudan by the United States and some Western countries pose a major hindrance to foreign investment, technological improvement and skilled employment opportunities in the oil sector (Adam, 2020).

Despite these challenges the oil industry is an important source of revenue for the economy of the Sudan. Due to oil funds government allocates for infrastructure projects, social programs and public services which are financed from oil revenue. Sudan's position, offering access to essential transport corridors and nearness to high potential emerging markets in East Africa and the Middle East, creates an attractive sourcing area for global oil and gas companies in quest of investment opportunities. The past years has witnessed efforts to create a diversified economy in Sudan and mainly attract foreign investment in non-oil sectors such as agriculture, mining as well as renewable energy. Nevertheless, oil still plays a major role of contributing to economic expansion and development of Sudan not without difficulties on its way to modernize the infrastructure and ensure environmental security and stable geopolitics among many others (Abdullah et al., 2020).

Sudan's oil industry has opportunities and challenges it needs to overcome head. The change in politics after the ousting of former President Omar al-Bashir in 2018 is encouraging economic reforms and better governance, which may create new investment avenues in the oil sector (El Mquirmi, 2021). On the other hand, the international sanctions and regional conflicts, as well as the energy transition on the global arena, present a set of very serious risks to the oil sector in Sudan, indicating that these matters should be addresses strategically and timely in case the sector would be able to sustain its contribution into the development of the country (Sørbø, 2020).

1.1.2 Production of Produced Water

Production of oil is one of the extremely complicated processes involving the extraction of oil from underground formations which produce less desirable and big volumes of a liquid called produced water (Kang et al., 2020). This water is normally discharged from the ground and is often with oil or gas. The process starts with drilling wells into the earth's crust so that it can access the oil-filled formations hundreds of meters deep in the ground. After drilling a well and the oil is contacted, various ways are used to get the oil from underground (Hadzihafizovic, 2024). The primary method of crude oil recovery are well known losses (natural pressures depleting) and man-made lift techniques (e.g. using pump jacks). The oil while draining from its reservoir is surrounded by the water that was trapped in the formation. This water, termed formation water, is the water that forms an integral part of the matrix of the rock where oil, gas and other hydrocarbons are stored (Seyyedi and Sohrabi, 2020).

Over time, the reservoir pressure gradually reduces as a result of oil production. As a result, the extractive methods applied may change to the secondary recovery methods which aim to maintain constant or even increase the well production rates. For example, water injection or gas injection is usually used in order to raise recovery rate. It assists in the displacement of more oil from the reservoir into our production well. For Pumping Methods, such as Water flooding, for example, the water is pumped into the reservoir to push the left-over oil towards the production wells (Mohammadi et al., 2024). As expected, the injected water in addition with the formation one are major contributors to the produced water in the whole field. Concurrently, with the beginning of the process of extraction the water that was originally used in drilling operations, known as drilling muds and completion fluids, may start to hold substances derived from oil and therefore become part of the produced water flow (Mao et al., 2020). This is the water which is termed as discharge or completion fluids, which might contain formation water and oil as it comes up with production processes. Composition of production water varies whether reservoir geology, of type oil being extracted and methods of production involve. In general, it contains a variety of hydrocarbon and salt solutions, heavy metal and other impurities, which were washed out by the reservoir wall and the formation fluids (Santos et al., 2014).

1.1.3 Characteristics of Produced Water

The produced water, a byproduct of oil exploration, has been found to possess some unique features in terms of physical, chemical and biological properties and therefore requiring special attention particularly in the petroleum activities in Sudan (Doreen, 2021). This identification is very important in determination of the problems faced and the feasible interventions measures. Distinct form physical characteristics produced water usually have wide spectra of temperature, from ambient to hotter based on the reservoir's depth and geothermal gradient (Sánchez-Pastor et al., 2021). The physical aspect of water appears in a incredible range from transparent to impenetrable, this is because of the suspended solids, oil droplets, and dissolved gases. The volume of produced water along with its flow rate might change in course of time what are the variables and the reasons such as reservoirs features, production technologies and seasonal changes (Coha et al., 2021).

Being the combination of organic and inorganic compounds of chemical nature the produced water reveals itself to the scientists as complex mixture containing hydrocarbons, salts, heavy metals, and naturally occurring radioactive materials (NORMs) (Neff, 2022). Mostly hydrocarbons in produced water fall in the following categories: discontent oil, dissolved and dispersed oil, and volatile organic compounds like benzene, toluene, ethylbenzene, and xylene (BTEX). The salinity extent can be very dynamic, including quite a lot of chlorides, sulfates and the whole dissolved salts (TDS) than fresh water (Li et al., 2021). With those of heavy metals (Lead, Mercury, Arsenic and Cadmium) possibly in the mix, this also includes the risks to human health and aquatic ecosystems. Furthermore, generated radioisotopes including radium and radon are among the issues that complicates the end of produced water.

Microbiologically, produced waters are an extraordinary source as they contain different types of microorganisms for instance bacteria, archaea, fungi, and algae (Shmeis, 2018). Microorganisms that could be present at any stage of the water life cycle or could have been introduced during the drilling and production operations can be recovered from the reservoir. Biodegradation of hydrocarbons by some microorganisms is possible via bioremediation processes. Other microbes can lead to MIC or biofilms on equipment use. The capability to explain microbial population structure and drawbacks in produced water is necessary to predict the environment impacts and create reliable treatment methods (Jiménez et al., 2018).

People in Sudan may understand these differences in what produced water can cause for those living nearby depending on regional geology, climate, or techniques used. Sudan's oil fields are a combination of surface and subsurface geological settings varying from sedimentary basins to volcanic formations and the resulting water is likely to differ from site to site in viscosity and fluid composition (Mohammad, 2021). This is in addition that there is a lot of arid climate in Sudan that brings more problems of water availability and also a big issue of salinity of the produced water through evaporation (Naorem et al., 2023). In addition, lack of infrastructure and regulatory oversight would be the other challenge. This should require designing context specific options that would cater for the Sudanese environment and economic situation for the proper management and disposal of produced water.

1.1.4 Environmental and Health Impacts

The treatment of produced water obtained from oil drilling process offers grave environmental and health concerns due to its intricate chemical structure and the toxicity of the various environmental contaminants (Zhang et al., 2024). It is critical that the risks related to it be therefore understood in order to avoid any negative effects on ecosystems, human health, and local communities. Disposal of produced water to surface and groundwater sources is one of the environmental risks associated with the produced water disposal (Silva et al., 2017). Often, produced water contains mostly high concentrations of salts, heavy metals, hydrocarbons, and other contaminants which can soil and bodies of water, penetrating water sources for human consumption and aquatic environments. Altered salinity levels can be a disruption for the osmoregulation of aquatic organisms as well as leading to the degradation of freshwater ecosystems, thus, negatively affecting biodiversity and ecosystem services.

In addition, the dumping of produced water over surface water bodies can cause the blooming of dangerous algae and eutrophication caused by nutrients like nitrogen and phosphorous in the water (Rahman et al., 2020). These ecological disruptions may result in oxygen deficiency, fish kills, and low quality of aquatic environments, affecting both aquatic organisms and communities relying on them for food and income (Nair and Nayak, 2023). Furthermore, produced water disposal has the potential to create health problems among the human who live near oil exploration zones. The contaminants including hydrocarbons, heavy metals and volatile organic compounds (VOCs) that may be found in the contaminated drinking water, air emissions or direct contact to the polluted soil can result in numerous health ailments like respiratory diseases, neurological problems, reproductive issues and cancer (Pandey, 2018).

Additionally, naturally occurring radioactive materials (NORMs) are found in produced water, e.g. radium and radon isotopes, which is one of the most serious issues (Koppel et al., 2022). Moreover, workers involved oil production and nearby populations are exposed to radiation effects. The constant exposure to radiation causes an elevation of the risk of radionuclide-related health effects, such as radiation burns, hereditary mutations, and cancer. The variables that contribute to the problems with produced water disposal include exposing vulnerable populations like children, pregnant women, and indigenous communities that can be disproportionally affected by environmental and health impacts of produced water disposal (Kuran et al., 2020). These populations experience more complications associated with the toxicity of the contaminants as well as limited access to healthcare services compared to others.

1.1.5 Current Practices for Disposal

The Sudanese government and the oil producing companies in the country, at present, dispose of the produced water through several mechanisms which are injection into the disposal wells, discharge into the surface water body, and the evaporation ponds with varying degrees of regulation.

Injection into disposal wells

One of the methods is known as reinjection that includes reinjection of produced water to deep disposal wells which are typically located in geological formations that make it safe to store without posing major risks to the environment and human health (Tomomewo, 2021). Injection wells are supervised by the Ministry of Energy and Mines, Sudan, which specifies, guidelines, and standards for the construction, operation, and monitoring of wells to ensure the integrity of the injection process and to protect the migration of leaked substances to underground sources of drinking water (Doreen, 2021).

Discharge into surface water bodies

Sometimes, the produced water could be directly released into surface water places such as rivers/streams/oceans following minimum basic treatment for solid removal and oil level reduction. On the other hand, water pollution might be the result of this common practice owing to the prior fear about water quality impairments and the possible damage in aquatic ecosystems (Akhtar et al., 2021). All discharge processes must adhere to the monitoring and regulations set by agencies that have control over water quality and the environment.

Evaporation ponds

Another approach employed in produced water disposal is the building of evaporation reservoirs in which water is kept and left to lose its water content through evaporation. This process takes its own time to leave the water behind with the concentrated brines as a residue. In arid regions, evaporation ponds are mostly used, where the main issues are related to water deficit and land availability (Esmaeilion et al., 2021). These large areas can be used for costly construction of salt water storage facilities. Meanwhile, such technique may cause water pollution and environmental hazards, if carried out without precautions. Furthermore, it also endangers the lives of animals in the locality as well as the people there (Allaire et al., 2018).

As far as regulating is concerned, Sudan has set a regulatory body that monitors the Oil and gas industry and the environment as a whole to ensure that the environmental standards and regulations are not contravened (Gathuoy, 2022). The Ministry of Energy and Mining, whose departments are the regulators of oil exploration and production activities, including the wastewater disposal, has the major impact on the regulation of oil exploration and production activities, including the wastewater (Shi et al., 2021). Moreover, the Environmental Protection Council (EPC) of Sudan is mandated to create and enforce ecological constraints, check air contamination levels, and guide towards sustainable resource utilization. Nevertheless, the utility of regulatory systems for produced water disposal in Sudan for instance may be hindered by factors like the weaknesses in the capacity for enforcement, lack of adequate monitoring and reporting mechanisms, and the cause of coordination problems across different governing agencies and jurisdictions. Furthermore, data and scientific knowledge bases on the recycling practices' environmental implications may result in decision-making and regulatory application problems (Meng et al., 2019).

1.1.6 Need for Sustainable Solutions

The issue of sustainable and eventually environment friendly water discharge from oil production industry is at the forefront and deserves to be addressed in the most relevant manner. The gushing of produced water has grown all over the world in countries like Sudan whose oil sector is booming. Therefore, within the environmental circle, the issue needs to be dealt with in fulfill of protecting water resources, public health, and sustaining the environment for longer (Hale et al., 2022).

Traditionally, surface water discharge and evaporation ponds have been the common methods of disposal and such have had negative impacts on water quality, aquatic ecosystems, and human welfare (Jiang et al., 2022). Releasing the specific waste water that is not pre-treated or minimally treated to the surface water is what causes the pollution of water utilities, destruction of aquatic ecosystems and endangering of lives of human beings and wild animals. Similarly, salt sediments (due the evaporation ponds) can cause soil and groundwater pollution, thus, environmental degradation will deteriorate further (and would reach nearby ecosystems), and may affect the adjacent ecosystems (Etikala et al., 2021).

On the other hand, the sustainable practice of the produced water management is aimed at utilization of effective and alternative treatment technologies besides applying innovative methods which reduce the environmental footprint and increase resource efficiency. These approaches may include:

Advanced treatment technologies

Utilization of advanced treatment technology which involves membrane filtration, activated carbon adsorption, and oxidation process enables the removal of contaminant from produced water such as hydrocarbon, heavy metals and dissolved solid (Ghafoori et al., 2022). Through the practice of producing the water to strict water quality criteria, the chance of environmental pollution and of humans meeting hazardous compounds can be tremendously dropped.

Water reuse and recycling

Compared to a mere disposal, sustainability related goals call for the treatment and reuse of the produced water for constructive utilities including irrigation, industrial processes and hydraulic fracturing operations (Rugland, 2021). By implementing water reuse and recycling advancements, the proper use of valuable freshwater resources for oil exploration activities can be maintained, decreasing the draw on freshwater withdrawals, and minimizing the footprint of such exploration activities on the environment.

Bioremediation and natural attenuation

To eliminate water pollution, making bioremediation and natural attenuation processes which use microorganisms' inherent degradation capabilities can be an environmentally friendly approach. Indigenous bacterial communities can catabolise hydrocarbons and other pollutants offering the reduced form of their initial forms and eventually the environmental effects later.

Integrated management strategies

Embarking on a holistic approach by integrating as a treatment methodology of physical, chemical, and biochemical processes on a whole can maximally yield produced water treatment efficiency and environmental performance (Abdelfattah and El-Shamy, 2024). Through integration of technologies that are synergetic and manageable practices, the produced water management shall be effective at all levels and in the end, shall bring about positive impacts to both natural environment and society.

1.2 Problem Statement

The produced water which is in connection with oil exploration in Sudan faces even greater environmental challenges as well as logistical challenges which need critical analysis and strategic solutions. However, what makes it different from produced water is that its microbe composition and the toxic pollutants that naturally stay in it all vary immensely, creating problems on the way to the disposal. The existing literature underline the necessity of specific actions towards the particular problem of environmental impacts and the sustainable development of the resource base in Sudan's oil industry (Azuazu et al., 2023). An important point is the mixture of complex chemicals and live organisms in the produced water, which is the other challenge. The composition of the effluent may include hydrocarbons, heavy metals, salts, and different organic compounds which bring along toxicity as well as environmental consequences (Saravanan et al., 2021). It is a definite command that identifying the specific features of the produced water resulted from the processes of Sudanese oil fields is absolutely essential to the development of good decontamination programmes. Besides, the coming up of more indigenous microorganisms that might contain hydrocarbon degrading bacteria, which can efficiently be used as biotechnological intervention also deserves exploration.

There are also issues with the size and capacity of the waste flow during the oil E&P; water produced treatment and disposal are bottlenecking factors. The Sudan oil industry deals with limited infrastructure and intricate requirements for regulating such huge daily production of oil industry wastewater (Abdelgadir, 2021). Standardization of protocols is what makes the whole effort even more difficult; it is different across various countries and regions and makes it harder to deal with the pollution problems. Subsequently, there is an urgent call-to-action about the disposal practices inspection process and guidance regulations drafting adherent to the sustainability principles. There is no doubt that the other important issue of produced water contamination is the socioeconomic factor associated with it. The residents of the neighborhoods near the oil fields can face various health risks and incapacitation of their economic life resulting from poisoning of the environment. Solving such socio-economic problems demands complexity-based form of practice that crosses scientific aid community interventions and policy-making. The relationship between the environment, public health, and the economy is interrelated and complicated in the Sudan oil-producing regions. The right approach in this regard is effective stakeholder collaboration (Thor, 2019).

To address the challenges mentioned, the proposed study will be focused on a systematic investigation of produced water from oil excavation in Sudan at the country level. Through applying advanced laboratory analysis methods, such as spectroscopy and chromatography, the study is going to show, at molecular level, the chemical mixture and the microbial diversity of produced water samples gathered from oil fields in diverse oil fields of Sudan. At the same time, the biotechnological strategies, including microbial consortia and enzymatic degradation, will be evaluated for the spillover effect of the ability of the technology to remove contaminants of the produced water and to mitigate environmental impacts. The purpose of this study was to assess feasibility of bioremediation for produced water cleaning (in reference to criteria of suitability of cost, environment and characterization of produced water particular to Block 5A Sudan, precisely) towards environmental safety.

1.3 Research Aim

This study was aimed to assess the suitability of applying bioremediation techniques for produced water treatment based on its characteristics, cost and environmental setup in Block 5A Sudan to achieve zero impact to the environment.

1.4 Research Objectives

1.4.1 Characterize produced water chemically and biologically extracted from oil drilled in Thar Jath (Block 5A), taking an average of one-year sampling to cover the seasonality factor.

1.4.2 To assess different remediation techniques & stages for produced water treatment (Physical, Chemical and biological).

1.4.3 To contribute in designing a proper remediation technique based on the specific criteria identified above.

1.5 Significance of Study

The proposed study examines the variety of produced water produced through the exploitation of oil resources in Sudan, with particular attention to defining its components and assessing biotechnologies as the possible way for its treatment and discharge. The main objective fulfilled in this quest is a detailed chemical and microbial characterization using water test samples obtained from various oil wells in Sudan. Much sophisticated analytical procedures such as spectroscopy and chromatography will be critical tools that will assist in unveiling complex composition of this fluid component by laying it bare to presence of hydrocarbons, heavy metals, salts, and other organics.

Beyond this, the research will study the technological concerning interventions which consider the consequences of the produced waters on the environment. This work focuses on researching microbial communities and enzymatic deterioration mechanisms to determine if these things could be used to offset the negative impacts of produced water discharge on surrounding ecosystems. Through native microorganisms' utilization, the study evaluates the acceptance and scale-up of bioremediation schemes that can be applied for Sudan's contaminated water remediation by responding to unique challenges of this water. The research differs from the one carried out in the Sudanese oil sector because the current study focuses on how these elements impact the treatment and handling of produced water. Realizing the significance of stakeholder engagement, the study will seek to draw on the backgrounds of specialists like the industry professionals, environmental agencies, local communities and regulators to get a better beauty of the issues that contain.

1.6 Research Method

The research methodology for the current study is based on a systematic approach aimed at detailed consideration of such parameters of produced water from oil production in Sudan as well as multiple biotechnological measures for its decontamination and eventual safe disposal. Data collection, laboratory analysis, field experiments, and validations were the main objectives of the approach, which were done for strengthening the replicability of the research and to produce the actionable insights. Data gathering started off with choosing Thar Jath oil field as the main place for studying produced water discharge. Site visits were held for observing the discharge areas and any existing treatment technologies used.

For systematic water samples we have chosen downstream places, some are near the discharge point and some are far away, to represent the variation in their characteristics. Among the parameters collected at each site were the date and time of the discharge, presence of the discharge permitted or not, approval for the oil field and permittee names, geographical coordinates using GPS, type of a separator, size of a pond, the presence of an oil sheen or wildlife carcasses, and the wildlife and their habitats. Samples of water were obtained at periodic intervals from the discharge locations to the engineered wetlands for further laboratory analysis. Soil contamination was demonstrated from the substances including many elements such as chlorides, sulphates, TDS (total dissolved solids), and oil and grease level, and pH level and heavy or trace metal substances. Moreover, radiometric testing as determining method to analyze the waste function was also considered. Estimation was made on a rule(s) of thumb basis and were therefore focused on the identification of trends in the discharged water volumes over time.

The investigation of numerous bacterial species within the produced water was a parallel process as well. The Heglig bioremediation project, a past one, gave insight concerning these bacteria whose attributes were thoroughly investigated for the use in remediation purposes. Whereas the soil and air samples were regularly scheduled to assess their particular attributes as well as microbial signatures. Trials and tests next executed to select the ideal bioremediation technologies and of the bacteria for disinfecting produced water. This research was heavily dependent on numerous indigenous bacteria, suggesting the collaboration with native ecological resources for sustainable pollution control. Consequences of the experiments were summarized and presented in a graphical form to make it easier to discuss them and find appropriate rectifications. While the data collection and assessment period were roughly within a range of 16 to 18 months, it also comprised field surveys, lab work, and pilot projects. The methodology of this study was able to provide a systematic understanding on the characteristics of oil produced water as well as biotechnology solutions all towards assisting the identification of sustainable practices for Sudan's oil industry.

1.7 Limitations

Nevertheless, the research is limited by some obstacles that affects the study. Research is primarily centered on characterization and treatment of produced water as generated by oil field development in Sudan that is different from other water (industrial) effluents or wastewater sources. Furthermore, the study is likely limited to a sample of certain oil fields in case of logistical constraints, an underdamping, which demands a selection of sites for data collection to cover the whole country. In conjunction, these biotechnology intervention results offer valuable insight but their applicability beyond the scope of the current study is subject to further investigation and needs to be determined. Moreover, the study is exposed to challenges emanating from the costs of doing research and the minimum time needed to complete some tests, as well as problems caused by the lack of needed professional skills or equipment. Although these factors were encountered, the research offers useful information about the problems and the chances of produced water management in oil production industry in Sudan; serving as a basis for subsequent researches.

Along with the outlined constraints, there are several other factors which could also be the reason for the limitations and in the choice of this exactly research methodology. On the one hand, the supervision techniques such as field visits and sampling will be conditioned by some external factors that are usually beyond human control, such as weather phenomena, accessibility to oil field sites and on the other hand, cooperation from industry stakeholders. Unseen logistical problems like red tape or security risks cannot be excluded in some cases. It will affect how quickly the samples can be taken in and the whole project comprehensiveness could be compromised. On the other hand, it may look different when biotechnological interventions which were successful in laboratory settings, which in most cases cannot be replicated in real-world applications. Situation in the field, like changing temperature, acidity level and the availability of nutrients, can significantly affect the activity and degradation rate of microbial consortia and enzymatic processes (Kebede et al., 2021). With this, applying findings from controlled laboratory experiments to highly demanding field settings must be done with a high level of carefulness and confirmation through field pilot or field trials which normally last long than the experimental phase and hence consume more resources.

Similarly, tremendous resource issues including those which are both financial and technical would also determine the adequacy and competency of study. The complex analytical tech used for the assessment of water quality, microbial extraction, and genetic characterization could not be available easily in Sudan, thus necessitating establishment of collaborations with external research institutions, use of substitutive instruments bearing inherent limitations. Also, the lack of expertise in biotechnological applications could be the additional constrain and impediment that will put some resources on the line that could also be the limit for the completing timeline by capacity building or by collaborating with the international experts. Such limitations though are not absolute, and as such the study approach is meant to overcome the challenges and give out meaningful conclusions that will not only broaden knowledge in the complex produced water management within the Sudan's oil industry but also pave the way for the sustainable management practices within and outside Sudan.

Chapter 2. Literature Review

2.1 Literature Review Structure

The literature review section in this dissertation underlines the present level of education regarding produced water management by the oil industries with an emphasis on biotechnological tactics. This part will be the synthesis of the current researches. It will identify the key themes and topics, review the treatment technologies, present case studies and examples, and discuss the challenges and opportunities in the field. The purpose of the literature review is twofold: in an attempt to provide a starting point for the reader by giving an overview of the key concepts, theories and methodologies involved in produced water management, on the one hand and to assess critically available literature to identify the deficiencies such as the unanswered questions and the areas in which the knowledge is still lacking on the other hand. Through the scrutiny of an array of academic articles, research papers, books and reports which discuss several factors surrounding sustainable solutions for produced water treatment in the oil industry, this literature review is designated to give a small contribution to the ongoing dialog regarding this issue.

The literature review is structured into a series of thematic sections. This review of literature serves as a broad outline of the major themes and areas covered that are related to produced water management. The discussion of these details would be followed in later chapters. Trends in treatment methods shall be traced including such technologies as the physical, chemical and biological ones which are widely used for water decontamination focusing on their effectiveness, upsides and downsides according to the study of (Ahmed et al., 2017). Biotechnologies for produced water treatment are the engineering techniques that address specifically microbial degradation, phytoremediation, and bioaugmentation as the most promising methods for reducing the environmental impacts of produced water disposal stated by (Saeed et al., 2022).

The case studies and examples are the real-world applications of biotechnologies for produced water treatment which show successful implementations and lessons learnt from different regions around the world both within and outside Sudan. Limitations and restrictions of Biotechnology raise concern and acknowledge the various difficulties of biotech-based solution deployment, like the oversight from regulators, technical difficulties, and societal and economic issues (Hornstein and Hornstein, 2023). The section continues with a discussion of what the future might hold in terms of more opportunities to do research and development. This might be in the form of new strains of bacteria being studied, the improvement of treatment methods and the combination of the new technologies with traditional treatments.

2.2 Background

The literature on produced water management in the oil industry is extensive and diversified, and this is due to the range of challenges and issues facing the industry in tackling this complex issue (Samuel et al., 2022). A major theme is the study of the different treatment technologies, which categorized identifies a large group of techniques designed for pollution removal and minimizing the environmental damage caused by waste disposal (Saravanan et al., 2021). From conventional physical and chemical technologies to cutting edge biological and advanced oxidation processes (AOPs), species are continuously being prospected, developed, assessed, and improved as researchers and practitioners seek to establish efficient, effective, and sustainable treatment options (M'Arimi et al. 2020; Puttasrinivasa et al. 2023). Besides the treatment technologies, the literature also goes into the study of the regulatory frameworks and policy measures governing the produced water management (Christodoulou and Stamatelatou, 2016). This examination, nevertheless, encompasses the roles and responsibilities of governmental agencies, industries, and environmental organizations in guiding such produced water disposal practices (Kabyl et al., 2020). Regulatory prospects, difficulties, and untapped areas for development are elaborated on, as well as case examples of how effective solutions have been implemented in different jurisdictions.

Moreover, the influence of environmental impacts and risk assessment is also a prominent topic in the literature, as the researchers like Cooper et al. (2021) try to find out the possible effects of produced water discharge on the soil quality, water resources, aquatic ecosystems, and human health. Additionally, scholars as Rathi et al. (2021) make use of risk assessment methodologies, modeling techniques as well as monitoring procedures in order to appraise the potential environmental hazards of produced water pollution and assist with subsequent decision-making processes. In this regard Santos et al.

(2023)demonstrated that economic and social factors are highlighted as paramount issues in literature since produced water management has been seen to involve broader socioeconomic implications. Cost-benefit analysis, economic feasibility study, and stakeholder engagement programs are carried out to evaluate the financial effects of different treatment methods and to see the community perceptions, concerns, and preferences about produced water disposal practices explained by (Kennedy, 2022).

2.2.1 Characterization of Produced Water

The characterization of produced water in the context of Sudan is of the utmost importance because of the specific environmental and socio-economic factors that influence oil exploration and production in the region. In this context, many researchers in the literature document and demonstrate the specific chemical and physical properties of produced water from the Sudanese oil fields, which may vary in its salt levels, hydrocarbon content, presence of heavy metals, and distribution of microorganisms (Zooalnoon and Musa, 2019; D. Atoufi and Lampert, 2020). The salinity concentrations in the produced water from the oil fields in Sudan are generally above regular levels, which is as a rule reflective of the geological characteristics of the area and also of the presence of naturally occurring salts in underground reservoirs (Ahmed et al., 2018). Salinity levels that are too high will cause problems for water treatment and reuse because they can affect the efficiency of the treatment technologies and raise the operations costs according to (Bhojwani et al., 2019). The content of hydrocarbons in the produced water is another significant parameter, because of the variable nature that can be related to the type of crude oil extracted, with the production methods used, and the age of the reservoir (Abbas et al., 2021).

Generally, Sudanese oilfields develop heavy crude oil with high viscosity and relatively more asphaltenes, a characteristic that is usually associated with a high concentration of hydrocarbons in produced water compared to light crude oil reservoirs (Ahmed, 2003; Mohamed, 2001; VAJPAYEE, 2023). Heavy metal concentrations in the produced water from Sudanese oil fields may be different because of the geological formations, water-rock interactions, and production processes (Jabbo et al., 2022). Research focused on the presence of heavy metals such as arsenic, lead, mercury, and cadmium which are of environmental significance as they can be placed in the soil, water and biota if they are released to the environment and they may have the tendency to accumulate in the same environment. Diverse microbial population in produced water is becoming a central topic of research, because microbes are the main players in biodegradation, corrosion and biofouling on the oil production facilities (Ziganshina et al., 2023). The microbial community structure, metabolic activities, and interactions with contaminants are essential to the designing of effective treatment strategies and the mitigation of the environmental impact associated with the produced water discharge.

2.2.2 Treatment Technologies

In the area of treatment technologies for produced water, continuous efforts on research and development towards the optimization and innovation of diverse physical, chemical, and biological methods are being pursued (Al-Ghouti et al., 2019). The utilization of physical methods, including the use of filtration, sedimentation, and evaporation as means for removal of suspended solids, hydrocarbons and other impurities from the produced water is the simplest of approaches (Amakiri et al., 2022; Salem, 2022; Gamwo et al., 2022). The filtration mechanisms can be as basic as the media filtration to the more advanced membrane filtration processes that effectively separate particles based on their size and molecular weight. The role of sedimentation is to act by gravitational forces to allow moving particles (suspension) to sink, and this process enables the removal of them from the water matrix (Viaene et al., 2021). With evaporation, process such as thermal and solar one can be used to concentrate dissolved solids and salts which will facilitates their separation from the water phase (Viaene et al., 2021).

Chemical methods of treatment are the main tools used in produced water management to eliminate the specific contaminants by using oxidation, coagulation, and ion exchange processes. Ozonation and other oxidation techniques called AOPs (Advanced Oxidation Processes) use reactive oxygen species to break down the organics and remove color, smell, and taste from the water we produce (Sadeghfar et al., 2021; Nikbeen, 2021). Coagulation is the addition and reaction of chemicals (ferric chloride or aluminum sulfate) which destabilizes colloidal particles which in turn begins the aggregation of these particles, and they are later removed through sedimentation or filtration (Wang et al., 2021). Ion exchange processes employ resin-based materials to selectively remove ions, like heavy metals and dissolved salts, from produced water through ion exchange reactions.

Biological treatment technologies emerge as an ever more optimistic direction of searching, where microorganisms and plants are employed in turning organic pollutants in produced water into harmless substances (Ahmed et al., 2021). Bioremediation methods, including aerobic and anaerobic regimes, relies on heterogenous microbial consortium for metabolism of most organic pollutants and hydrocarbons, transforming them to fewer toxic substances (Chatterjee et al., 2022). Phytoremediation, on the other hand, is based on the use of aquatic plants such as reeds and cattails to absorb and accumulate contaminants from produced water, which is a cost-effective and environmentally friendly way of water treatment (Mohebi, 2021).

2.2.3 Regulatory Frameworks and Policy

The literature on regulatory frameworks and policy measures for produced water management is a challenging one as it is a varied landscape at different levels of governance. On the national stage, government agencies are the central figures in setting and supervising laws that guarantee careful and appropriate utilization of any produced water from oil and gas exploration and production operations. These restrictions apply to various aspects including: release limits, monitoring requirements, reporting obligations, and issuance of permits. In addition to that, studies explore the roles and responsibilities of different stakeholders in the industry, such as oil companies and service providers, in following the regulatory requirements and using the best practices for produced water management (Emeka-Okoli et al., 2024). Apart from publicly-led avenues such as industry codes, standards, or social responsibility schemes, private industry efforts too are investigated as supportive tools for raising environmental standards and sustainability in the oil sector.

Regarding regional and international level literature, intergovernmental organizations like the United Nations Environment Programme and the International Maritime Organization are put into the spotlight (Coady et al., 2013). The literature examines the role of these organizations as proponents of harmonized approaches to produced water management across different borders. Regional agreements, conventions, and protocols may help neighboring countries and jurisdictions to work together to address common environmental problems and ensure that the transboundary water resources are used equally and sustainably. In addition to that, regulatory problems and gaps are investigated and proven in the literature by means of topics related to enforcement capacity, regulatory compliance, data transparency, and stakeholder involvement. These difficulties may come from scarce budget, problematic performance of institutions, different interests, and also from complexities of jurisdictions. That is why it is important to carry on the process of adjusting of legal frameworks to new environmental and socio-economic conditions. The case studies of the successful regulatory projects implemented in different regions are a source of information on effective strategies for tackling regulatory problems and promoting the sustainable produced water management practices. Through the examination of experiences drawn from a multitude of contexts, researchers and policymakers can garner knowledge on areas for improvement, building capacity, and finding ways to work together to achieve harmonisation in environmental objectives.

2.2.4 Environmental Impacts and Risk Assessment

Through the examination of environmental impacts and risk assessment that comes with produced water disposal, the literature sheds light on the problems that could eventually stand out due to change in various ecological and human systems. Scientists in several studies deal with the very complex interrelation between produced waters discharge and the state of the soil, taking such contaminants present in produced water as possible factors which infiltrate soils and subsequently lead to soil degradation, nutrient imbalances, and reduced agricultural productivity (Ghafoori et al., 2022). It is fundamental to understand how produced water affects the soil quality and how to prevent it from harming the soil for the future generations. In addition, the literature specifically explores the science behind discharge of produced water on water resources such as surface water bodies, ground water aquifers and drinking water sources (Mukhopadhyay et al., 2022). Surface water sources that are polluted by different contaminants may destroy aquatic ecosystems, cause water impurity, and pose danger to variety of fish species and other aquatic population. Likewise, the introduction of contaminants into groundwater aquifers poses a danger to drinking water supplies, which in turn underlies the necessity of the development of a reliable monitoring and remediation system to protect human health and the environment.

Another area of research is around the aquatic ecosystems, as scientists conduct studies examining the possibility of ecological effects of produced water discharge on freshwater and marine environments (Folkerts et al., 2020) This includes changes in species consist as well as their structure and biodiversity, disruptions in the process of nutrient cycling and food web dynamics–literature which describes the various interconnections between produced water contaminants and aquatic organisms, thus stressing the importance of ecosystem-based management techniques to reduce ecological impact and to restore the sustainability of natural ecosystems. In addition, the human health concerns must be the first priority in the evaluation of the environmental risks of produced water disposal (Ghafoori et al., 2022). Studies plan possible ways in which human exposure may occur regarding produced water contaminants, namely ingestion, dermal contact and inhalation and the associated health risk with carcinogenicity, mutagenicity and developmental toxicity. The risk assessment methodologies, modelling approaches and monitoring techniques are applied to quantify the magnitude and likelihood of negative health outcome and the result of them are used in the decision making and regulatory processes that are targeted for public health protection.

2.2.5 Economic and Social Considerations

Considering the relationship of economic and social elements in produced water management, the literature goes into the association of the underlying financial implications, community acceptance, and engagement of stakeholders. Cost-benefit analysis makes it possible for an evaluation of different treatments' economic viability of choice for the water industry investment decisions. The researchers and the policy makers can get to know the costs that are related to the treatment technologies, regulatory compliance, and the environmental mitigation measures, which will help them to decide whether these expenses are worth the benefits like the improvement in the environmental quality, the reduced liability risks, and the enhanced corporate reputation (Eaton et al., 2021).

Economic feasibility investigations play a very important role in comprehending the economics of used water management, considering the financial feasibility of conducting different treatment methods while considering in particular the restrictions of individual operations and market conditions. The common methods of these research are that, they analyze factors like capital and operating costs, revenue streams from treated water reuse or resource recovery, and the possible cost cuts that can be achieved through the compliance with the regulations and avoiding the liability. Economic feasibility studies help in the elimination of costly solutions and in the optimization of the use of resources and thus they support the adoption of sustainable produced water management practices (Eaton et al., 2021).

Stakeholder engagement initiatives are vitally important to ensure that the decision-making process around produced water management considers all different aspects, opinions, concerns, and interests of the present communities, industries, and regulating authorities. Stakeholders' opinions can be represented via dialogue, consultation, and participatory decision-making processes, transmitting their features, demands, and local wisdom facilitating production water strategy development and execution (Eaton et al., 2021). The community`s perception, concerns, and preferences on the practices of disposal of produced water are also considered, acknowledging the need to build trust, collaborate and deal with the social and environmental justice issues.

In addition, the narration accounts for both positive and negative socio-economic circumstances evolving from produced water management with job opportunities generation, the stimulation of economic growth and sustainability guaranteed for oil-producing regions (Manu, 2011). Through employing produced water as a vital potential for irrigation, industrial processes, as well as groundwater charge, societies might accordingly benefit by economical and social values, while at the same time producing a reducing deviation from virgin water resources for the next generation.

2.2.6 Innovations and Emerging Technologies

Technological advances and emerging water produced technologies remain one of the fast-growing spheres of research primarily due to the environmental issues and efforts for production operations improvement as well as the need to achieve a sustainability in natural resource usage. The literature emphasizes how sustainable treatment technologies equipped with high-grade innovation that produce clean produced water while reducing energy consumption, waste output, and the potential for environmental issues should all be promoted. The main concern of the researches is the way of reducing the cost and the time of the existing treatment technologies by the technological improvements and the process optimization. Researchers investigate into the core materials, such as Nano materials and membranes, having filtration and removal rates higher for the common pollutants present in produced water (Farooq et al., 2021). Explicitly, the development of new reactor designs and process modules is employed to achieve the highest level of treatment performance with minimized footprint and maximized process efficiency, which eventually ends up in lower capital and operation expenses for produced water treatment facilities.

In addition, the literature presents the possibility of investigating the different applications of treated produced water apart from its conventional disposal practices. Scientists examine if reclaimed effluent can be applied to beneficial usages like irrigation of farms and the use of treated wastewater for industrial processes and groundwater recharge among others. Ultimately, the reuse of treated industrial waste water for different human and environmental purposes can ease the burden off freshwater sources, provide more diverse water supply options, and promote the long-term sustainability of water management in drought areas (Kesari et al., 2021). Additionally, the latest technologies, like electrocoagulation, forward osmosis, and membrane distillation, are already being explored for the specific challenges that the produced water treatment presents, like the removal of dissolved solids, organic compounds, and emerging contaminants. They apply advanced concepts of engineering concepts and creative approaches for operation to produce higher treatment efficiencies, low energy consumption, and expanded range of produced water in comparison to conventional technologies.

2.3 Treatment Technologies

In the context of Sudan and South Sudan, the treatment of produced water is a critical aspect of oil production operations due to its significant environmental impact and the unique challenges posed by the local geological and regulatory landscape. Various treatment technologies are employed to decontaminate produced water, encompassing physical, chemical, and biological methods. This review examines these treatment technologies, their applicability, challenges, and advancements within the context of Sudan.

2.3.1 Physical Treatment Technologies

Physical treatment technologies encompass the techniques of display or elimination of contaminants from brine by using filtration, sedimentation, absorption, and ion exchange (Ahmad and Azam, 2019). In Sudan and South Sudan, common physical treatment methods include:

- Filtration is applied to separated water for deep treatment in order to remove suspended solids, oil droplets, and all other particles. Membrane filtration, which encompasses microfiltration, ultrafiltration, and reverse osmosis, has been proven to have high removal efficiencies for contaminants and therefore is a good way to treat produced water with high salinity levels that are often found in the Sudanese oil fields (Charcosset, 2016).
- Sedimentation: Sedimentation techniques, which allow gravity to separate suspended solids and oil particles from the treatment water, are applied to produced water. In Sudan and South Sudan, the sedimentation tanks are the tanks in which the sedimentation slope facilitates the settling of solids allowing for their skimming or sludge collection. This may have led to increased agricultural productivity and food security in the region (Kiefer, 2009)
- Evaporation: The technologies of evaporation like thermal evaporation and solar evaporation, work on the principle of concentration of dissolved solids and salts in the produced water which in turn facilitates their separation from the water phase. Easing and evaporator can be utilized to treat produced water in arid regions which has a high evaporation rate.

2.3.2 Chemical Treatment Technologies

Adding chemicals in water treatment technologies brings forth the separation or conversion of the contaminants in the produced water. undefined

- Oxidation: Oxidation processes e.g. ozonation and advanced oxidation processes (AOPs) are the ones that are operated with oxidizing agents to break down the organic matters and to eliminate the color, smell and taste from the produced water. Ozone treatment, in particular, has been investigated for its capability in lowering the hydrocarbon content in the produced water from Sudanese oil fields (Al-Ameri et al., 2023).

- Coagulation and Flocculation: The treatment includes the addition of flocculants and coagulants to the produced water to destabilize the colloids and make their aggregation for precipitation or filtration easier. Aluminum sulfate (alum) and polyacrylamide polymers are the widely employed in Sudan coagulant and flocculant (Abiola 2019).
- Ion Exchange: Ion exchange techniques make use of resin-based materials to selectively remove ions, like heavy metals and dissolved salts, from produced water by means of ion exchange reactions. Ion exchange resins could be used to treat produced water with high heavy metal concentration from Sudanese oil fields to improve the quality of water being discharge into the environment.

2.3.3 Biological Treatment Technologies

The organic pollutants found in produced water can be treated with biotechnologies which utilize microorganisms' natural ability for degradation.

- Bioremediation: The microbial consortium used in bioremediation plays an important role of converting hydrocarbons and other organic contaminants present in produced water to byproducts that are less harmful (Kumar et al., 2022). Aerobic and anaerobic bioreactors could be used to accelerate the biodegradation rates and enhance the treatment efficiencies.
- Phytoremediation: Phytoremediation is the application of the aquatic plants like reeds and cattails to take away and build up contaminants from produced water by phytoextraction, hypofiltration, and Phyto stabilization (Ali et al., 2020). Establishment of constructed wetlands planted with local vegetation may prove to be an affordable and eco-friendly solution to remove produced water which is a byproduct of an oil field in Sudan.

2.4 Case Studies Evaluation

2.4.1 Overview

Produced water is the mixture of natural water or called the formation water which is certainly found with petroleum in a reservoir. “Produced water” means water that is trapped in subsurface formations during oil or gas production and is brought to the surface. In some cases, it is called"flowback water" if it is brought from wellbores or reservoir during fracturing operations. It is barely acidic and lies under hydrocarbons in the storage area which is called media reservoir extraction of oil and gas results in the decrease of pressure from reservoir, and the route of water called layer of water reservoir is used to maintain the hydraulic pressure and improve oil recovery. The compounds in processed water can be roughly classified as organic, inorganic, dissolved, dispersed oils, grease, heavy metals, radionuclides, treating chemicals, formation solids, salts, dissolved gases like CO2 and H2S, scale products, waxes, erias, and suspended gases. (Elbrir, 2018).

2.4.2 Explaining Different Cases

As described in the study of Osman and Musa (2016) bioremediation involves the use of naturally occurring microorganisms (yeast, fungi, or bacteria) to influence the conversion of hazardous substances into other less toxic or nontoxic ones. Bacteria fed via fermentation in a controlled environment, which utilizes organic matter as their food face the emission of products of respiration as including CO2 for aerobic and CH4 for fermentation. The treatment system must have medium and long residence time, as the plants need this time for establish themselves and function effectively. However, the literature by Sheehan (1997); Totowa (2010) suggests that bioremediation is enhancing the process of the natural biodegradation by bacteria, contaminants are converted to harmless substances through alteration and plants called phytoremediation are used to improve the soil conditions for chemical breakdown.

According to Osman and Musa (2016) the process involves the mechanical pre-treatment to remove impurities such as oil, grease and solids from produced water. The effluent is then into a series of reed bed lagoons which are planted accumulatively with reed Phragmites Australis. Where the contaminated effluent has been long exposed to the soil mass that is full of the reed's organisms, the water purifying bacteria occupying the soil will have completely consumed the chemicals such as hydrocarbons and other pollution causing chemicals hence generating pure water. A reed also utilizes a certain quantity of carbon and nitrogen from the water needed for the cellular building found in the material of the reed. Upon their development and spread, the roots increase soil's permeability, thus smoothing the passage of the wastewater. In addition, the reed contributes to the oxygenation of the soil that is due to a root system. Microbes colonize in the root mass and then turn the dissolved oxygen in the effluents into their food to digest contaminants present in the structures.

In addition, Osman E. and M. Musa M. (2016) showed that the bio-remediation procedure used to eliminate hydrocarbons from produced water in the Heglig oil field, by Phragmites Australis plant, is a viable option that can lead to clean water and valuable materials recovery with no threat on the environment. Through case study, this paper critically examines the core findings while looking into its effectiveness, methodology, and implication within the wider context of produced water management. The research uses three quantitative approaches (gravimetric, spectrophotometric, IR methods) to assessment the performance of bioremediation system against oily produced water. Results point to IR which is more precise than other methods used, 86% of the bioremediation system is able to remove pollutants. Over 72% of the oil concentration that is found in produced water. This result is quite impressive and definitely proves that the Phragmites Australis potted plant can be used as a bioremediation technique for spilled hydrocarbon water.

A major aspect of the study is the use of diversifiedness data analytical techniques to obtain accurate and reliable results. Through the use of standard methods of measuring and reporting as outlined in the American Public Health Association (APHA), the American Water Works Association (AWWA), and the Water Environment Federation (WEF) guidelines, the study follows the guidelines that are well established and this ensures that the study findings are of credibility and also reliable. However, the study has produced a number of beneficial results as well as limitations that are associated with the bioremediation system. For example, by using the process, a considerable fraction of hydrocarbons could be removed from produced water; however, n-C22 to n-C29 carbon number that have residue will go through untreated. Herewith, the limitation indicates the need for further improvement in biological decontamination technology to be able to deal with more kinds of contamination and supply extensive purification.

Besides, the clasification of the useful analytical methods for assessing remediation performance stands out as a significant study finding. While the IR technique is found to be a more precise practice for oil content determination, the gravimetric method is generally considered as inefficient alone in assessing extremely low amounts of contaminants. This insight highlights the influence of method choice and validation to environmental testing and remediation research. Besides that, the study defines the operational requirements of the system designed for the treatment of the Heglig oil field. To provide those responsible with the concrete tools and guidance for the design and implementation of rehabilitation systems similar to the one studied, the investigation specifies the construction, management, and maintenance stages.

The research made by Löw et al. (2021), considers one of most significant problems with mapping the areas polluted with oil in the Sudd Wetlands of South Sudan being this area is protected under the Ramsar Convention on Wetlands of International Importance. The key importance of this research is the specific environmental predicament due to oil spills occurring in the sensitive ecosystems such as wetlands, as well as their heavy dependence on oil revenues for the oil industry. Oil constitutes the basis (approx. 98 %) of the government budget and, consequently, sustainable economic and environmental development of the country depend on proper management of oil-related problems. Primarily, this study aims at the construction of a reliable method for mapping the oil-contaminated areas with remote sensing techniques focusing on the optical and Synthetic Aperture Radar (SAR) satellite data. The research focuses on defining the oil-polluted and unpolluted parts to detect the environmental pollution in the earlier stage and timely monitoring to take proper measures of mitigation and responses.

The methodology of the study includes the sampling of the areas where no oil was found far afield from the observed sites of oil spill. In this case 500 m buffer zone is built around on-site spill area to exclude in-situ waters from falling back on the observation wells. In oil-contaminated locations, unpolluted sites are then chosen at random outside the contaminated area with a simple random sampling procedure, thereby ensuring the proper representation of landscape classes and unbiased estimates of accuracy. To find a correct sample size, we apply a formula which includes the desired total probe, percentile of the Normal distribution, and the margin of error. It is considered that certain 85% overall accuracy is necessary, so the study needs 553 candidate locations per test site for the analysis to get the statistical significance.

Analysis of the precision measure showed encouraging findings, as general accuracies of the classification had improved by adding more variables to the optic data (Sentinel-2) in both study sites. In this study, the authors compare the accuracies achieved using different classifiers and inputs which comprise multi-spectral bands, spectral indices, and OSM informatiom. It is worth mentioning that the combination of vegetation indices and proximity layers heightens the accuracy, thus categorically multi-temporal models being vastly accurate. Relatedly, there is an evaluation of SAR data derived from (Sentinel-1) and the study indicates that they have the tendency to cause a lower overall classification accuracy than optical data, while the multi-temporal predictors improve the accuracy considerably. The connection of these is that we need data gathered at several time intervals in order to create an oil contaminated area map that is more accurate.

Satellite image inspection employed in the case study of the oil spills proves to be a feasible method for the rapid assessment of oil contamination using recent and pre-processed satellite imagery. The developed method gives the tool to recognize the oil pollution's spatio-temporal dynamics, that is in what places and at what frequencies it happens for different parts of the landscape. Through all, the research shows the necessity of improved techniques of pinpointing and outlining the areas polluted with oil, especially in ecologically sensitive places like Sudd Wetlands. The method extracted from this study proves highly appropriate for practical use as a monitoring tool for outbreaks of environmental pollution in South Sudan. It is envisaged that its utilization could be extended to policy prescriptions and problematic streamlining of environmental processes. Moreover, the study underscores the critical need for free to-use databases for oil mapping, which will facilitate the participation of a wider stakeholder community in environmental conservation activities.

Atoufi and Lampert's study ventures into the environmental pollution problems driven by the oil and gas production boom in the US, taking a special look at wastewater management. The new forms of unconventional energy (tight gas, shale gas, shale oil, and other technological innovations) have in recent times been unlocked leading to sharp rise in oil and gas production with the result of creating new challenges in environmental management. From the research one major concern raised is the dumping of the produced waters which are being done through the deep well injection and in most cases are associated with the induced seismicity. In light of these issues, the paper mainly addressed published studies about sediment pollution caused by oil and gas production route will be highlighted as an environmental risk due to the released water management (Atoufi and Lampert, 2022).

The study embeds that contaminants from the produced waters are made up of organic and inorganic compounds that are hazardous in nature. It discussed three indicators developed for assessing sediment pollution: the geoacumulation index, the pollution load index, and enrichment factor. This allows to delve deeper into the degree of pollution in sediments. Classifying of the key pollutants that are normally contained in sediments as an effect of oil and gas production include heavy metals, salts, naturally occurring radioactive materials (NORMs), oil and grease (O&G), benzene, toluene, ethylbenzene, and xylene (BTEX), total petroleum hydrocarbon (TPH) and polycyclic aromatic hydro. These contaminant entities largely reach bodies of water and sediment through different pathways including pipeline leaks, road vehicle spills, wrong discarding, and underground injections (Atoufi and Lampert, 2022).

The study of Atoufi and Lampert (2022) furthermore, investigated a number of strategies in order to minimize the contaminant risks that gravitate in the sediments, which comprise of surface capping, bioremediation, and phytoremediation. The mitigation plan was focused on the reduction of the concentration of pollutants in sediments and on the restitution environmental quality in the affected areas. This research additionally, highlighted the factors for consideration such as kinds and components of contaminants and sediments, sources of these contaminants, concentrations and effects of at pollution sites and methods of handling pollution.

Another important outcome of the research showed the worsening of the produced water handling problems because of shale oil and gas boom. Along with states tending toward the regulating of treated produced waters, the possibilities of such water by being contaminated and its impact on the surrounding environment should be taken into consideration. The study conducts several case studies, some from different areas of the world, such as the U.S, Middle East, Africa, Asia, and South America, as the measure of the levels of contamination around the sediment in the regions actively extracting oil and gas. The study in the end stresses the concern of correct management of residual pollution from the oil and gas activities which should take into consideration the complexity of associations of contaminants, sediments, distribution paths and remedies put in place. Through its revelations of the ecological risks resulting from produced water disposal and sediment pollution, the study provides highly useable information-based clues that are instrumental for policy makers, regulators and environmentalists to devise solutions to questions that are raised by oil and gas production.

Fakhru'l-Razi et al.'s study focuses on produced water management and treatment that is the most significant waste stream generated in the oil and gas sectors. The study starts by introducing the augmenting global care at the discharge of the produced water and their ecological impact. There is a myriad of organic and inorganic substances appearing in produced water, so treating it calls for great treatment skills. Different treatment technologies such as physical, chemical, and biological are discussed in this text along with the idea of multi-purpose and combination methods in order to satisfy regulations and to ease the reuse and recycling (Fakhru'l-Razi et al., 2009).

In the commencement of the discourse, the toxic flux of waste liquids generated during oil and gas production activities is highlighted as an alarming environmental danger that may arise in case of improper management. Usually, produced water is characterized by the presence of oil soluble in a dissolved or dispersed state, formation stones, production chemicals, production shales, dissolved gases and radioactive materials. Release of the untreated effluent water source can lead to the adulteration of surface, groundwater, and the soil, which often require the application of adequate treatment methods. Regulatory discharge limits for produced water differ from one country to another. The quantities mentioned include oil and grease (O&G), chemical oxygen demand (COD) and dispersed oil concentration. In light of the tighter controls, and the need for sustainable treatment, the researchers focused on developing/enhancing the treatment of produced water technologies. One of the goals of these technologies is the decrease in the oil, salinity and other pollutants content to meet reuse, discharge, and recycle standards (Fakhru'l-Razi et al., 2009).

The article emphasizes the difficulties of successfully erasing produced water, particularly when offshore platforms or other areas with space restrictions. Offshore, these small treatment technologies often use denser and compacted systems, but they may not always fully remove minute suspended oil particles and dissolved chemical entities. Besides, chemical ones are costly and generate noxious sludge that must be disposed of safely leading to less expensive and eco-friendly approaches.

Biological pretreatment of oil wastewater is brought up as a possible technology especially during the onshore rigs. While the biological treatment is effective at eliminating organic pollutants from wastewater, salty high concentrations and fluctuations of the influent characteristics can sometimes hinder the treatment process (Ogunbiyi et al., 2023). In light of this observation, the authors employ an additional physical treatment technique like reverse osmosis membrane filtration in an attempt to enhance the effluent quality. According to Mushtaq et al. (2022) future research drive can be towards perfecting the already existing technologies and designing integrated chemical and biological or physio-chemical solutions in order to adequately handle the problem of produced water management.

The study offers insights in the production water quality that is influenced by the naturally occurring minerals, chemistry of reservoir, and production processes parameters. Produced water composition may differ widely, but normally it is a mixture of hydrocarbon, dissolved minerals, production chemicals including production solids, and gases. Once the main components of produced water are comprehended, then it becomes easy to develop effective treatment techniques. Secondly, the paper shows the impact of produced water on the environment: for example, salts, oil, heavy metals, and radioactive materials that may be safely treated and disposed of occur within the produced water compounds. These toxins may have an influence of marine systems and in freshwater habitats constituting hazard to fish and human health. Hence, one has to explore the possible threats of the created waters which should be handled by applying environmental control measures (Fakhru'l-Razi et al., 2009).

The given research of Fakhru'l-Razi et al. (2009) outlines the pollution prevention hierarchy of three-stepped method of minimizing production, introducing reuse and reclamation and proper disposal if no other option is available. The produced water management alternatives are isolated, such as injection, evaporator, and treatment for release or even reuse is highlighted. In addition, the authors assess different techs performance and cost-effectiveness, listing variables vital for success, for instance, removal efficiency from contaminants, resource consumption, durability, and transportation. Ultimately, this study serves as an overall assessment of produced water management with the focus to address the challenges, disposal methods, and future directions of research and technological advancements. Through the study of the water treatment and disposal issues, it serves to promote purposes advancement of sustainability in the oil and gas industry, without causing much ecological impact.

In order to comprehensively investigate the nature of environmental pollution concerns concerning the treatment of called produced waters from shale oil and gas in the United States, the researchers embarked on a research review. Their interest was mainly centered on sediment pollution which is one of the unforeseen outcomes of O&G production and they sought to bring out concerns over the lifecycle impacts of produced waters disposal and management.

At first the researchers Atoufi and Lampert (2022), identified that because of the advancement in technology the recovery of oil and gas from shale resources has boosted in the U.S. but it has resulted in the following environment pollutions where management of produced water is an important challenge. The wastewaters include produced waters, which are usually accompanied by various toxic organic and inorganic chemicals and are usually injected in deep well injection. In this method, it is possible to treat large volume of wastewater within a short span of time and this aggression has been attributed to been the cause of induced seismicity hence the search for other management techniques that bring about new unknown environmental impacts.

The researchers like Atoufi and Lampert (2022), did a general overview of different cross-sectional studies that were conducted to envisage sediment pollution due to oil as well as gas production. Key contaminants in affected sediments that were revealed included: They consisted of heavy metals and salts, NORM, oil and grease, BTEX, TPH, and PAHs also known as representative contaminants. These pollutants get to sediments and water resources through various processes including pipeline leakage, accidental truck spillage, usage of unseemly methods of waste disposal, or injection well disposal.

To quantify and assess sediment pollution, the researchers discussed three indicators that had been developed: such as, the index of geoaccumulation, the load of pollution and the factor of enrichment. These served to identify the levels of contamination and also contrast these levels with the natural background levels. The geoaccumulation index indicates the extent or level of pollution in relation to the pre-industrial and most recent time of analysis, the pollution load index gives an integrated picture of the pollution status and the enrichment factor quantifies the anthropogenic impact or contamination by standardizing the concentration of one substance to a reference element.

This contamination can result in undesirable effects on the environment, and the studies reviewed in the present paper have indicated high levels of contamination in sediments connected to the oil and gas production industry. Lead, arsenic, and mercury were listed as of priority that appeared at higher levels, which can easily affect the water quality and hence the lives of humans and aquatic life. Chlorides and bromides with the basic material of salt were found to have influenced salinisation of water, affecting the fresh water aquatics. NORMs posed a threat due to their radioactive character of the substance and the ability for accumulation in living organism. Other volatile and semi-volatile organic compounds such as BTEX, TPH and PAHs have also been reported to be more concentrated due to incomplete combustion of hydrocarbons that escapes through vents, leaks from oil/gas installations or transportation of petroleum products.

The researchers also presented a number of strategies that could be used to minimize the risks posed by contaminants within sediments. Many techniques are used for containing contaminated sediments amongst them being surface capping whereby clean material is put over contaminated sediments thus blocking the spread of pollutants (Atoufi and

Lampert, 2022). Bioremediation involves the use of biological organisms to reduce the impact of hazardous substances on the environment because it is an active treatment method of removing organic contaminants such as BTEX and PAHs. Phytoremediation involves the use of plants in order to filter, concentrate, and stabilize hazardous chemicals which are more effective for some heavy metals and some of the organic wastes.

This review also included the case of various parts of the world like USA, Middle East, Africa, Asia and South America. These cases offered information on the concentration levels together with efficiency of the management practices in various geographical areas and environments governed by different regulations. For example, while the increase in allowable produced water volumes in the U.S., as well as advances in facilitated treatability and modernization of regulations provided more efficient handling of the produced waters, there are still problems with combating sediment pollution. For instance, places where the regulatory systems are not so strict like in a part of Africa, Asia, experience high contamination levels because of improper disposal of wastes and limited structures for the purpose (Atoufi and Lampert, 2022).

The researchers concluded that effective management frameworks were those that reflect the characteristics of migrating pollutants, paths of contamination, and properties of affected sites. They stressed the importance of further surveys to determine how some of the effects of the penetration of produced water influence sediment and the overall health of a community. Furthermore, they urged for the emergence of new injection alternatives that are safer to the environment than deep well including the use of produced water that has gone through treatment cycles for industrial applications or irrigation purposes thus reducing the volume that requires the injection process (Atoufi and Lampert, 2022).

Concisely, the researchers highlighted that the difficulties of managing the produced water have been made worst by the shale oil and gas boom. Developing states and regulatory authorities must ensure that potential contaminants of concern are given due consideration when controlling treated produced waters. Voluntary and involuntary hydrocarbon releases from upstream oil and gas activities necessitate effective risk assessment measurement, sound legal requirements and executive programs, and the efficient application of superior remediation techniques. The conclusions drawn by the researchers are important and a reminder of environmental consequences of consumption and use of natural resources are important to ensure sustainable exploitation of resources for the future travelers to avoid areas that are sensitive to environmental degradation.

Moreover, the review by da Silva Gonçalves et al (2023) discussed the ex-situ methods of biotreatment for microorganisms to deal with the PW in which they found that PW is a major byproduct of oil extraction processes. The quality of PW is quite low as it contains several pollutants that include COD, nitrogen, phosphorous, heavy metals and hydrocarbons amongst others. Earlier conventional methods employed in the treatment of PW are quite apparent but they depend mostly on the physical and chemical processes; they are often very expensive to run in terms of operation costs, and as a result, the final cost of the treated water is also expensive. Therefore, biological treatment methods were only assessed in the study regarding their effectiveness, as a potentially cheaper and more efficient method, learning about recent developments and methods of microbial treatments ex situ.

The biological treatment of PW by microorganisms involves passing the water through biologically active and pollutant acclimated bioreactors (Asante-Sackey et al., 2022). These bioreactors are specifically developed to maintain suitable environmental conditions as regards to the salinity of water, pH, temperature and light intensity (where microalgae are used in the treatment)'. The requirements for the growth of microorganisms encompass macronutrients and micronutrients whereby the concentration of the contaminants must not inhibit nutrient availability to the microorganisms or caused limited amounts of nutrients (Hakim et al., 2021). Substrate inhibition is quite important to think over since it results from hydrocarbons that are known to be present in PW (Pessôa et al., 2022). The design features, the type of microorganisms used, the treatment period and mode of operation either in a batch or continuous mode bioreactor are optimized to achieve the best result.

Based on the findings of the study of da Silva Gonçalves et al (2023), it was revealed that bacteria were the most commonly applied microorganisms in the process of PW treatment. Research and application of bacteria has been carried out widely because of its mechanical strength and capabilities to assimilate a wide variety of pollutants. Among them, microalgae, yeasts, and filamentous fungi have been thoroughly investigated, especially in the last decade, with different benefits and drawbacks. For instance, microalgae can offer the additional advantages related to photosynthetic activity, which may be useful for nutrient attenuation and biomass generation. Meanwhile, yeasts and fungi have displayed an aptitude of bio-degradation of more complicated hydrocarbons and other organic contents of pollution (da Silva Gonçalves et al., 2023).

The researchers da Silva Gonçalves et al (2023) in the review were able to describe the different classes of microorganisms and their strengths and weaknesses of each of them. Moreover, even though bacteria are easy to use, well-studied, and very effective in their tasks, they can be rather picky about the environment in which they function or offered as food and can react poorly to extreme fluctuations in the PW composition. Microalgae exhibit the characteristic of bioflocculation and also helps in treating PW and also producing valuable biomass for biofuel and other bioproducts. However, because they depend mostly on light and particular nutrient demands, their uses may be somewhat restricted. Yeasts and fungi are quite efficient in breaking down more composite organic material, but they have higher nutrition demands and slower doubling times which can be problematic at times.

This study also uncovered several case studies and experimental installations where ex situ biological treatment methods were effectively used in the treatment of PW. In these cases, the bioreactors were precisely designed to enable the enhancement of the reduction of these contaminants. For instance, utilization of bacterial consortia in bioreactors significantly recorded high pollutants elimination efficiency of total oil and grease, nitrogen, phosphorus and heavy metals. Such setups commonly entailed long-term control of the environmental and nutritional conditions and constant adjusting to promote microbial growth.

In addition, the researchers highlighted the imperativeness to continue conducting researches and improving technology on these aspects. However, the improvements for these methodologies still have to be pursued constantly to further increase the efficiency, and reduce the cost of the task. Future development is expected to go into the adjustment of bioreactor factors, the enhancement of the stability of microbial consortia and the collocation of the biological and a number of physical chemical treatments to produce a symbiotic system.

Therefore, the review equipped the potential and the complexity of ex situ biological treatment methods in the removal of PW using microorganisms. There is evidence that bacteria, microalgae, yeasts, and fungi can degrade natural organic matter effectively and easily; therefore, using these microorganisms can help in the development of cheap and efficient treatment processes that provide both safe water and microbial biomass. This way not only works on the environmental problems related to PW but can also implicate opportunities for the resource salvage and sustainable management of wastewater. The study also emphasized the need to strive for more development and investigation in this kind of treatment employing biological science solution particularly for industrial effluence like the produced water (da Silva Gonçalves et al., 2023).

2.5 Produced Water Production and Management

Produced Water remains one of the most complex and unavoidable issues in the oil and gas industry as across the globe, its generation is estimated at 250 million barrels per day. It is anticipated that this volume will increase with the increase in the production of petroleum and gas and also with the growth of old aging wells. PW from oil and gas exploration fields, all year round, account for 60% of the generation, while offshore production makes up to 30% of the global oil production (Yacovitch et al., 2020). For instance, in the United States of America, about 21%. The rising level of awareness of mental health concerns has potentially been triggered by the increase of mentally ill people in the society, as well as the initiatives made by various organizations to enhance the number of mentally healthy individuals (Baza et al., 2019).

The increased likelihood of mentally ill people in the society has made the level of awareness of mental health issues to rise, while the enhanced number of mentally healthy people to result from efforts by PW of 6 billion barrels is produced every year, and about 97 percent of it is produced from the onshore facility. Offshore sites contribute approximately 3% to the total PW; virtually all of the PW from these sites is released directly into the surrounding aquatic environment.

Owing to the toxicity and environmental unsustainability of PW, its management is governed by a number of policies and legislation meant at reducing the Environmental impact. These regulations are country specific and failing to adhere to these set regulations attracts big penalties in form of civil penalties, international criminal charges and a deferred or loss of production time. These legal factors are the primary motivation behind these concerns, there are bioeffects of PW. Some of the practices that have been adopted to manage PW includes reinjection of the water to wells with drilling and operational requirements which in essence implies that the water is not produced back to surface. Deep well injection, despite its great usage, is energy-consuming, carbon-consuming and costly it costs between $ 0. In its current state, Brent crude forecasts a tentative range of $3 to $10 USD per barrel. It also comes with some environmental concerns such as pollution of underground water resources and below ground movements (Echchelh et al., 2021)

2.5.1 Characteristics of Produced Water

PW always contains a lot of salt and it has been proved that its density is higher than that of the seawater. While seawater has an average of about 30g/L TDS, PW from sources in some oil and gas fields can contain rather high amount of TDS in the range of 300-400g/L. The maximum recorded concentration is hypersaline covering up to 800 g/L of solar salinisation. The most dominant PLS contributors include sodium and chloride ions as opposed to the chloride content of calcium, magnesium, and potassium. This shows that high reservoir temperature influenced the increase in TDS concentrations in PW as evidenced by the research findings. Besides Cl –, PW also contains SO 4 2-, CO 3 2-, and HCO 3 – anions. Society and environmental issues become more sensitive when PW is released on the land surface and released into freshwaters as compared to the ocean as recognised in the study of (Asante-Sackey et al., 2022).

It is difficult to describe PW in terms of chemical components, since numerous chemical agents are applied during drilling, extraction, and production. The chemicals used in the well drilling process and production include; corrosion and scaling inhibitors, emulsion breakers, fracturing fluids, clarifiers, solvents, coagulants, surfactants, biocides, and flocculants. Such substances, for instance, fat soluble and at such low concentrations as 0. Many of these treatment chemicals which are added at the rate of 1 part per million (ppm) are highly toxic. In some cases, PW can include special type of radioactive materials, known as technologically enhanced naturally occurring radioactive materials (TENORM) and naturally occurring radioactive materials (NORM), which can be found in such products as drillings, flow back water, pipe scale, sludge, sediments, and filters in the liquid and gaseous forms (Babatunde et al., 2019)

The comparison is done of the PW fetched from various extraction fields: The investigation shows that the PW from the gaseous fields holds comparatively lower volume but higher degree of acidity and concentration of volatile components. PW from oil fields has a general pH of 4 to 10 but the pH for any PW may fluctuation anywhere between 4 to 10 and beyond. As for the pH of the water, it is as low as 3 to 10, whereas the pH of PW from gas fields is usually between 3. 1 and 4. 4. Furthermore, it was also observed that the contents of benzene, toluene, ethylbenzene, xylene (BTEx) and naphthalene are higher in the PW obtained from the gas fields than in the PW gains from the oil fields. Regarding the composition of PW, it is crucial to highlight that straight chain alkanes (C10–C30) were identified as the main hydrocarbons accounting to about 90% of all the detected hydrocarbons with 25% of the overall hydrocarbon content being highly molecular weight n-alkanes that included those with carbon numbers from 21 to 34. Similarly, the total organic carbon content, since PW is known to contain compounds from petrolium waxes, is also expected to have high value (Asante-Sackey et al., 2022).

Given the fact that PW contains several hazardous constituents and is in even larger volume compared to any radioactive waste, extra efforts have to be made in order to prevent adverse effects on the environment. Treatment techniques for removing pollutants from PW are well known and include physical and chemical processes and technologies. However, many of these technologies are costly to operate, thus contributing to the augmented price of the water treated by these techniques. Hence, it has become possible to observe some interest in the biological treatment methods and more particularly the one with the help of microorganisms as it has the advantage of being more economical and effective (Asante-Sackey et al., 2022).

Biological treatment of PW includes passing the water through bioreactors that contain adapted microorganisms. The bioreactors described here are custom built to mimic the desired internal environment like salinity, pH, temperature, and light intensity, should the treatment method involve microalgae. However, the macronutrient and micronutrient requirements of the microorganisms also have to be considered so as not to reach a level whereby the concentration of contaminants retards the rate of microbial growth due to nutrient limitation or inhibition by high concentrations of substrate. PW may contain hydrocarbons which are responsible for substrate inhibition which is of much concern. Ordinary technical factors such as the kind of bioreactor, class of microorganisms used, period of treatment and mode of treatment; whether it is a batch or continuous process, are adjusted in such a way to enhance the efficiency of the treatment.

Among all the candidates, bacteria are the most widely used microorganisms for the treatment of PW due to their ability to withstand highly toxic conditions and their effectiveness in the removal of various pollutants. Some other species, such as microalgae, yeasts, and different filamentous fungi, have also been studied more intensively, especially over the past decade, and they present numerous benefits and drawbacks. Microalgae, for instance, have such advantages as photosynthetic properties that could help in nutrient adsorption and biomass generation. Nevertheless, dependence on light and particular nutrient demand makes them restricted to certain specific uses. Organisms such as yeasts and fungi are very effective at utilizing more complex organic substrates for nutrition; however, they grow more slowly and require different nutrients for nutrition (Asante-Sackey et al., 2022).

Future research and subsequent technological advancement will be directed towards enhancing the form and function of the bioreactors, enhancing the stability of the microbial communities, and developing methods of interconnecting biological treatments with physical/chemical processes to form composite treatment systems. As well as attending to the environmental impacts posed by PW, this strategy has the likelihood of resource extraction and sound management of wastewaters. Biological treatment of PW through microorganisms as used in this study is therefore a potential approach of minimizing pollution from oil and gas extraction processes and decreasing overall cost of treatment while enhancing quality of the water.

2.6 Treatment Methods

Wastewater treatment technologies can be broadly categorized into four classes, namely, preliminary, primary, secondary and tertiary treatments. This is whereby unwanted materials such as sticks, grits, rags, and floatable suspended solids which are in solution or entrained in the liquid are removed. The initial one includes removal by plunging and sedimentation, the level of which is between 50-70 % for suspensions and 35-40% for BOD. The secondary treatment involves using biological processes such as Activated sludge and trickling filtration then treated with Chemical precipitation to generate high quality effluent. The secondary treatment plants when properly designed and managed, can effectively treat and eliminate about 85 – 95% of the BOD and suspended solid. Tertiary treatment is also referred to as the polishing stage, and it is needed in case the effluent from the second phase fails to meet the regulatory standard. The efficiency of this stage can accomplish 99% particles' removal and might be enabled by various PCTs.

In the context of the PW treatment, numerous physico-chemical and biological methods singular to the conventional wastewater treatment technologies have been shifted. Some of the known treatment methods include the use of addition agents, such as chemical precipitation, adsorption, ion exchange, membrane separation, and coagulation-flocculation. There are technologies like hydrocyclone, gas floatation and gravity base separator which has been widely used for water treatment and minimizing the percentage of oil–water emulsion in the industry. The next section will describe each method in detail.

2.6.1 Hydro cyclones

Cyclones are essential equipment in produced water (PW) treatment, mainly addressing the solid phase and oil separation (as sand) with the assistance of density variations (Quteishat, 2020). Normally hydro cyclone is made up of cylindrical part where the liquid stream enters from perpendicular direction and a base of conical shape (Ni et al., 2019). The efficiency and performance of hydro cyclones are affected by the orientation of the conical section. The operation of a hydro cyclone results in two discharge streams: the underflow or reject stream that includes the heavier phase and released from the bottom, and the overflow or product stream that has the lighter phase and taken out from the top

(Vallabhan, 2022). Compared to others, this particle elimination technology is capable of removing particles within 5 to 15 μm but highly ineffective against soluble particles (Sheng et al., 2020). The use of Hydrocyclones is very popular in PW treatment because they are simple and do not need to apply chemicals and energy for their operation (Nasiri et al., 2017). In addition, they eliminate the treating process or treating equipment stages to serve as standalone treatment equipment. But, this drops condition depends on their size and shape. The waste produced in form of a concentrated slurry of solids should be disposed using the proper method. Where offshore platforms are with space limitations, hydrocyclones of compact design is used (Gamwo et al., 2022). These facilitates provide for the treatment of effluents in a minimal footprint which makes the process perfect for operation offshore.

2.6.2 Thermal Separation Processes

The process of thermal separation has been conventionally used in large desalting facilities, like PW plants with the treatment processes involved (Chen et al., 2019). These methods would be more suitable in places like the Middle East where energy resources are abundant and cheap enough to plan for lower energy intensity. A typical thermal unit separation technology is Multiple Stage Flash (MSF) distillation, where feed water is exposed to high temperatures and to a lower pressure to create evaporation (Al-Mutaz, 2022). The achieved water is then desalinated. MSF operates through the various stages where the temperature and pressure gradually and linearly run out. It filtering water with high TDS concentration up to 40,000 mg/l is a top-notch method (Al-Shayji et al., 2005). A good example of an anti-scaling chemical is the one that is used to protect the membranes from scaling, and the screening and rough filtering take place upstream of the unit to eliminate the big suspended solids. The next method of thermal approach is the multiple-effect distillation (MED) which takes feed water through a succession of the evaporators (Chandra et al., 2024). The vapour created in each unit is utilized to evaporate water of the following stage. The same as MSF, the MED system demands three different energy forms which are thermal, electrical and pre-treatment with anti-scaling agents. Although its price is on the low side in contrast to MSF, it, however, has a lifetime span of up to 20years. Aiming at the problematic waste disposal, heat-related technologies like brine concentrators and crystallizers with no liquid discharge are being developed. Moreover, toward this goal, hybrid systems such as MED-RO/NF or MSF-RO/NF combine high water recovery rate with the low hypersaline waste discharge.

2.6.3 Adsorption Treatment Processes

Adsorption treatment includes use of several materials, consisting of organoclays, zeolites, chitosan, and activated charcoal to remove contaminants from PW (Yousif et al., 2020). Unless it is necessary for the regeneration of medium using active sites are relatively used only during normal operation. Adsorption media is a powerful means for the treatment of wastewater most notably iron, total organic carbon (TOC), heavy metals, and oil (Rashid et al., 2021). While their efficiency is dependent on factors such as pH, temperature, suspended solids, oil and associated impurities, dissolved contaminants, and salts. The backwash of course is used cyclically to get rid of the big materials that block the void space of this medium. The adsorption processes are most of the time dealt with as an integrated unit process which is done alongside the other treatment methods as opposed to a standalone method (Yousif et al., 2020). They are especially suitable when they have a function of completing the treatment because there is a possibility of an organic overload. The operational costs are mainly depended on the usage rate of adsorbents, which involves regeneration or substitution, and waste disposal aspects cannot be overlooked here as well.

2.6.4 Membrane Bioreactors

The use of Membrane Bioreactors (MBRs), which are recognisable as a form of integrating a selective membrane process such as microfiltration or ultrafiltration with a biological process within a single system has been identified as a potential solution. They are used as replacements to CAS system since some of the goals of this system are more economical and efficient. For instance, in MBRs, the biological process is the degradation of the organic pollutants through adapted microorganisms, and the membrane acts as a number of barriers that prevent the biomass to mix with the treated wastewater. This method enables the use of activated sludge to be used as recycled activated sludge (RAS) (Asante-Sackey et al., 2022).

The introduction of MBRs has allowed for a significant reduction for plant area since the following processes have been removed: secondary clarification, tertiary filtration, and UV disinfection. MBRs function at a low flow to microorganism ratio, and the process has some significant benefits, such as efficient disinfection, high quality of the effluent, efficient separation of organic and inorganic materials, good SH ability to uptake the organic loading, no ability to control SRT, and low HRT. Thirdly, MBRs also generate a small quantity of sludge because they have poor settle ability. The longer SRT in MBRs benefits in cultivating slow-growing microorganisms that result in nitrogen compounds degradation. Huge successes with general industry and municipal wastewater treatment results point to MBRs treating industrial and municipal wastewater at MLSS levels up to 12mg/L- a capability far higher than CAS can offer (Asante-Sackey et al., 2022).

Nonetheless, MBRs feature benefits such as high removal efficiency of pollutants, increased versatility, relatively simple design and operation, but some disadvantages include high operational and capital costs, membrane fouling, and high energy consumption. These have been a major limiting factor for the expansion of MBR technology. Nevertheless, they have certain limitations in their operation compared to other methods, despite the fact that their benefits outweigh the drawbacks in various applications, especially those which involve the need for high quality effluent and reliable disinfection.

It has been evaluated that MBRs could have high efficiency in treating PW. Experimental investigations continue revealing that MBRs have high efficiency in the removal of pollutants from PW. MBRs have demonstrated the organic removal efficiency of oil and grieas with higher than 80% to over 90% while the chemical oxygen demand (COD) over 90%, total organic carbon (TOC) more than 90%, and phosphate more than 30% to over 60%. These findings justify the promising trend of MBR technology in the realistic pollution control of PW (Asante-Sackey et al., 2022).

2.7 Challenges Associated with Produced Water Management

2.7.1 Technologies Utilized in Produced Water Treatment

The management of PW for further utilization in the oil and gas industry requires consideration of costs of isolation of PW components commonly associated with considerable negative impacts on production processes. All these causes produced water to have high concentration of certain ions including strontium (Sr), calcium (Ca), magnesium (Mg) and barium (Ba) ions that precipitate in the production tubing to form scales thus slowing down the production rates. Sulfate ion, for instance, can cause scaling and foster the production of sulfate-reducing bacteria (SRB), which cause corrosion and pollute the environment through well bore clogging, hydrocarbon losses and natural gas souring (Abou Khalil et al., 2021). High concentrations of TOC, sodium, Ca, Fe, borate, phosphate can substantially reduce the viscosity of gel-based fracturing fluids, thus influencing well stimulation while high levels of B, Fe cross-linkers can also hamper the efficiency of fracturing fluids (Oetjen et al., 2018).

The produced water is highly complicated biogeochemical since it contains microorganisms, heavy metals, oil particulates, and NORMS; hence, multiple treatments are required. The well-known treatment technologies are chemical oxidation, adsorption, membrane filtration, electrocoagulation, distillation (Sanchez-Rosario and Hildenbrand, 2022).

Chemical Oxidation

Chemical oxidation is used to enhance the coagulant reaction of volatile and semi-volatile organic matters, the sedimentation of inorganic matters and the deodorization of bacterial substances. This also eliminates bad smells and stains, by the help of oxidizing agents like ozone, hydrogen peroxide, chlorinated chemicals and permanganate. The applicability of AOPs in the removal of COD is considered eco-friendly since the processes employ hydroxyl radicals of organic matters to degrade the pollutants. Development in AOPs include use of nanoparticles to improve the removal of dominant organics from fracking wastewater (Sanchez-Rosario and Hildenbrand, 2022).

Adsorption

Adsorption is utilized for the removal of organic and metal impurities mostly as a final treatment process to augment more conventional techniques. The Effect of Water Salinity on the Adsorption Efficiency of Various Adsorption Media Organic pollutant, on the other hand, can easily be treated with activated carbon whereas activated zeolite can effectively remove scaling ions such as Ca^{2+} and Mg^{2+}. Alumina and organoclays are also used as adsorbents. Literature review reveals that Fe-impregnated biochar can remove several metal ions including Cu (II), As (V), Cr (VI), Cr (III) and Zn (II) as discussed by (Sun et al., 2019).

Membrane Filtration

It involves use of a surface through which only fluids pass while leaving dissolved substances on the surface; it includes reverse osmosis, micro filtration, nan filtration, ultra filtration, and forward osmosis. RO operates on water molecule pressure to pump water through a membrane with more permeability as compared to MF which mechanically filters suspended solids, thereby reducing turbidity. UF eliminates odor, organic substances, and color while NF removes particles by size and charge, effectively reducing multivalent ions. FO reduces the TDS content in the high salinity brines using osmotic pressure. Challenges connected with the process include membrane fouling/clogging caused by VOCs and high Fe concentrations in the water and scaling in RO. The range of the RO process is up to an IS lower than seawater that is roughly 40,000 ppm (Panagopoulos et al., 2019).

Electrocoagulation (EC)

Electrocoagulation facilitates the coagulation of metals as hydroxides employing direct current through an immersed metal electrode. The given method is very advantageous for wastewater treatment and can efficiently remove turbidity and COD, oils, and greases. EC has proved worth as it separates TOC and scaling ions such as Ca^{2+}, Mg^{22}, CO^{32}, and HCO^{32} from synthetic and real produced water samples. These metal hydroxides can be precipitated, and therefore sold hence making the treatment cheaper. Moreover, hydrolysis of Cl_2 gas produced during the process can also give HCl (Moradi et al., 2021).

Distillation

Distillation is a technique that separates solids from liquids depending on the difference in boiling points. Multistage flash distillation (MSF) is suitable to treat brine where dissolved salts are transformed into vapor and recirculated through several stages with evaporation and condensation, resulting to fresh water. For future applications in produced water treatment it is suggested that incoming water is treated with chemical softeners or filtration/ ion exchange to avoid scaling or fouling of equipment (Panagopoulos et al., 2019). Replacement of infrastructure materials with stainless steel will eliminate chances of corrosion but at the same time will lead to higher capital investment. Thus, the salts obtained through distillation may be used in electrocatalytic reactions to obtain other chemicals such as acids (HCl) and caustic agents (NaOH). Thus, treatment of the produced water from the oil and gas production is a challenging task because of the presence of various compositions in the water. This study majorly focused on the treatment of water utilizing chemical oxidation, adsorption, membrane filtration, electro coagulation and distillation methods that specifically target individual pollutants. These technologies collectively improve the pollutants removal efficiencies and make it possible for the treated produced water to be reused while managing the impacts on environment.

2.7.2 Costs Associated with Produced Water Treatment

As earlier explained, successful management of FP treatment impacts the decisions made with regards to the terminal disposal of the treated water. However, the aspect of operational cost, particularly with regard to FP reuse and / or recycling options, has a much bigger impact on the feasibility and sustainability of the process. It is important to note that range of cost that may be incurred for deep-well injections begins from about USD $. Sixty-five cents for every barrel in private wells to approximately. USD $0. 50 to 2. In commercial wells, they cost approximately $50/bbl. Considering the cost add up to transportation costs to disposal sites which is approximately $0. 03/bbl/mile may add up significantly provided that the disposal sites are far [86]. Indeed, the costs associated with transport may vary from USD $2. 00–20. 00/bbl [87]. Also, these values may be expected to rise due to distances of disposal sites that are likely to extend further than they used to be. Moreover, the practice of allowing SWDs is poignant because of earthquake issues may lead to an emergence of other costs. However, FP can also be transported through pipeline at a cost, which is approximately estimated to be at USD $0. The cost of achieving the 'sweet water' limit of 25/bbl (personal correspondence with water treatment provider), but this takes much capital which is often lacking in the most of the shale energy basins. With normal conventional treatments, the average cost of treatment is approximately USD $3. 00 to $30. This charged only $00/bbl, inclusive of storage and transport (Chang et al., 2019)

Recently, MD modalities were investigated for the reuse waste waters of HF operations with the implication of costs that ranged from USD $0. 11 to $0. The treatment of the fluid at each site was reported to range between 90/bbl and 89/bbl. Several factors affect the operational costs of RO and FO, but these are sometimes as low as USD ~$1. 00/bbl. Presenting an emergent price for the purchase of these membranes can be difficult since they depend on influent TDS and throughput capacity.

2.7.3 Costs Structure Associated with Produced Water Treatment from Oil in Sudan

The cost of dealing with produced water from oil extraction in Sudan is high due to some of the following factors: The nature of the water the technologies used in the treatment and disposal of the water and the overall cost of the process (Barimah, 2019) The expense associated with produced water treatment can be broken down into several key categories: First cost, cost of operations and maintenance, compliance costs and certain potential costs associated with impact on the environment too.

Initial Investment in Infrastructure

The most notable cost of treating produced water are the fixed cost taking into consideration the initial cost for the construction of the treatment facility (Murashko et al., 2018). This includes construction of treatment plants, and fixing of equipment like filters, chemical oxidizing beds, and distillers. This cost is relatively high especially in Sudan where to handle the high salinity and high content of contaminants it requires strong infrastructure (Omer, 2019). Furthermore, most of the oil fields in Sudan are located in remote areas, thus making it costly to transport resources and establish structures.

Operational and Maintenance Costs

Treatments costs are a major fixed expenditure in the treatment of produced water. These include the cost of the chemicals that form the basis of processes such as chemical oxidation and electro coagulation, the costs incurred in energy consuming processes such as distillation and membrane filtration and the cost of labor required in the operation and maintainance of the treatment systems (Ghafoori et al., 2022). In Sudan for instance where there could be instability of energy structures ensuring the supply of electricity adds to operation costs. Maintenance of equipment, which entails the prevention of the breakdown of equipment and ensuring that it operates optimally, is also costly and has to be done continuously.

Environmental Compliance Costs

Sudan like many oil producing countries has environmental standards where the produced water is given certain treatment before it is discharged or reused (Lado, 2021). Implementation of these regulations is not only in the treatment process itself but also in the supervision that forms a significant part of the documentation to support compliance to environmental provisions. Environmental compliance also implies constant testing of water and the acquisition and implementation of record keeping protocols, more often than not entities will need to invest in upgrades in order to meet the required standard (Martínez et al., 2022). This added risk for noncompliance also translated to monetary penalties and enhanced enforcement which means that more attention must be accorded to compliance.

Transportation and Disposal Costs

There are other related costs that are incurred in the management of produced water treatment such as the cost of transportation and disposal of solid wastes that are produced during the treatment of the water. In Sudan the location of the oil fields implies that the treated water and solid waste can be hardly transported to proper disposal areas as this would be very costly. Other aspects include costs of conveyance in form of vehicles, fuel, and staff for transportation and disposal facility expenses (Bundhoo, 2018).

Costs of Environmental Impact

Although not being a direct cost for treatment of water, the environmental nature of people handling and providing produced water is another disadvantage of produced water management cost. Failure to treat produced water effectively or disposing of the effluent erroneously impacts the soil and water resources with negative effects on the ecosystems and communities in a particular region. Such an environment deterioration brings about high cost of rectifying the mess, legal implication and effects the image of the oil business companies. Hence, it is crucial to pay attention to the risk factors that cause such complications, and provide adequate support by utilizing efficient treatment methods and strategies for reducing the costs (Sanchez-Rosario and Hildenbrand, 2022).

Technology-Specific Costs

There are also variations as to which treatment technology is more expensive to operate and maintain. For example, chemical oxidation processes demand a constant necessity for chemical solutions such as ozone or hydrogen peroxide, which increases cost. AOPs can be even more effective and perhaps friendlier towards environment when compared with more traditional methods, though they are generally rather expensive to initiate due to the necessity of using elaborate equipment and specialized chemicals (Capodaglio, 2020). Among the advanced water treatment technologies, membrane filtration technologies, reverse osmosis, and nanofiltration, have been ranked high, because they are very effective but the membranes foul easily, and the membranes require frequent replacement and general overhauling. Despite this, electrocoagulation may be cheaper as it relies on electricity for powering the electrodes and constant replacement of the electrodes. Distillation processes, especially multistage flash distillation involve high power input and since Sudan is rich in heat energy as compared to electrical energy the cost maybe high (Alkhadra et al., 2022).

The economic context and funding challenges were therefore shaped by the following variables:

In the light of the foregoing discussions about produced water treatment in the current context of Sudan's economic environment, it might be relatively hard to finance. This study also examines how the country's economy impacts the finance that supports large infrastructural development and the capacity of the existing oil firms to fund state of the art treatment solutions. In some cases, it might be required to seek external support or seek collaboration with international partners in order to close the gaps in the funding for produced water management and sustainably continue with the practices as need be.

Chapter 3. Research Methodology

3.1 Research Design

This is a brief guide on how the individual parts of the study fit together into a cohesive and sequential framework of the research problem and the proposed solution. The research design of this study can be further classified in to two categories in light of the technicalities of this study.

3.1.1 Descriptive Design

3.1.1.1 Definition

Descriptive research design entails providing a description of a phenomenon, or a population, with a view of providing an analysis of their features without any modification of the environment or sample. Its main goal is to denote the process or state of events, subject, or conditions taking place in real life.

3.1.1.1 Application to the Study

In characterizing the produced water from oil drilling in Thar Jath (Block 5A), descriptive research design is inevitable. This approach involves providing detailed chemical and biological characterization of the produced water for a baseline assessment of its current state. The objective is to represent as much variation and complexity of produced water as possible by taking samples more frequently and throughout the entire year to account for the differences between the seasons.

3.1.1.3 Chemical Characterization

This part of analysis encompasses determination of the various forms of chemicals that are contained in produced water. Some of the variables to be analyzed are acidity, salt content, heavy metal content, oil and grease content, polycyclic aromatic hydrocarbons, and other organic and inorganic species. For metal analysis techniques such as Inductively Coupled Plasma Mass Spectrometry (ICP-MS) will be used, whereas for hydrocarbons Gas Chromatography-Mass Spectrometry (GC-MS) analysis will be used among other analytical techniques. It will reveal quantitative information on the level of presence of polluting chemicals and other compounds and help set up a platform for additional research and treatment.

3.1.1.4 Biological Characterization

Biological characterization is simply the isolation of microorganisms that may be found in the produced water. This is by culturing bacteria or microorganisms, DNA sequencing, and other methods of microbiology to recognize bacteria, archaea, and other microorganisms. This paper will also explore the presence of pathogens in these microorganisms as well as possibilities of pollutant bioaccumulation. This information is vital in providing knowledge on the biological activities of produced water as well as analyzing the possible health implications of microbial intrusion.

3.1.1.5 Seasonality Factor

To reduce the impact of seasonality factor on the result, samples will be taken on monthly bases for the full year. This is because the study aims at capturing seasonal fluctuations h of produced water characteristics. Some of the key influencing parameters include the temperature and the rainfall as well as operating deviations from the normal drilling procedures on oil wells, which affect the concentration of produced water. This research ensures that the collected samples are representative of those produced during a year, and therefore ensures that the sample collected at Thar Jath (Block 5A) provides an all-round picture of the type of produced water produced in the area.

3.1.1.6 Study Outcome

The selected research design of descriptive type will have a broad array of chemical and biological characteristics of the produced water. These will serve as a basis for future stages of the work, including evaluating the effectiveness of remediation processes. The identification of specific pollutants and bacteria present in produced water will enable a more effective aimed remedial programmes to be developed and therefore contribute to the assessment of the overall effect of oil drilling and production on the environment in the area.

3.1.2 Experimental Design

3.1.2.1 Definition

Experimental research design focuses on manipulating one or more independent variables in a controlled manner with the aim of studying their relationship with the dependent variable. This design is used to determine the effect of an intervention by establishing the cause of a variable that changes with time.

3.1.2.2 Application to the Study

Awakening to that fundamental fact leads to the conclusion that, in comparing the various remediation approaches for treating produced water, an experimental design is essential. This includes a comprehensive examination of physical/chemical/biological treatment technologies on a laboratory-scale basis with a view to assessing optimum efficiency in dealing with produced water. It is thus the aim of this investigation to identify which of the techniques or potion of them are the most successful when it comes to cutting on pollutants and enhancing water quality.

3.1.2.3 Physical Remediation Techniques

Filtration and sedimentation, distillation separates mixtures through the process of physical means will undergo experimentation. These techniques are directed towards the physical processes of particulate removal of produced water some dissolved pollutants. Selective experiments are going to be applied wherein factors including filter openings, sedimentation time and distillation temperature will be adjusted in the continuous effort to refine the degree of removal. Efficacies of all the methods will be ascertained by the following: Levels of contaminants before application of each method were recorded and the same process done again after the application of each method.

3.1.2.4 Chemical Remediation Techniques

Among the chemical remediation technologies, coagulation and flocculation, precipitation, and advanced oxidation processes (AOP) shall be considered. These techniques comprise of the use of chemical reagents in the produced water to coagulate or degrade the pollutants. For example, lime softening or chemical precipitation may be applied to coagulate and flocculate suspended particles, or AOPs such as ozonation and hydrogen peroxide may be applied to oxidize organic contaminants. The experiments will include, changing the concentration and reaction time of the chemical agents in order to achieve the maximum capacity for pollutant elimination.

3.1.2.5 Biological Remediation Techniques

Some of the biological tests will include bioremediation of specific microorganisms, constructed wetlands as well as phytoremediation. These techniques make use of natural mechanisms of the microorganisms and the plants in reducing or immobilizing the contaminants. Hypotheses will include introducing produced water to certain bacterial strains/ types that are known to degrade pollution or cultivating certain plants in constructed wetland systems. These biological treatments will be assessed by continual evaluation of the biodegradation of the pollutants and the activity of the biological treatment organisms.

3.1.2.6 Study Outcome

The experimental design shall produce results that would indicate the extent to which the remediation strategies are useful under the outlined controlled setting. This will assist in finding out the best approach that can be employed in the treatment of produced water with regards to the level of pollutants that can be removed together with the cost and feasibility of such a process. The results are expected to inform the design of effective and comprehensive remediation approaches where physical, chemical, and biological treatments will be utilized in order to offer the best results.

3.1.3 Applied Research Design

3.1.3.1 Definition

The applied research design involves defining problems and finding solutions via the use of scientific knowledge. This type of design is meant to generate outcomes that can be applied to practice in order to enhance actual processes, service delivery, or circumstances in some manner.

3.1.3.2 Application to the Study

The aim of each stage of the study is to provide recommendations for proper characterization of produced water for further research and to offer appropriate method for the treatment of produced water based on the criteria determined during the descriptive and experimental investigations. An applied research design is very important in order to be able to take theory and put it into use by using the real-life situations.

3.1.3.3 Integrating Findings

In the applied research design the first step to be followed is the combination made from the descriptive and experimental phase results. Produced water is the most significant waste stream from the oil and gas industry; the chemical and biological analysis of produced water helps to understand the pollutants and microbial population present in produced water. The methods for determining the efficiency of the remediation methods include the experimental evaluation of the pollutants which show the best practices for remediation. Collectively, these suggestions enable the generation of appropriate mitigation measures that can be tailored to the type of produced water discovered in Thar Jath (Block 5A).

3.1.3.4 Designing Remediation Techniques

The study will use the findings across the integrated study to develop specific remediation strategies that applies to the general environment of the study locality. This concerns the ability to choose and integrate the most suitable physical, chemical, and biological techniques in order to have a holistic approach. For example, a series of treatment processes might be designed such as physical removal of sediments, chemical addition to cause suspension of dissolved impurities, and biological aerated chambers to treat organic compounds.

3.1.3.5 Pilot Testing

In order to test the efficacy of the designed remediation techniques before large-scale application, these techniques will first be pilot Applied in a natural environment. Pilot testing implies the exposure of the treatment system to a small scale produced water sample under field like conditions in order to assess the viability of the treatment system. The listed step is important in terms of understanding any key operation issues and defining appropriate operational parameters aimed at making the remediation techniques efficient and feasible.

3.1.3.6 Implementation and Monitoring

After the application of the remediation techniques at a pilot scale the process of eliminating contamination will be performed at a larger scale. This entails implementing treatment facilities in the oil export site in Thar Jath (Block 5A) and evaluating their efficiency over time. In this context, future sustainability of the remediation approaches and their efficiency will be measured by conducting performance analyses based on pollutant removal efficiency, operational costs and the potential environmental effects.

3.1.3.7 Study Outcome

The research design for an applied nature will provide practical workable strategies for treatment of produced water resulting from oil drilling operations. With the applied remediation techniques, the water quality will be improved and environmental and health hazards from the produced water will be reduced with ease. Further, the study will become an example for the other regions, which faced the similar issues in the framework of environmental and rational use of the resources' management.

3.2 Research Philosophy

The underlying belief about how data about a phenomenon should be gathered, analyzed, and used. This study is based on the following research philosophies.

3.2.1 Pragmatism

Specifically, pragmatism as a research philosophy concentrates on practical repercussions and conclusions that guide and suit context-bound research that seeks to solve specific problems. Therefore, when studying produced water, defining its composition, and exploring solutions for the treatment of this liquid, pragmatism can be applied successfully as it coincides with the priorities of the given research. Most of the pragmatists who espouse the pragmatic paradigm pay attention to usability, which entails the application of findings aimed at identifying areas of improvement. This philosophy can be seen as especially important in environmental studies, in which the purpose of studying phenomena is to introduce effective measures. This work is founded upon a pragmatic epistemology that invites procedures and interpretations that enable the quick application of solutions. The characterization of produced water is done with sometime specific intention of trying to design a remedial action plan on the outcome of the characterization. This requires data on chemical and biological characteristics, which is important for detecting pollutants and predicting their interactions. This is beneficial in ensuring that only efficient method of data collection that can, in one way or another, be of value in identifying proper methods of remediation are used.

Moreover, the evaluation of various remediation methods comprising physical, chemical, and biological methods within a pragmatic perspective really means experimentation of these approaches in dynamic practical environments. Unlike other attempts that attempt to measure or model effectiveness, the study establishes the effectiveness, cost, and workability of each technique. This guarantees that the suggested course of action is both theoretically and practically feasible and admissible. Iteration also becomes a constructive concept shaped by pragmatism’s commitment to the flexible organisation of the world. Data that is collected and processed over time refine and improve the consecutive phases of the research in order to provide better effectiveness of the remediation techniques. This type of an approach helps in making sure that the study will always be as flexible as to address both the difficulties and the changes in the produced water of Thar Jath (Block 5A). Finally, the pragmatic philosophy ensures that the research adds value and helps create tangible environmental changes since it considers the temporary and long-term concerns about managing produced water.

3.2.2 Positivism

Positivism is a research philosophy that assumes that reality is tangible and that the quantitative dimensions of it can be rationally ascertained. The philosophy is most relevant with the descriptive/empirical aspects of the study since it is in the analysis of produced water and the evaluation of treatment methods based on objective data that assumption minimization is most important.

As for the method of studying produced water, it is founded on the Positivism philosophy to characterize the object. Some of the well-defined and measurable tests used to detect and analyze chemical and biological composition include the ICP-MS for metal analysis and GC-MS for hydrocarbons. It also applies these methods with the understanding that these methods can offer accurate and well characterized sample data of the produced water composition. This approach is chosen in order to maintain the objectivity of data, which received in the framework of positivist paradigm and can be effectively analyzed with the help of statistical means. In the same manner, positivism underpins the method that is adopted in the conducting of experiments to assess the various remediation methods. Experiments in the form of controlled tests are carried out to determine the extent of attenuation and effectiveness of the physical, chemical, and biological treatments on produced water samples. This typically entails controlling certain facets of the experiment while observing the corresponding impacts and developing equations to identify cause-and-effect links between the anticipated treatment approaches and their performance in neutralizing pollutants. This approach is a basic function of positivism, the research paradigm that aims at identifying common scientifically discoverable laws governing phenomena.

In addition, positivism lays a great deal of focus on hypothesis testing as one of its main tenets. Based on the above facts, the study establishes hypothesis of chemical and biological nature of the produced water and the extent of produced water treatment.

These hypotheses are then tested through empirical research, and the results produced are statistics that prove/ disproves them. It is because, due to the scientific scrutiny, the conclusions drawn have existing reference points, making them more realistic and accurate. Due to the aforesaid flow of the research in a highly positivist way, it can be ascertained that its findings are founded upon irrefutable evidences. The results show that by adopting this approach, produced water can be properly characterized, and it will be possible to determine the best approach for dealing with it. It indeed delivers a comprehensive platform for decision making and consequently pin-point recommendations that may help to establish the scientifically and workable solutions towards the management of produced water in Thar Jath (Block 5A).

3.3 Research Strategy

3.3.1 Quantitative Strategy

Employing a quantitative approach is important in the chemical and biological assessment of the produced water as mentioned in this study. This approach relies on the use of quantitative data collected through quantitative measurements and assessment and whereby statistics is used to analyze the results acquired. Quantitative methods makes the data meaningful, accurate and can be recorded more than once. In chemical characterization, it entails quantifying levels of contaminants including heavy metals, hydrocarbons and salts for instance through ICP-MS and GC-MS analysis test. In biological aspect, it is used to determine the number of microorganisms that are present in a sample and identify certain strains of microorganisms through DNA sequencing analysis and microbial culturing. Various statistical techniques are going to be employed in order to assess the data, in terms of some sort of pattern, association as well as variance. In this way, the quantitative approach helps the study to create accurate and statistical characterizations of produced water and qualitative analyses of its chemical and biological content that serve as a strong base to measure and analyze the efficiency of remediation approaches.

3.3.2 Experimental Analysis

The reason for an experimental analysis is valuable in measuring the performance of various remediation methods. This involves a process of experimentation where the physical, chemical and biological performance of produced water is tested under a set standard treatment program. Since the study has to compare different treatment methods, it has to vary a number of factors, including the concentration of the treatment agents and the treatment duration as well as environmental conditions, so that it can more easily identify the effects of each method. Pollutant concentrations before and after the applications of each technique will be documented to determine how effective the technique is. For instance, the experiments can be done using different materials such as the filtration media, chemical coagulations, or biological treatments involving bacteria and plants. Optimizing conditions mean that many factors are kept constant during the remediation processes, and therefore, the results obtained are purely based on the remediation techniques being studied. This approach contributes to the existence of strong, practical data necessary in identifying the most efficient treatments for use in the elaboration of enhanced remediation techniques.

3.3.3 Comparative Analysis

The analytical method adopted for comparison of the performances of the various remediation techniques for the treatment of produced water. Now, after data extraction by the experimental phase, the study will contrast the effect of physical, chemical, and biological treatments. The parameters to be compared will be quantified in terms of: the efficiency of pollutant removal, cost analysis, technical viability, and its efficacy on the environment. Comparative analysis encompasses the testing of statistical variables to measure variation in treatments to determine which methods are effective given specific circumstances. This approach is beneficial in terms of recognizing the results achieved by each approach as well as the strengths and weaknesses of each one. To give an example, a certain chemical treatment might be very efficient in removing specific pollutants while a biological treatment might be more environmentally friendly and economically efficient in the long run. Thus, the analysis of these features made it possible to determine the applicability of particular remediation methods for particular conditions and to suggest the major elements for the development of an efficient and comprehensive system for the treatment of produced water.

3.4 Data Collection Methods

The data collection techniques used in this current study are structured and will encompass various techniques in order to collect information on the qualities of produced water from Thar Jath oil field and the various techniques used to treat it. The field surveys are a crucial component in the primary data collection process, while the systematic sampling is useful for reaching the sample size. Site visits of oil field sites will be made for purpose of ascertaining how produced water is disposed of and if any measures have been employed in the treatment of the said water. To ensure contextual data is obtained, weekly visits to the targeted school will be conducted to capture any necessary contextual information. Close to the discharge sites, samples will be collected on systematic basis using symmetric sampling and the collected samples will discharged water along with properties such as chemical, biological and physical. This information will include flow documentation of the locations where the discharge happens, the effects caused to the wild lives, the conditions of the environment. Water, soil, and air quality samples will be occasionally collected for examination in laboratories concerning contamination and other factors of interest. Furthermore, tests will be carried out in order to find the most effective biodegradative technologies and local flora that can be used to overcome with the above-mentioned produced water.

3.5 Data Collection Process

3.5.1 Field Surveys and Site Visits

Primary data collection through field surveys and site visits can provide the first-hand information and background of the disturbing produced water discharges from the Thar Jath oil field. During site visits, specific site characteristics/issues will be documented in a systematic manner by the researchers. First, the time and date of each observation will be recorded to capture the temporal aspect of the obtained data. The location of each site will be identified with a greater accuracy by using a Global Positioning System (GPS) to obtain co-ordinates important for spatial applications. Moreover, the name of oil field and the necessary permit information will be recorded to identify the legal provisions concerning the discharge. The observations will include identification of the separators installed in the oil production process and the type of separators, which will help in discussing the few initial steps of handling the produced water. The total number of separation pits and size will be determined since the number and size of these pits dictate the overall capacity of the primary treatment in removing contaminants.

Observations of the environment will include indicators for pollution and the consequences it holds for the overall environment. This includes the inspection of the pits for sheen on the surface, which is suggestive of the possible contamination by oil. Oil in the pits will also be photographed/ videotaped and any measures put in place to keep away wildlife from accessing contaminated areas will also be evidenced. Several records shall be made by observers, including the number of wildlife carcasses (mammals, birds, amphibians and reptiles) in or close to the pits, live wildlife and/or tracks.

3.5.2 Systematic Sampling

The method of systematic sampling requires collection of water samples at several points downstream of the discharge outlets to get a holistic view of the effects on the environment. Both surface and subsurface samples will be collected from sites close to the discharge areas as well as from locations that are far off to incorporate the effect of dilution in the rate of dispersion and pollutant concentration. This approach makes certain that while sampling the landscape the impacts and conditions will comprise a strong data base for the study. Precise environmental conditions and characteristics will be collected to obtain a description of the environment at each sampling site. This is important to establish the type of wetland or stream where the discharge is to be let out because this can define the ecological structure of the respective habitat. The stream class, meaning a perennial or an intermittent stream, shall mention, since it influences the water flow and dilution potential. The degree of mixing of contaminated water with the wetland or stream will be quantified in order to determine the degree of impact reaching a specific distance from the discharge point.

Records of oil-stained soil and/or vegetation will be made as the sign of ground pollution. These observations serve to present an opportunity of realizing the effectiveness of oil pollution and its effects on land tendencies. Moreover, data on the nature of water and other characteristics such as the sheen or oil at the discharge and receiving wetland will also be captured to determine the level of impact of the discharge on the water bodies. Presence of wildlife or signs of its activity such as tracks, dung, etc, of the discharge and receiving areas will be recorded to get an immediate test effect. Therefore, systematic sampling enables the obtainment of detailed data that demonstrates the various environmental effects linked to the discharge of produced water. This information is important in the diagnosis and formulation of remedial measures for problems noted in ESI geometries.

3.6 Sampling

3.6.1 Water Samples

Water samples will be collected periodically from two primary sources: discharge pits that host the produced water and engineered wetlands which are for treatment purposes. The sampling frequency should be planned to reflect changes with time; for instance, water composition may change by the seasons owing to changes in operations or environmental factors. Several chemical and biological parameters will be measured in each sample in order to get more information on the produced water. Some of the analytes may include the chloride and sulfate ions since chloride gives an indication of the salinity of the water and sulfate depicts the likelihood of scaling formation. TDS will also be measured to determine the general salinity of the water sample since it depicts the extent of water purity in that particular site for discharge or reuse. Oil and grease content will be measured to check for hydrocarbons as well as other related compounds since they are known to have dire effects on the environment and health of living organisms.

This parameter will reveal the water's pH for its acidity or alkalinity, which influences pollutant solubility and danger. Components including lead, mercury, cadmium, and arsenic will be measured through methods like inductively coupled plasma/mass spectrometry because of their toxicity and non-degradable characteristics. If required, medical testing will include radioactivity testing, with the samples being tested for radioactive isotopes in order to evaluate any possible radiological risks. Given the nature of produced water, the study therefore seeks to achieve the following broad objective: To develop a good understanding of the quality of the produced water and its likely effect on the environment by analyzing water samples with a view of coming up with efficient measures for abatement.

3.6.2 Soil Samples

In order to evaluate the severity of contaminated soil and the impact on the terrestrial environment, the samples will be collected from the points in close proximity to the discharge points and from the areas located far from them. Sampling will be done in a GRS around the discharge areas to cover space data and to detect if there is a gradient in the concentration of contaminants. This will assist in identifying the patterns by which pollutants from the discharge point infiltrate into the adjacent soil. For the soil sample collected, physical and chemical attributes such as texture, Organic matter content, PH and nutrients will be determined. They are useful to know the initial state of the soil and how effectively it can support plant and microbial processes. Contaminant analysis for this study will involve disclosure of hydrocarbons, heavy metals and other materials that may have been delivered through the produced water disposal. Specifically, methods such as GC-MS and ICP-MS will be used to identify and calculate the presence of these contaminants.

Besides chemical testing of the samples, the soil samples collected would be tested for biochemical analysis in terms of soil biological activities, especially the population and types of microbial populations of the soils. This is important in the assessment of the ability of natural biological systems to remediate the environment. The traditional method of microbial enrichment and molecular methods of DNA analysis will be employed to obtain native microbial strains proficient in the degradation of pollutants. This study collects samples of soil at various sites and depths with the intention of constructing a comprehensive picture of the extent, distribution, and chronology of contamination and the ability of the ground to assuage contamination naturally. These data will be crucial for further preparation of specific approaches aimed at the improvement of soil quality.

3.7 Air Samples

In order to determine the airborne emissions and the impact of the produced water discharge on the aerial space, air samples will be taken nearby the discharge areas. Sampling will be done using air sampling pumps which are equipped with filters or sorbent tubes which is made to capture the pollutants within a wide range such as volatile organic compounds (VOCs), particulate matter (PM) and other gaseous contaminants. The sampling procedure will involve deploying air samplers at several locations within the discharge points, and further afield upstream and downstream locations with a view of ascertaining the dispersion of the pollutants. Sampling will be carried at different time of the day ad in different kinds of weather to be able to capture temporal variability and impact of the weather in dispensing pollutants.

The air samples collected will be analyzed chemically using techniques like; GC-MS for Volatile Organic Compounds (VOCs) and HPLC for semi-volatile compounds. The amount of particulate matter will be assessed gravimetrically and the characteristics of the specimens will be determined microscopically. These analyses will enable the identification of hazardous pollutants which may cause health effects to workers and the neighboring folks and whether they would influence the environment. In order to measure the levels of air pollution caused by produced water blow-out, the study will attempt to quantify the overall air pollution, determine which pollutants are most common in the air samples and how these compare to the recommended permissible exposure levels for both human health and the environment. These outcome values would be beneficial in offering the right strategy in air quality management and controlling measures in order to prevent the deterioration of human health and detriment of the environment.

3.8 Data Validation and Results Interpretation

It is important to learn how to validate data and interpret the results, as these are the steps which guarantee credibility of the research. Specifically, to ensure the end result is accurate, there are certain measures that will be taken during data collection and analysis: Quality control measures. These aspects include the calibration of instruments, following of standard operating procedures, and performing duplicate analysis to validate the observed results. Replicates are known to be the duplicate tests that are carried out on a similar sample to make sure that the results obtained are consistent. Any differences that may be observed during these replicates will then be investigated to either confirm or prove the existence of the observed differences.

Further detected outliers and errors will be established using statistical tools to determine the accuracy of the information taken finally. Once the input data has been verified, results will be processed and analyzed to draw conclusions pertinent to the chemical and biological properties of the produced water and the efficiency of the remediation processes. For an easy comprehension and presentation of the results, graphs, charts, and maps shall be used. These will aid in bringing out trends, relationships, similarities, and differences that otherwise could be difficult to portray. Graphical presentations will also be beneficial in assessing the performance of the various remediation methods under different scenarios to assist in the identification of ideal treatment processes. In conclusion, we can configure that strict data validation process combined with clear graphical outputs will improve the credibility of the study result and guarantee its reliability and usability.

3.9 Pilot Project Data Analysis

The specific objectives of the pilot project phase of the study are therefore to test the efficiency of bioremediation technologies and isolated bacterial species in the actual treatment of produced water effluents. This phase will entail deploying the most effective bioremediation techniques to be tested in the laboratory in filed exercises. The first aim will be the examination of temporal trends concerning the concentrations of these contaminants and the second purpose will be the evaluation of the efficiency of these treatment measures.

3.9.1 Field Monitoring and Data Collection

In the pilot project, frequent field surveys will be necessary in order to obtain the basic input data and samples from various sources within the treated areas. These comprises water samples collected from discharge point, engineered wetland, soil and air samples within the vicinity. This information will enable them to have a better understanding of the environmental conditions prevailing at the site, as well as the efficiency of bioremediation. Data will be collected through sampling and will be done systematically to allow for the determination of temporal trends as well as to enhance the credibility and reliability of gathered data.

3.9.2 Laboratory Analysis

The collected samples will be pooled and taken for analysis in the laboratory in order to identify the contaminated concentration. The analysis of chlorides, sulfates, total dissolved solids (TDS), oil and grease, pH, heavy metals and trace metals will be seen by applying standardized sampling techniques. Furthermore, microbial assessment of the samples will also be made in order to observe the functionality of the isolated bacterial species in the degradation of pollutants. This entails determining how the microbial density changes and from it, determine the specific changes that occur to microbial community composition.

3.9.3 Isolation and Testing of Bacterial Species

Culturing of bacteria and subsequent DNA sequencing for identification to species level will be carried out at the laboratory. The chosen bacterial strains will be later subjected to further laboratory experiments to analyze their possibility for bioremediation. These tests will comprise of exposing the bacteria to contaminants in the produced water, to assess their degradative capacity. Promising strains will be used for further testing in the context of the field pilot project.

3.9.4 Field Implementation

In the field it will implement the pilot project with the application of the selected bacterial species and bioremediation technologies to the affected sites. These may be the addition of fertilizers or specific microorganisms that will help in the degradation process such as bioaugmentation and adjusting the parameters of the environment to encourage growth of indigenous microbes such as bio stimulation. Daily sampling and chemical analysis of the contaminants will be carried during the field monitoring to determine the impact of the treatments on the contaminant levels.

3.9.5 Data Presentation and Analysis

The outcomes of the pilot scheme will be depicted via charts and graphs to ease conversation and assessment. These visualizations will focus on the patterns of reduction of contaminants, and it is something that will offer concrete proof of the efficiency of the bioremediation techniques. Advanced statistical methods will be employed to describe effectiveness of the treatment options, as well as to determine the best practices to implement.

3.9.6 Refinement and Optimization

Subsequent to understanding the pilot project outcomes, the remediation strategies used will be enhanced and adjusted. In this, we look at data to try and see which methods worked best and why this was so. It will be possible to discuss the type of contaminant, its concentration, the environment, and microbial processes. The idea, therefore, is to create a more effective, adaptable bio-cleanup system that can easily be implemented for use in cleaning produced water in such places.

The pilot project phase is estimated to be between 16 to 18 months to enable protracted observation of the treatments and any required modifications. Thus, upon the completion of this phase of the study, the following can be achieved: Development of a validated and operational bioremediation technique for the management of produced water contaminated environments.

3.10 Duration and Work Plan

3.10.1 Pre-assessment Stage

The first month of the research process is dedicated to the pre-assessment stage, during which the necessary preparations are made for the subsequent stages of the work. This phase shall involve the review of the existing literature on produced water, its properties and the available treatments. In this study, these sources will be analyzed by the research team to determine the state of knowledge and the potential gaps that this study can fill. Also, the team will scrutinize produced water regulations and policies that exist to ensure the study complies with the applicable legal framework and standards.

Another important point of this stage is establishing a comprehensive data gathering plan. This involves development of sampling strategies, estimation of sample volume, and choice of analytical methods for chemical and biological analysis. The approach will reflect the characteristics of oil field of Thar Jath including contamination type, climate of the area, and other limiting factors. Other preparations will also be made involving tools and equipment like GPS for site identification and laboratory instruments for sample tests. This stage leads to the formulation of a detailed research plan that documents the procedures, time frame, and resources needed for the field stage.

3.10.2 Field Stage

The field stage, which lasts for one month, is actually the most critical stage of the research since field work is conducted where hypothesis testing and preliminary analysis start takes place. In this period, after some time, samples of water will be taken at several stations following variation of the produced water discharge points to obtain different effects of water pollution. There will also be conducted simple observations at study fields to collect data concerning contemporary environmental situation: water.

Documentation will be done by the team and will include the general location of the site with help of GPS tracking system, physical effects having oil sheen, staining of the soil, and any visible sign affecting the wildlife. Samples to be collected will be tested for certain aspects like chlorides, sulfate, TDS, oil& grease, pH, heavy metal and traces metal also, biological studies will involve the ability to isolate and identify native bacterial strain with bioremediation capabilities. All these cumulative data will help in assessing general environment status as well as contamination levels necessary to determine the effectiveness of different remediation strategies going to be implemented in the next phase.

3.10.3 Post-assessment Stage

The post-assessment stage is carried out in the third month after implementing the CBA, aiming at data collection and synthesizing, analysis and recommendation. In addition, the gathered data for this period will be critically analyzed and given a detailed interpretation so as to determine the degree of contamination and how efficient various methods of remediation are. This kind of comparison will be kept up to assess the benefits and demerits of physical, chemical, and bio-based treatments in response to the stipulated physical environment of Thar Jath oil field.

Charts and graphs which are effective means of presenting trends and other findings in simple manner will be made during the discussion and analysis of the results. It will also require the identification of critical issues and limitation of the remediation techniques, along with issues on its applicability, feasibility, and sustainability. It will also be important to provide other useful recommendations for improving the local environmental conditions by implementing the effective remediation measures adapted to the conditions of the specific regions and the production water samples.

The last step of this stage is to prepare the thesis and present it to the chair. The thesis will incorporate all phases of the research procedure, outcomes, and recommendations regarding the remediation techniques and their rationales. As a result of the study, by the end of this stage, the study will propose practical measures that could reduce the contamination of produced water, which will be useful contribution in the area of environmental protection and restoration.

3.11 Work Plan

Duration and Plan of Work

Schedule of thesis activities

Year 1:

No	Month / **Activity**	1	2	3	4	5	6	7	8	9	10	11	12
1	literature survey & collection	■	■	■	■	■	■	■	■	■	■	■	■
2	Methodology identification		■	■									
3	secondary data processing				■	■	■						
4	Review & discussion with Supervisors							■					
5	Editing and progress report								■	■			
6	Reviewing report										■		
7	Planning for next phase											■	■

Year 2:

No	Month / **Activity**	1	2	3	4	5	6	7	8	9	10	11	12
1	Field data collection & analysis	■	■	■	■	■	■						
2	Review produced water remediation technologies							■	■	■	■		
3	Review & discussion with Supervisors											■	
4	Feedback & planning for next phase												■

Year 3:

No	Month / **Activity**	1	2	3	4	5	6	7	8	9	10	11	12
1	Modelling the technique	■	■	■	■	■	■						
2	Writing up the thesis							■	■	■	■		
3	Review & Editing											■	■

Chapter 4. Environmental setup in Thar Jath operations (Sudan)

This chapter entails the operation manual for Thar Jath operations in Sudan and investigates the crucial aspects of the environmental setup. This part offers so much on different critical components required to initiate and sustain an environmentally friendly operational system in the area. It has many subheadings, which are as explained below, each carrying a different component needed to minimize the adverse environmental effects for the area and ensure proper compliance mechanisms with the stipulated regulations.

4.1 Geographic Location

The geographical background of Thar Jath undertaking in Sudan is therefore the basis of appreciating environmental consequences and prospects of the region. Thar Jath lies at the north of South Sudan central region, in the larger Upper Nile area (Thor, 2019). The climate system of the area is a major factor which is determined to be of the type that is semi-arid with influence from the wet and dry seasons. For Thar Jath the wet months are from May to October when the area receives a considerable amount of rainfall which, relative to a desert environment, ‘floods’ the area while filling up water sources. Wet season experienced in the region from May to October is characterized by cooler temperatures and plentiful rainfall causing floods while dry season is experienced between November and April characterized by hot and dry conditions in the region which lack adequate rainfall to support human and animal consumption (Ruach, 2015).

The geographic features of Thar Jath in terms of the ground surface feature include broad extensive flat region with frequent savannah grasslands occasionally by broken wooded and scrub lands. It has seasonal river and streams running across the region from the northern part to the southern part of the region and these are of great importance to the lives of both human and animals. These water sources help in supporting aquatic lives within the region and generate income through agriculture especially during the dry season when water from the surface sources is depleted (Tai et al., 2021).

The plant and animal life of Thar Jath give stunning testimony to the coping models of the semi-arid zone. It consists of a variety of vegetation comprising of plants that are well adapted to water scarcity such as the Acacia trees, cacti, thorny bushes, and short dry grass. These vegetation types are pivotal in supporting the wildlife population as well as their feeding ground; the wildlife comprises antelopes, gazelles, warthog, birds of various kinds, migrating birds, and raptors among others (Benansio et al., 2022).

Knowledge of these specific environmental characteristics is crucial in developing practical means of avoiding potential ecological interference inhering with the operations of Thar Jath. Given the climatic conditions of this region, namely the semi-arid climate and irregularity in precipitation, the sustainable management of water resources and the introduction of water-saving technologies and activities along with improvement and development of resistant methods of agriculture becomes crucial. Furthermore, insecurity of ecosystem and wildlife bear the aspect of habitat and good biodiversity as critical factors to be worked around by operations (Altinbilek, 2020).

Moreover, it is important to note that geographical implications of Thar Jath are also tied with planning of infrastructural projects as well as the transport systems. The topographical characteristics within the region are quite flat, allowing for ease of road construction and other forms of infrastructure development; however, seasonal patterns of flooding and erosion are limiting factors on the sustainability of such development initiatives. As with the other constraints, transportation may also be hampered, especially where there may be some tracks that are inaccessible during the rainy season, and this will need to be closely managed and avoided (Raiter et al., 2018).

Some of the environmental factors that form the geographical context related to Thar Jath operation include; landform/ terrain, climate, vegetation and they types of animals present in the Sudan. Knowledge of these peculiarities is critical to responding to possible sources of bio-interference and, therefore, the optimal protection of the threatened species; effective water management; preventing and preventing the depletion of bird, mammal, plant, fish and other species; and addressing the issues of constructing new roads, bridges, and other facilities, as well as the delivery of resources to them. Therefore, by applying such information into the formulation of operational practices, the Thar Jath operations' aim can be achieved to undertake all their activities with minimal impacts on the environment (Mukherjee, 2021).

4. 2 Environmental Risk Assessment

The Environmental Risk Assessment section of the operations manual for Thar Jath in Sudan play a significant role in evaluating various potential environmental risks posed by operational activities in a given area (Fallet, 2010). In systematic analysis, the operational team always seeks to avoid and control the difficulties likely to be caused by the environment in order to provide sustainability and conservation of resources.

Environmental risk assessment involves identification and evaluation of various risks with emphasis on air and water pollution being one of them. Some of the activities include industrial process, transportation, and even discharging waste can emit polluting substances in to atmosphere and water sources, which are dangers to the life and habitats of living organisms (Paustenbach et al., 2024). To address these liabilities, assessment identifies risks of pollutant generation, its distribution, and vulnerable targets, before ascertaining probability and severity of environmental effects. Action steps listed to address pollution include utilizing emission controls, adopting treatment for wastes, and having protocols for monitoring and maintaining the quality of the air and water.

Another typical aspect the assessment focuses on is the degradation of the soil as another environmental threat. Implementation of Land clearing, farming and construction for instance may result to loss of soil structure, example erosion, compaction of land, decline in nutrient capital and hence reduced productivity of the soil in question and degrading the health of ecosystems (Nweke, 2019). The assessment reveals areas that are likely to experience soil degradations, determines key factors that point at such chances, and proposes ways of implementing soils conservation measures like ways of controlling erosion, regeneration of vegetation, and reasonable utilization of the lands. Conservation of rangelands and wise practices for better management of Thar Jath can prevent or reverse current trends of soil degradation and contribute to sustaining terrestrial ecosystems.

Another important component looked at in the context of the environmental risk assessment is the loss of biological diversity in Thar Jath since it is one of the areas that has a diverse bio-diversity. The activities that take place in the habitat like destruction of these habitats, cutting down trees for timber, and disturbing the wildlife might work towards extinction of the species and disruption of their habitats. The assessment involves determination of the extent to which operational activities may affect biodiversity of the area through factors such as the loss and fragmentation of the habitats and displacement of species. Solutions to reduce species annihilation may involve activities such as:

Conservation of natural habitats, protection of endangered species, and afforestation, which will be addressed in the section of the manual focused on biodiversity conservation (Di Sacco et al., 2021). The Thar Jath activities also impact on sustainability through the respect of distinction between ecosystems by preserving species diversity as well as protecting several habitats.

Furthermore, the environmental risk assessment evaluates possible effects of operation actions and solutions on people and their surroundings in organizational socio-economic, cultural, and health. The operational processes of mining or any involvement in land, enhancement of resource through extraction and infrastructure development impact almost all aspects of the cultural and economic life of a community. It comprises the findings of consultations conducted with the communities with specific regard to the advantages and disadvantages of the government’s proposed polices with special emphasis on; … outlined needs and concerns of the communities through community consultation and involvement, strategies to improve the government’s take-up of measures that would promote community involvement and socio-economic development. Thus, community concerns are met and important insights into the operations are incorporated into the decision making at Thar Jath, with the goal of developing and maintaining a positive relationship with the communities, and the achievement of successful and sustainable developments.

4.3 Biodiversity Conservation

Lack of bio-diversity conservation in Thar Jath, Sudan is an essential element of sustainable development since it affects the status of the ecological system of Thar Jath besides affecting the social well-being of the people who live in Thar Jath. In this regard, the operations manual explains several measures in Thar Jath that are applicable in an effort to preserve and prevent the damages that negative impacts of overall operational actions in the region.

Comprehensive conservation of habitat forms one of the central methods of biodiversity conservations that has been presented in the manual. This will involve protection of ecosystems that are bio-diverse or feeding grounds for all forms of plant and animal life. Some of the important areas where the focus should be placed on the preservation of habitats may include wetlands, some areas of riparian, or areas with high species density known as hot spots. Selecting these areas as protected area or a conservation reserve will greatly help in Thar Jath operations to avoid deforestation and thereby minimize habitat fragmentation which possess threats to the existence of biological diversity (Saha et al., 2021).

Concerning the challenges of conserving biological diversity, the protection of endangered species is identified as another topic covered by the manual. Many species of different animals that are listed here as endangered or threatened reside in Thar Jath wildlife Section, and major attractions are Nile crocodile and the African elephant. In order to address the current situation, the manual suggests employing specific methods of protecting the above-mentioned species, including rehabilitation and restoration of their habitats, fighting against poaching and hunting and involving communities into conservation. Hence, through ensuring the protection of endangered species /habitats as part of social responsibilities, Thar Jath group supports the overall cause of conservation of Biodiversity across the region of the world (Bianchi et al., 2022).

These efforts thus, help in forest regeneration reducing the factors that hinder positive growth for the plant and animal societies. Thar Jath operations may include afforestation activities of local tree species in parts of the landscape, which are threatened by deforestation, soil erosion, or other forms of land degradation. Is another tool that assists with controlling the emission of greenhouse gases with, inter alia, the focus of afforestation being on carbon storage, preventing climate change, wildlife conservation, improving fertility of the soils, and increasing the stability of ecosystems. These analyses demonstrate that Thar Jath is improving the provision of ecosystem services and sustaining the biological diversity in the area through the provision of reforestation initiatives in daily operations.

Periodic assessment of biodiversity information is also required for decision-making and to monitor the effectiveness of conservation actions taken. Thus, by the systematic documentation of species composition, abundance, and distribution, Thar Jath operations will be able to identify priority areas for conservation, evaluate the effect of operational activities on biodiversity, and monitor changes in ecological community structure over time. Such assessments are valuable as they provide a perspective of software that leads toward the biodiversity status of Thar Jath in guiding all conservation planning and adaptive management strategies for less disruption of habitat and fewer impacts on local ecosystems.

4.4 Water Resource Management

Thar Jath is an operation of arid climate and water resources; water resource management is thus the very heart of its activities in maintaining the area's ecosystems, agriculture, and human support. This section of the operation manual discusses the various factors concerning water resource management: applied strategies of protection, efficient practices in its use, mitigation of pollution, and the role of community engagement and stakeholder collaboration (Lado, 2021).

First and foremost, the handbook points out the importance of water conservation measures in alleviating the consequences of water scarcity and guaranteeing the sustainable use of the available water resources. There are very distinctive wet and dry seasons at Thar Jath; thus, during the dry season, there is very little rainfall that aggravates water stress and scarcity. To tackle this most pressing challenge, the operations team is urged to apply water-saving methods, such as rainwater harvesting and drip irrigation, and recycle water at source. In a similar manner, wastewater recycling abides by the same tenets as conserving a natural resource through its use in an alternative application—otherwise known as irrigation, industrial production, and general cleaning, thus effectively minimizing freshwater use and pollution. Drip irrigation spreads the water through the root surface of a plant, which substantially reduces the loss of moisture by evaporation, minimizes hoteling, and maximizes efficiency in agriculture. With these described conservation measures, Thar Jath's operations are to maximize water use, reduce waste, and optimize water resilience in the face of changing climates (Tree, 2020).

Other essential components of water resource management in Thar Jath include effective water use practices. The report emphasizes optimizing water use for agriculture, industry, and the domestic sector. These activities include drip irrigation, sprinkler systems, and monitoring soil moisture, which helps in reducing the losses of water and improving the efficiency of water productivity in crops. Besides, in industries, the incorporation of water-efficient technologies and processes - such as a closed-loop system, the recycling of water, and using water-efficient types of machinery - has decreased water use and minimized the amount of wastewater generated. The other technologies applied in the domestic sector include low-flow faucets, water-efficient equipment, and fixtures with educational programs for water conservation - which help change people's behavioral patterns toward a responsible use of water. The Thar Jath operations can reduce pressure on the water resources, enhance water security, and further reduce risks of a water shortage and conflict by bringing efficient water use practices across all the sectors.

Another significant issue in water resources management in Thar Jath is pollution abatement. The manual acknowledges potential sources of water pollution like industrial discharge, agricultural runoffs, sewage effluents, and solid waste disposal that degrade the water quality and pose a possible threat to human health and the integrity of the ecosystem. To overcome such obstacles, the operations team is recommended to devise pollution prevention up to the feasibility of it. It includes source control, treatment technologies, and pollution monitoring enforcement. Source control is the identification and elimination or minimization of sources of pollutants at their origin, basically through the incorporation of best management practices in agriculture, upgrade of industrial processes for the reduction of pollution, and proper waste management to prevent the contamination of water bodies. Treatment technologies, for example, wastewater treatment plants, constructed wetlands, or natural filtration systems, among others, remove pollutants from wastewater before releasing it into water bodies, thus protecting the quality of the water and the aquatic ecosystems. In addition to the physically visible actions required, pollution monitoring and enforcement mechanisms, like water quality monitoring programs and regulatory standards for compliance inspections, ensure that the measures to prevent pollution are effective on the ground and implementers are held accountable.

Some of the key principle underpinning community engagement and stakeholder collaboration in water resource management initiatives, including socio-economic development, cultural values, and the community's well-being at Thar Jath. This manual recognizes that water resources are linked with socio-economic development, cultural issues, and community well-being. The involvement of local communities and stakeholders in the decision-making process becomes significant for proper water management. In this regard, community engagement can be done in the following ways: awareness campaigns, participatory planning, capacity-building initiatives, and collaborative governance structures for empowering local communities to take ownership of water resources and its management and conservation. However, stakeholder collaboration involves forging partnerships and alliances among different actors—government agencies, nongovernmental organizations, the private sector, and civil society groups—to mobilize resources, share knowledge and experiences, and coordinate actions towards common water management goals. Community participation and stakeholder collaboration will help to build social capital, trust, and cooperation in the Thar Jath operations, and through this, they will be able to get more equitable and sustainable outcomes in water resource management.

Water resource management is essential in Thar Jath operations. It prioritizes it appropriately because the area is arid and dependent on water for life support systems of the ecosystem, agriculture, and human livelihoods in the region. This section of the operations manual shall outline the importance attached to various water conservation measures, efficient use of water practices, mitigation strategies of pollution, community engagement, and stakeholder collaboration in ensuring the sustainable management of water resources. Applying these principles to Thar Jath operations with the right interventions will ensure water resilience, water quality, and safeguarding the health and well-being of local communities and ecosystems for years to come.

4.5 Waste Management

Environmental assessment at Thar Jath considers waste management given an operation that should be effectively conducted to reduce pollution, not endanger the environment, and, in the end, should be a fine protector of the environment. This section of the manual describes the types of wastes that operational activities result in, mainly solid waste, wastewater, and hazardous materials. It also explains how to reduce, reuse, and dispose of these wastes to attain environmental friendliness.

The management of solid waste is considered one of the fundamental concerns in Thar Jath operations since incorrect solid waste disposal can lead to pollution, habitat destruction, and risks to public health. The source identification for different activities of operations that result in solid waste generation is identified or mentioned clearly in the manual, including the packaging materials, construction waste, and household waste. It suggests reducing, reusing, and recycling measures to mitigate waste.

Source reduction minimizes the amount of waste from its source through process optimization, reduction in packaging, and stimulation of sustainable consumption. Reuse could be in the form of materials being made to serve their purpose for a longer time using repair, refurbishment, or the finding of another assignment of substantially reduced raw material inputs and resulting waste. Recycling is collecting and processing recyclable materials—paper, plastic, glass, and metal—for remanufacturing. It helps sustain the environment by conserving resources and reducing landfill space. The operations in Thar Jath aim to work according to a closed-loop economy principle, where resources are used and re-used at their maximum recycling point to leave an almost negligible environmental footprint.

Wastewater management is also an essential area of waste management for Thar Jath operations because of the relevance and need for water resources in this dry climate zone. The report recognizes that these operational activities can generate significant effluent volumes from industrial processes, agricultural practices, and domestic sewage containing several pollutants, including organic matter, nutrients, and pathogens. This is addressed by the treatment in wastewater treatment systems recommended in the manual. That is, it suggests the removal of pollutants to discharge or reuse adequately treated water. Further, treatment technologies like biological treatment, physical-chemical treatment, and advanced oxidation treatments are recommended to remove contaminants from wastewater.

It further focused on the importance of implementing decentralized treatment systems for wastewater, such as constructed wetlands and decentralized treatment units, to provide cost-effective and sustainable solutions for remote areas where centralized infrastructure may be impractical or unattainable. Investment in wastewater treatment infrastructure and responsible wastewater management practices would help protect water resources and public health by minimizing pollution risks.

Hazardous waste management is an essential segment of the waste management plan related to Thar Jath operations, as improper handling and disposal methodologies of dangerous materials may bring potential risks to human health and the environment. The manual aims at identifying the hazardous materials ordinarily used in operational activities: chemicals, solvents, fuels, and pesticides that can pose risks such as toxicity, flammability, corrosiveness, or reactivity. According to the manual, some hazardous waste management practices to be implemented include dangerous waste identification, segregation, storage, transportation, treatment, and disposal. This is important in the sense that it involves identifying and categorizing dangerous materials within the regulatory standards and guidelines so that it ensures a proper handling system and safe storage and disposal system.

Segregation: The isolation of hazardous waste from non-hazardous waste prevents contamination and facilitates safe management. Storage: Involves storing dangerous waste in designated areas, but within appropriate containment measures, to prevent the spilling, leaking, or release of such wastes. Transportation: Entails the transportation of hazardous wastes from generation points to treatment, storage, or disposal facilities. Treatment may be defined as the process of reducing the toxicity, volume, or mobility of hazardous wastes before their disposal by incineration, chemical treatment, or physical treatment. Disposal can be defined as doing away with hazardous waste appropriately under the law, for example, landfilling, deep well injection, or unsafe waste land treatment. The practice for the management of hazardous waste at Thar Jath shall ensure human health is safe, prevent the environment, and comply with the held regulatory requirements for the management of such wastes. Consequently, besides ensuring environmental cleanliness and waste management, the Thar Jath operation will need to put appropriate management practices in place that will prevent pollution and minimize environmental degradation. This section of the operational manual also picks up on reasonable strategies to emphasize waste reduction, recycling, and disposal to achieve ecological sustainability. This practice, if affected within the Thar Jath operation, will reduce ecological footprints, save natural resources, and provide a much cleaner and healthier environment for people and posterity.

Community engagement is a vital component of sustainable development and environmental stewardship in Thar Jath, Sudan. This section of the operation manual complements that by ensuring efforts to develop sound and sustainable relationships with local communities are respectful of their knowledge, values, and needs within the decision-making process and promote joint approaches toward problem solutions for sustainable development results.

Community consultation is the backbone of effective community engagement in Thar Jath operations.

The contention from the guidebook is that communities should be consulted in every stage of project planning, implementation, and review. Their voices are heard, their concerns are addressed, and their interests are attended to through such consultation processes. This could be done through community meetings, focus group discussions, participatory workshops, and stakeholder forums, which will provide an opportunity for the community members to express their opinions, give feedback, and make suggestions on the activities of the projects, the priorities, and the outcomes envisaged to be achieved. Communities are also engaged through dialogue and consultations, ensuring that Thar Jath operations have meaningful community engagement that increases trust and transparency about environmental initiatives, besides enabling shared responsibility with the communities in working towards a common goal. Another principle that underlies community engagement efforts at Thar Jath operations is participation.

The manual recognizes that participation is meaningful when local communities are empowered and have a say in decisions, as well as taking control of projects and initiatives in planning, implementing, and monitoring the activities of the environment. Such mechanisms might be put in place within community-based organizations and user groups, even cooperatives, formed as an underlying strength to members wherein resources may be mobilized, and knowledge and skills are shared towards collective work on environmental projects and activities. Such ownership and accountability for more sustainable and locally relevant environmental outcomes catalyze greater realization of the social capital associated with community involvement in Thar Jath operations. Building capacity is vital to providing empowerment for local people in the engagement of environmental stewardship and sustainable development activities.

This points to investments in capacity-building programs that empower community members with knowledge, skills, and capabilities to appreciate, manage, and mitigate environmental challenges properly. These may include activities such as training workshops, educational programs, initiatives of skill development, and technical assistance services given to community members on the handling of environmental issues and the uptake of sustainable practices. By building local community capacity, Thar Jath operations can empower locals to take control of their development processes, leading to more resilient, self-reliant, and environmentally conscious communities. Environmental awareness is essential in letting local communities have a buy-in culture of environmental protection.

The manual identifies that long-term environmental goals must include the raising of awareness in environmental issues, the promotion of sustainable practices, and development among community members of a sense of environmental responsibility. Awareness-raising may involve community education programs, public outreach campaigns, environmental workshops, or information dissemination initiatives which provide access for community members to relevant information, resources, and learning opportunities related to environmental problems as well as solutions. Environmental awareness supported by operations in Thar Jath could bring a behavior change, build consensus toward ecological endeavors, and develop a culture of sustainability within the communities. The livelihood opportunity support also forms an integral part of the community engagement program in operations at Thar Jath.

The manual accepts that sustainable development can only be achieved when the socio-economic issues get taken into account and the local communities' livelihoods are uplifted in means that respect environmental conservation principles. Such initiatives can come in the form of income-generating activities, micro-enterprise creation schemes, access to vocational training, initiation of sustainable livelihood projects leading to alternative income generation; all these work towards economically empowering community members and making them resilient. As such, livelihood support in Thar Jath operations can uplift the socioeconomic well-being of local communities, reduce the rate of dependency on the exploitation of natural resources, and increase community resilience to environmental shocks and stresses. Positive relationships with community stakeholders will create trust and encourage cooperation at Thar Jath operations that deliver mutual benefits.

The guidebook insists on building and maintaining strong links of partnership with community leaders, traditional authorities, local institutions, and other stakeholders so that environmental initiatives can be in synchronization with the priorities, values, and aspirations of communities. Building positive relationships requires open communication, mutual respect, and a willingness to listen and learn from community perspectives. Engagement with the community stakeholders is also expected to create an enabling environment for environmental initiatives among the Thar Jath operations and further enhance social cohesion and resilience to environmental challenges. In summary, community engagement is believed to be one of the critical drivers for promoting environmental stewardship and sustainable development at Thar Jath, Sudan.

This section of the operations manual elaborates on the importance of community consultation and participation, capacity building, environmental awareness, and livelihood support, such as developing positive relationships with stakeholders in realizing environmental objectives and building a culture of sustainability at the local level. By meaningful engagement, Thar Jath operations will harness local knowledge and expertise, build social capital, and empower the local community to become an active partner in the development of environmental conservation designs and efforts towards sustainable development for the benefit of the present and future generations.

Chapter 5 Theoretical Framework

5.1 Introduction

The Theoretical Framework chapter will present the theoretical foundation of this study, especially identifying existing theories and models related to produced water (PW) treatment. Scientific authority, technology, and regulation come under scrutiny in this chapter to understand methodologies utilized in PW management. Through analyzing the mechanisms of biological and physio-chemical processes of treatment, the framework is designed to compare enhancing and inhibitory impacts of applicability of the treatment technologies. This analysis is significant in the sense that it establishes the methodology to untie the intricate rationales and processes of PW treatment to design effective and feasible solutions.

5.2 Mediterranean Region

The article by Bellefontaine et al. (2016) which is also from the series of "The Handbook of Environmental Chemistry" focuses on the important problem of oil transportation at sea and its possible consequences for the environment. About the importance of the shipping industry, they stressed the necessity of sea transportation in the global economy with reference to the constantly high demand for oil as the product which finds a wide application in various industries. The authors mentioned that although there has been a slight reduction in the occurrences of oil tanker incidents, oil accident spills are still a topical issue especially because of their randomness and their ability to have severe impacts on the environment.

This process involved analyzing of some of the major oil spill events including the Torrey Canyon, Amoco Cadiz and Exxon Valdez and emphasized the lack of contingent national plans. The authors highlighted that operational spills can easily dealt by following strict regulatory measures but accidental spills need a distinctive approach since they are probabilistic. They pointed out that another growing idea called 'oil spill intervention' which involves preparedness even before a spill and immediate containment when a spill happens, which countries in North America are currently researching on.

The theoretical foundation used in this study centered on comparing the national actions occurring in Mediterranean States with the international laws in reactive immediate response and intervention. The authors pointed out that while the Mediterranean has seen little in the way of big oil Blowouts, with the volume of traffic shipping only set to rise, governments need to be keener and the plans to deal with the disasters faster. They encouraged Mediterranean States to reconsider and possibly reinforce their current thirty-year action plans as regards intervention and protection of the marine environment. In their study Bellefontaine et al. asserted that previous happenings have proven the need for such measures aimed at reducing the costs of oil spills in the maritime sector.

Angela Carpenter and Tafsir Johansson's study of 2018, in the series of The Handbook of Environmental Chemistry also discussed the issues related to oil spills in the Mediterranean region. They focused on the negative effects, such as stating that an oil spill be considered an ecological catastrophe leaving significant consequences on the aquatic world. The authors also assessed the Barcelona Convention and its Protocols, pointing at the IR as the soft law that can be used legislatively to address the issue of oil pollution. This framework fosters cooperation among the coastal states in the assessment of measures for the prevention, elimination, and reduction of oil pollution. The study exemplified the importance of maintaining the frequency in addressing options to address oil pollution risk and its overall benefits to operations and disadvantages on the environment.

In the current study, the theoretical framework constituted in a legislative review of the Barcelona Convention, and Its Protocols. To investigate these development, Carpenter and Johansson reviewed how these documents have been used to lay the foundations of coordinated political actions with Mediterranean countries. They also discussed the idea that overall management of oil pollution additionally involves shared participation and immediate actions by coastal regions. About the protocols, the authors presented a rich analysis with relevant suggestions on how to safeguard and maintain the Mediterranean marine environment, non-polluted by oil. It was developed for the purpose of having a broad strategy and blue print with regard to oil spill, and in the process, it was expected that there would be a common strategy under taken in both preventing as well as responding to such a disaster.

In their study, Carpenter and Johansson (2018) affirmed that the Barcelona Convention, alongside with Protocols, can be viewed as invaluable instruments for the Mediterranean states as it offers the adequate framework for collective actions towards efficient oil pollution combating. They were describing the utilization of those legislative instruments in combating oil pollution, pointing to the fact that achieving strong positive outcomes could only be realized on the level of the nation.

The Barcelona Convention and its Protocols play an important role of being a means through which Mediterranean states can address the issue of oil pollution and the conservation of the marine environment. Designed to overcome some of the specific challenges of the Mediterranean Sea area, these legislative measures offer a common legal platform to ensure coordinated measures were taken to prevent, minimize and combat oil slicks. The Convention is a part of a system of regional treaties that entails legally binding obligations and cooperation between different Mediterranean states in the effort to maintain the ecological integrity of the Mediterranean.

The Convention also has several protocols that deal with controlling marine pollution from different sources, whereby some of them include: They have provided comprehensive information on how preparedness and response to oil pollution events should be done covering every state and calling for swift and coordinated response. The stricter measures developed and advocated by the Protocols aim at making states ready to respond to both operational and accidental oil-spills through improved national contingency plans.

The authors, Carpenter and Johansson, have pointed out that through the Convention, is an avenue through which regional cooperation has to be enhanced due to the interdependency of marine ecosystems. They contended that participative leadership in implementing the Convention and its Protocols at the national level can improve the Mediterranean states' capacity for combating the effects of oil pollution. Furthermore, these tools enhance the distribution of resources and information that is vital in swift and efficient intervention of pollution events.

The "Protocol Concerning Co-Operation in Combating Pollution of the Mediterranean Sea by Oil and other Harmful Substances in Cases of Emergency" was accented in the 1976 Barcelona Conference of Plenipotentiary of the Coastal States of the Mediterranean Region thereby acknowledging that both major oil spills and on-going minor spills adversely impacted the economic activities and marine environment of the Mediterranean states. It prescribed exact roles of the signatory nations in committing to technical cooperation and exchanging information and emergency communication, including through third parties even in the absence of direct contractual relations.

Accordingly, the desired goals of the protocol were to be backed by Resolution 7 due to the formation of the Regional Oil Combating Center (ROCC) for Mediterranean Sea. These requirements include the gathering of data relating to technical capability, clean-up equipment and materials, and help in the formulation of national contingency plans; and co-ordinate the states' plans, strategies, and activities in the handling and management of massive spillages. Practical experience in the mitigation of the effects of pollution was sought in several aspects such as training programs and technical assistance from states that had prior experience in handling spill cases.

However, different perceptions towards contingency planning were reasons why the ROCC was challenged at times. Several nations, especially the industrialized ones in the northern-tier Mediterranean, which are more exposed to potential oil spills, favored the additional planning to improve the spread laid out for how a country should monitor, prevent, and rectify an incident. They also wanted to avoid diluting their national sovereignty to be dismissed from participating in ROCC activities in dealing with the damages inflicted by spill to their national interests or properties as highlighted by (Boxer, 1972).

There are comprehensive intergovernmental plans and cooperation permanently in prospect for Mediterranean Sea oil spill contingency and response through United Nations Environment Program (UNEP) and an Inter-governmental Maritime Consultative Organization (IMCO). Essentially, this paper evaluates technical and institutional issues of coordinating national needs and capabilities with international commitments of Mediterranean coastal countries in compliance with the freshly enacted 1976 Barcelona Convention. Problems include: problem areas include: definition of the coordinating role of the Malta-based Regional Oil Combating Center for the Mediterranean Sea, which is supported by UNEP and administered by IMCO; uses of the test results achieved through monitoring of oils and petroleum hydro carbons in regional anti-spill prevention and emergency plans; jurisdiction as a component of coastal state regulation and enforcement rights; and inability to agree on some technical considerations essential for planning and responding to oil spills due (Boxer, 1972).

Both, UNEP and IMCO have thus effected a new factor in major international efforts to plan for and react to major spills with the establishment of the ROCC. The effectiveness of the ROCC in achieving the targets set by the treaty in Mediterranean is an indicator of the useful of the international agency contribution in contingency and response planning. This is because following the attempts made by UNEP in other “regional seas” areas to foster intergovernmental cooperation with similar institutional mechanisms that are solely intended for governance and coordination functions (Boxer, 1972).

5.3 Kuwait Region

Darabinia and Nagafi Asfad (2012) highlighted that the effectiveness of the 1978 Kuwait Regional Convention for Co-operation on the Protection of the Marine Environment from Pollution in the Persian Gulf was the focus of the study in the research. It is a conven-tion signed by Iran, Saudi Arab-ia, Kuwait, Iraq, United Arab Emirates and Qatar that has as its goal to pre-vent and posi-tively suppress the mar-ine pol-lu-tion resulted from oil exports. When analysing data on pollution incidents, the authors relied on the official records and evaluated them with reference to global sea pollution rates. A computer package for statistical analysis was also employed in the analysis of the collected data.

Findings indicated that relatively, the rate of pollution by oil in the Persian Gulf was less than in the world but increased in 1983 and 1991 as a result of conflict. Preliminary evidence shows that pollution rates during 1978-1982 and 1984-1990 were significantly lower compared to most parts of the world. Still, the pollution rate rising to 63. 63% especially in the two wars in the Persian Gulf (Darabinia and Nagafi Asfad, 2012).

In this respect, the study brought out the fact that the Kuwait Regional Convention was not capable of handling pollution issues whenever oil infrastructures and tankers were targeted. That was because the convention lacks either a protocol rider that will act as a deterrent to member states from attacking oil related installations during conflicts or agree on the emergency operations to protect them.

This theoretical perspective utilised in this study comes from exploring an assessment of international environmental agreements within the global context and the extent to which they prevented pollution. Although the authors elaborated on the impact of Kuwait Convention on the regional control and measures towards pollution, as well as the necessity for better protocols towards the war pollution. Using this framework, it was possible to assess the success or lack thereof of the convention as well as get an understanding of the areas in which it was implemented poorly (Darabinia and Nagafi Asfad, 2012).

The specific research interest of Dr. Talal Aladwani is in the aspects of international treaties and conventions that deal with the issues of preventing the pollution of the sea and the protection of life at sea. The paper categorizes these agreements into five types: Those involved in decisions on construction and maintenance of the infrastructure, crew training and competency, safety management measures and personnel, civil law liability, and criminal responsibility and penalties. These various agreements were explained by Aladwani in ways to prevent human and technical mistakes in sea transportation and save the marine environment.

The study used an organisational theoretical perspective that placed emphasis on regulatory compliance and standardisation. It looked at the impact of what remains as a series of specific requirements that the ship owners and operators must adhere to in order to avoid mishaps and contamination. Aladwani pointed out both weaknesses and discrepancies in the existing conventions noting that international coordination towards prevention of marine pollution could be further enhanced by a universally structured instrument. This framework considers the necessity of the international coordination of measures that involve prevention of marine pollution in order to be able to maintain equal standards across the international border.

Aladwani also stated that if there are many agreements present, their effectiveness is not so due to dispersion. Through the call for one universal convention, the study stresses on the need for coherent and international rules and regulations necessary in preserving several aspects of the marine environment.

One of the important agreements in place that safeguards the management and elimination of hazardous wastes across the relevant member nations is the “Protocol concerning Marine Transboundary Movement and Disposal of Hazardous Wastes and other wastes” under the

ROPME. This protocol was negotiated in 1998 and later came to be packaged and ratified by these member countries in the interest of controlling and curtailing the movement of hazardous wastes across their borders with a view to saving the marine environment in the ROPME Sea Area (ROPME, 1998).

The framework provides detailed procedures and standards for handling, transport and disposal of hazardous wastes to avoid pollution and negative impact to health of marines. This sets up a clear legal and working framework of the actions and steps that are within the confines of the law that each member nation is supposed to undertake in order to conform to international environmentalism and work within a framework where intergovernmental cooperation is encouraged (ROPME, 1998).

This is one of the most important aspects of the protocol where the contracting parties have agreed upon the principle of not exporting hazardous wastes to countries that have liability for reception of such wastes or countries that cannot exercise adequate environmentally sound management of such wastes. This is important in avoiding the exportation of dangerous goods to areas that will have a difficult time dealing with them and which could harm environments and people. Another vital article holds parties accountable for the obligation of reducing the generation of hazardous wastes to the barest minimum as well as minimizing their hazardousness. This corresponds with the overall objective of Sustainable Development with aim at promotion of cleaner production and reduction of waste.

The protocol also requires that export and import of hazardous wastes must occur in such a way that would not lead to pollution or potential risk to people's health. This involves reporting as well as the procedure for obtaining prior informed consent in which the exporting country has to inform the competent authority in the importing country on the nature and specification of the waste, the method to be used in disposal, the risks involved amongst others (ROPME, 1998).

In addition, the framework sets some rigorous conditions to guide packaging and labelling of hazardous wastes, transport of these wastes and every phase of the-transboundary movement. This assists in reducing the possibility of accidental releases or spillages occurring whilst in the process of transportation. Regarding the problem of the illicit traffic of hazardous wastes, the treaty also states that any traffic in hazardous wastes that is performed in violation of the terms of the protocol is deemed illicit. To this effect, member states are obliged to assist in the prevention and repression of such transnational crimes for instance by legal prosecution of the culprits (ROPME, 1998).

Apart from the regulatory measures, the protocol also provides for the enactment of national legislation and regulations in member states concerning the protocol provisions and thus aims at achieving relative homogeneity in the management of the hazardous waste within the region. Besides advocating for the exchange of information and technical assistance as well as sharing best practices and cooperation among the member states, it also strengthens the ability of member states to deal with hazardous wastes.

The protocol also addresses important features such as reporting and monitoring as one of the key aspects of the approach. Each developing member state is expected to provide annual reports of the compliance with the provisions of the protocol concerning the information on the amounts and categories of hazardous wastes produced, exported and imported, and the steps that have been taken on their management. This is important in monitoring the progress, setting up milestones and goals to monitor, the achievement of set objectives and checking accountability.

The protocol also contains provisions for the emergency response that requires the member states to prepare for contingencies and to act swiftly in case of an accidental discharge of hazardous wastes that could have potential adverse impacts on the sea or the human beings alike. This ensures that there is swift and effective response in as far as such instances are concerned. In its general, the "Protocol Concerning Marine Transboundary Movements and Disposal of Hazardous Wastes" is a comprehensive measure for a decennial protection the marine environment of ROPME Sea Area against the impact of hazardous wastes. It aims at protecting the ocean and all forms of life within it and maintaining the general welfare of the population in the region through the encouragement of strict measures, collaborative measures, and sustainable actions (ROPME, 1998).

5.4 West and Central Africa Region

According to the report by (United Nations Terminology Database) the Protocol on Environmental Protection to the Antarctic Treaty, or the Madrid Protocol, is an important legal instrument that is aiming to protect the Antarctic environment. Signed in Madrid, Spain in 1991 with the effective date in 1998, the Protocol recognizes Antarctica as a 'Natural Reserve, for peaceful and scientific purposes', which puts in place very stringent protection measures, with permit for any mineral resource exploration or exploitation for strictly scientific purposes only, to ensure that region remains untouched and not turned into-industrialized zone.

Perhaps one of the most significant innovations of the Madrid Protocol is the proper waste management system that it recommends and embraces. This involves the need to ensure that all waste, except food waste and sewage waste, must be cleared from the firm and must not be dumped anywhere within the firm's premises, but rather be incinerated or otherwise treated before any disposal. This provision is intended to drastically reduce human interference that the continent's delicate environment of Antarctica (United Nations Terminology Database, n.d.).

Under the Protocol there is condition that requires that all activities taking place in the region must first undertake an environmental impact assessment activity to determine whether there are any negative impacts that the activity may be likely to cause to the environment. This helps in filtering out various scientific and logistic activities that pose a threat to the natural surroundings. Marine pollution is another main concern of the Protocol as well. It involves deterrent to marine pollution by ships and seeing to it the sea environment is not affected by human activities. Littering especially of wastes which include plastics and deadly materials is prohibited at the beach. These provisions are relevant for the maintenance of diversity in the seas surrounding Antarctica and within the region in general.

The Protocol also provides for the designation of specially protected areas for the conservation of specific types of geological and geographic features and other unique and fragile ecosystems. These districts are restricted through permits for entry and usage, leaving them intact. ASPAs and ASMAs under the Protocol are implemented for protection of the areas of the inherent ecological interest, scientific or aesthetic interest. Additionally, the Protocol calls for the formulation and adoption of national disaster management plans for environmental disasters, which are oil spills and other accidental discharges of pollution. This entails the preparation of mechanisms that can quickly and efficiently prevent or contain such impacts in the event of an accident (United Nations Terminology Database, n.d.).

One of the major features of the Protocol right from its inception is the application of green technology. They ask the parties to employ technology capable of having least effects on the environment, hence adopting sustainable process in their dealings in the area of Antarctica. This is through ensuring that the organization harness renewable energy and technologies that minimize on the release of gasses and disposal of wastes. The Protocol also provides institution of governance that has the Committee for Environmental Protection where affair advice and formulation of recommendations concerning Protocol are made. The CEP is also greatly involved in the function of ensuring compliance and augmenting on the implementation of environmental standards outlined by the Protocol.

The Protocol on Environmental Protection to the Antarctic Treaty is a Guidelines to the Treaty which through its detailed and prophetic provisions, can be seen as a true example of international collaboration in environmental stewardship. It creates a high level of threshold to protect sensitive environments and shows that the whole world wants to keep Antarctica safe for the generations to come. The Protocol, which was adopted by the countries that participated in the exercise of the Antarctic area, can be seen as major success in international environmental regulation and a perfect example of other international environmental treaties (United Nations Terminology Database, n.d.).

5.5 South-east Pacific region

The Convention for the Protection of the Marine Environment and Coastal Area of the South-East Pacific is the central framework whose goal focuses on the protection of the sea and the coastal areas of the South-East Pacific region. It was signed on November 12, 1981 in Lima-Peru and was a consensus of the countries that were situated in South-Eastern Pacific rim include Chile, Colombia, Ecuador and Peru. This convention also popularly known as the Lima Convention, aims to provide recognition of the biotic interrelationship of seas and reminds the significance of collective vigor when it comes to environmental issues (Convention for the Protection, 1981).

Some of the findings of Lima convention as a care call for collective effort towards pollution, degradation of the marine environment and towards sustainable development within the South-East Pacific region. It supports the safeguard of marine species, conservation of vulnerable coastal habitats, and management of marine resources. This also has helped in stressing on various important roles of environmental scientific research, monitoring, and exchange of information for the formulation and implementation of better and more effective environmental policies (Convention for the Protection, 1981).

However, there is an important article within the framework of the Lima Convention, which is Article 4, and it sets out the non-specific measures that member states must undertake that could be aimed at preventing, reducing, and controlling pollution of the marine environment. This article also implies that it is necessary to implement provisions with regards to the prevention and control of emissions of pollutants from both the land and through sea from ships and offshore platforms. It also underscores the necessity of having recruitment and response plans and structures to contain pollution scenarios.

Another important article is the Article 6, which should provide for the measures of protection and conservation of coastal environment. Unlike some coastal development activities, this article suggests that measures should be taken to protect and conserve these areas such as mangroves, wetlands, and coral reefs. In this context, the ICZM strategies was revealed as key solution for achieving a sustainable use of coastal areas through conservation of endangered ecosystems together with sustainable piloting of economic activities like tourism and fishery (Convention for the Protection, 1981).

Supplementary Protocol to the Agreement on Regional Cooperation in combating pollution of the South-East Pacific by hydrocarbons and other harmful substances: is an essential framework that has been created and designed to enforce and foster regional cooperation on pollution occurrences in the South-East Pacific. This protocol was adopted on November 18, 1983 in Quito, Ecuador where it sought to establish and enhance the measures towards combating pollution occurrences by hydrocarbons or other undesirable substances. Major observations of the Supplementary Protocol provide appending evidence regarding the significance of timely and synergistic approach towards the conservation of marine environment and sustainable development of coastal population. It focuses on prevention and readiness, intervention and management, as well as cooperation between the member countries in tackling the problem of pollution events and their impact on the environment. The policy also lays focus on the creation of response mechanisms including contingency plans and joint emergency operations, in an endeavour to enhance the quick and effective approaches to the pollution related disasters.

Among these, Article 3 introduced as an important one that assigns obligations of the member states in regard to the prevention and combating of pollution of the South-East Pacific by hydrocarbons or other noxious substances. This article finalise with the practical means of preventing the occurrences of such pollutions through the implementation of some regulations in the carriage and storage of dangerous products, regular checks on the pollution hazard by creating policing and monitoring mechanisms. It is possible to consider this aspect of the name of this protocol as quite illustrative – the term 'Supplementary' points to the fact that it enhances the regional cooperation structure created by the original agreement, and the emphasis on 'Agreement' highlights its function in developing this structure. Being designed to address the issues related to pollution in the South-East Pacific region, it is but natural for the protocol to be named after the area it is intended to preserve, and thus the signing took place in Quito, the capital of Ecuador.

5.6 Red sea and Gulf of Aden

In accordance with the Consolidated Jeddah Convention Image: The Consolidated Jeddah Convention is a significant source of the legal regime for the protection of the RSGA's marine and coastal ecosystems. Started in 1974 as the Programme for the Environment of the Red Sea and Gulf of Aden (PERSGA), it got significant legal support in 1982 in in the Jeddah Convention. This convention which was established after a Regional Intergovernmental Conference that was held in Jeddah, KSA stresses the compliance of regional governments to environmental issues based on some level of solidarity.

Together with the international treaties like MARPOL, Basel Convention and The United Nations Convention on the Law of The Sea, the Jeddah convention also focuses toward the effective cooperation of the coastal states in order to safeguard the marine environment and prevent pollution. The following link includes an Action Plan for the Conservation of the Marine Environment and Coastal Areas in the Red Sea and Gulf of Aden: HIGHLIGHTED

ACTION PLAN highlighting the overall framework of the conservation plans thus making the Red Sea one of the best-preserved places on the globe.

It concentrates on the urgent issues of marine pollution, fishing quotas, and coastal management relying on regional cooperation. This line of approach is well supported by other protocols that were negotiated under the auspices of PERSGA such as the protocol on biological diversity, protocol from land-based activities, and protocol to cooperate in technical emergencies. Based on the Jeddah Convention signed by Djibouti, Egypt, Jordan, KSA, Somalia, Sudan, and Yemen, parties have realised the necessity of collective endeavours to counterbalance the consequences of innovative growth on the distribution of natural endowments. These are the developing the environment management and contingency capability by involving the regional and International organization like ALECSO, UNEP, IMO and etc., for sustainable future in Red Sea & Gulf of Aden Region.

5.7 Wider Caribbean Region

The Cartagena Convention is one of the most important legal instruments designed to address the sustainable conservation and management of the marine and coastal areas of the Wider Caribbean Region. Signed in 1983 in Cartagena, Colombia, is a keystone agreement that deals with numerous matters, particularly those related to pollution, destructive alterations of natural habitats, and loss of bio-diversity. It has to do this through the cooperation of its member states who are required to work together in managing and conserving the Caribbean Sea and its surrounding waters (UNEP).

One of the novelties of the Cartagena Convention is its emphasis on the prevention of direct and indirect discharge from land-based sources (LBS) of marine pollution since such activity is considered a major threat to the marine environment. This makes LBS pollution significant, especially in the emission of pollutants into the coastal waters and marine environments. The Cartagena Convention’s Article Six is designed to focus on the pollution emerging from the land-based sources, including the necessity for member states to establish legal and regulatory measures for combating pollution originating from activities took place on land. In this article, the authors strongly advocate for the necessity to introduce prevention measures in pollutions, encourage appropriate behavior and raise the public awareness of environmental protection (UNEP).

The term Cartagena Convention comes from Cartagena, Colombia, the city in which this convention was signed. This framework is called the ‘Colombia agreement,’ and Columbia had a substantial role in hosting the negotiations and the formation of this successful agreement in its region. The Cartagena Convention is an agreement made where countries in the Wider Caribbean Region agree to cooperate in order to protect the marine environment as well as support sustainable development so that the current population and the future population can benefit from the riches of the sea (UNEP).

Moreover, the SPAW Protocol, abbreviated for the Protocol Concerning Specially Protected Areas and Wildlife, is one of the most important frameworks aimed at boosting the conservation and sustainable use and management of biological diversity in the Caribbean area. Signed in 1990 under the umbrella of the Cartagena Convention, it focuses on the idea of species and populations and habitats rather than single species. The goal of this approach is to conserve the biological diversity given that this approach embraces the conservation of ecosystems as well as important ecological processes that control the health of the marine and coastal environments (University of the West Indies, Cave Hill).

Major conclusions of the SPAW Protocol demonstrate the necessity for regional cooperation among the Caribbean nations to combat the processes that threat biodiversity such as habitat destruction, pollution, overfishing and climate change. The procedures for the identification of protected areas and species of particular concern are listed in the Article 11 of the SPAW Protocol so as to enable the creation of a protected area network in the Caribbean. Also, Article 12 deals with measures to control and mitigate the impact of human activities in these regions in order to enhance the conservation of the bio diverse areas. The name commonly used for the protocol is the SPAW Protocol because it is designed to protect specially protected areas and wildlife in the Caribbean region. As the SPAW Protocol under the Cartagena Convention shows, Caribbean nations are committed to sustainable use and preservation of their biophysical endowment to underpin the region’s environmental capital and socio-economic well-being (University of the West Indies, Cave Hill).

The LBS Protocol which is also known as the Protocol Concerning Pollution from Land-Based Sources and Activities is an important framework that has been applicable in the fight against marine pollution in the Wider Caribbean Region. It bears mentioning that this was adopted under the Cartagena Convention; given the high risk resulting from pollutants from land-based activities. This narrative complies with internationally recognized conventions, including the United Nations Convention on the Law of the Sea (UNCLOS), which also recognizes states' obligations to control pollution of the marine environment.

Recent observations from the LBS Protocol accentuate in regard to the general significance of polluting substances controlling and limitation coming from the land into the sea environment. This covers aspects like industrial effluent, control of effluent from agricultural practices, and regulation of sewage. Section 8 of article III of the LBS Protocol speaks tenets about member states to formulate and adopt national measures and line of action plans on the control of pollution. It also aims at promoting regional integration and shar ing of experiences in order to improve on the efficacy of such approaches.

The term LBS stands for Land-Based Sources Pollution, which defines the nomenclature of the protocol in question. It was to draw more attention towards the fact the SPMAs are quite common form of marine pollution in the Caribbean area. This policy was adopted by Caribbean countries and signed by individuals in the Wider Caribbean region as a way of protecting the marine environment and encouraging the sustainable use of natural resources within the region.

5.8 Eastern Africa Region

The Nairobi Convention, the full name of which is the Convention for the Protection, Management and Development of the Marine and Coastal Environment of the Eastern African Region, was signed in 1985 and ratified in 1996. Its goal is to encourage collaboration of countries in the utilization and conservation of marine and coastal environment. The primary approach to Environmental protection is reached through the Protocol on Protected Areas and Wild Fauna and Flora which chiefly speaks of conservation of biological diversity and requires the creation of different protected areas as well as protection of endangered species. The Cooperation in Combating Marine Pollution emergency protocol is aimed to prevent, suppress, and eliminate pollution incidents and emphasizes the necessity to be prepared, share information, and to provide mutual assistance in situations concerning maritime pollution. Majestic, these instruments serve as a comprehensive development roof of environment friendly changes that are specifically pronounced for the marine and coastal areas of the eastern African region which sought to reduce the effects of human activities or even the natural calamities on the marine eco-space.

5.9 South Pacific Region

The Noumea Convention on the Conservation of Natural Resources and the Environment in the South Pacific region was adopted in 1986 and entered into force in 1990. This is in line with the key objective of the programme that deals with the sustainable management of the marine and coastal environments. The South Pacific Region Dumping Protocol seeks to lessen the level of marine pollution emanating from dumping exercise by urging people to contain their wastes in the right manner. Furthermore, the Protocol on Cooperation in Combating Oil Slicks in the South Pacific Area and the Protocol for the Protection of the Natural Resources and Environment of the South Pacific address the issue of cooperation as a means of combatting pollution emergencies by calling for prompt action, sharing of resources and coordination in the southern pacific region. These frameworks in their compendium, seek to conserve the sensitive oceanic environment of the South Pacific, promote the proper utilisation of resources in the region and general bolster the capacity to withstand ecological shocks.

5.10 Black Sea

The Convention on the Protection of the Black Sea AGAINST Pollution, sometimes also referred to as the Bucharest Convention, was signed in 1992 and came into force in 1994. It aims at preventing the pollution of Black Sea and its attempt at correcting the imbalance of its ecosystem . The Black Sea Protection Protocol that covers pollution from land sources includes agricultural drainage, industrial effluence and urban wastewater discharge that have necessary anti-pollution measures. The present cooperation protocols aim at the regional cooperation and response mechanism to environmental pollutions by oil and other dangerous substances in case of accidents while the above-mentioned protocols are specific to the Black Sea region in combating pollution of its marine environment by oil and other harmful substances in emergency situations. Protocol concerning Sustainable Use of the Black Sea and Its Protection Against Pollution by Dumping deals mainly on the effective prevention of pollution as a result of waste disposal at sea. These protocols offer a comprehensive segregation of pollutive inputs to the Black Sea, securing the body's physical health and environmental balance.

5.11 North-East Pacific region

The convention for the protection and sustainable development of the marine and coastal environment of the northeast pacific signed in 2002 is to provide adequate standards for the conservation, protection, and sustainable use and development of the biological, physical and social resources of the northeastern pacific region. This convention focuses on the collaboration between the regions, as well as scientific and technologic advancement in handling out environmental issues. This promotes the formulation and implementation of measures, policies that address pollution, conserve species diversity and rational use of the sea's resources. Thus, at the present time, the fundamental goal of the convention is to strengthen cooperation between member states to increase the sustainability of marine and coastal areas, ensure sustainable social development, and improve the quality of life of coastal populations dependent on the mentioned sources.

5.12 Antarctic Region

The Convention on the Conservation of Antarctic Marine Living Resources established in 1982 works to preserve marine life in the Southern Ocean around the Antarctic region. The utilization of marine living resources is also discussed, calling for prevention of over-fishing and exercising measures to balance the supply within the seas. The convention employs an ecosystem friendly approach to the exploitation of these resources in a bid to not harm the Antarctica marine ecosystem. It also encourages the carrying out of scientific research and monitoring systems with the aim of having better management information and sustainable use of marine resources in the area of operation that is Antarctic. Thus, by addressing such concerns, the convention intends to preserve the more vulnerable and sensitive species of the Antarctic zone which is significant for the entire world's biodiversity.

5.13 Baltic Sea Region

The Helsinki Convention also referred to as The Convention on the Protection of the Marine Environment of the Baltic Sea Area was signed in 1974 and came into force in 1980, with acceding changes in 1992, which took force again in the year 2000. In an attempt to contribute to environmental management, it aims at reducing and/or eradicating pollution in the Baltic Sea as well as encouraging sustainable development within the context of the COM. It deals with pollution from the terrestrial anthropogenic sources, shipping, and the aerial fall out. It focuses on collaboration, integrated surveillance, and commitment to proper regulatory procedures in emission reduction. The main objectives of the Helsinki Convention provide for the recovery of the Baltic Sea's ecosystems, the preservation of the species and: population diversity, as well as promote sustainable utilization of its resources, as a driving force for the welfare of the inhabitants of the region.

5.14 Caspian Sea Region

The Framework Convention for the Protection of the Marine Environment of the Caspian Sea is a legally-binding instrument adopted in 2003 that focuses on the conservation and sustainable use of the marine and coastal environment of the Caspian Sea region. It tracks core concerns regarding the ecological environment including pollution, habitat destruction, and biodiversity. It encourages cooperation among regions, scientific voices, and rational decision-making in tackling potential threats to the environment. It also places a significant focus on the issue of proper monitoring and evaluating the conditions around the Caspian Sea in order to make further appropriate decisions towards the preservation and the optimum utilization of the sea's products. Through cooperation and adherence to the provisions of the convention, the Caspian littoral states, as well as the residents of the region, will be able to assess the positive implications of sustainable development based on the successful management of the Caspian Sea ecosystems.

5.15 North-East Atlantic Region

The Conservation of the Marine Environment of the North-East Atlantic, also called the OSPAR Convention, for abbreviation of the name of the convention was adopted in 1992, replacing and enhancing the earlier two conventions the Oslo and the Paris convention of 1974. The OSPAR Convention entered into force in 1998 and its primary goal lies in combating and reducing the adverse impact of marine pollution or preserving the North-East Atlantic marine environment. It covers different types of pollution which are done on the lands of the country and offshore and through Maritime transport. Through the convention it showcases the need for regional cooperation in the aspect of environmental care and the need for applying measures concerned with the environmental consequence in relation to the marine environment. These include the sustainable use and conservation of the resources of the North-East Atlantic, the improvement of the overall capacity of the marine and coastal ecosystems in the region, and the increase in the contribution of the OSPAR Convention to these goals.

5.16 Conventions Pending Development

Several regions, including the East Asian Seas, South Asian Seas, North-West Pacific, North-East Pacific, and the Arctic, have yet to develop comprehensive conventions for the protection and sustainable management of their marine and coastal environments. These regions face unique environmental challenges and opportunities, necessitating the development of tailored frameworks to address their specific needs. The establishment of such conventions would promote regional cooperation, scientific research, and the implementation of effective management practices to protect marine and coastal ecosystems, ensure the sustainable use of resources, and enhance the resilience of these regions to environmental threats.

5.17 Rationale of Chapter

As mentioned in the previous section that the main aim of the study that involves the identification of produced water qualities extracted from oil drilling in Thar Jath (Block 5A) by chemical and biological analysis and the assessment of various rehabilitation strategies are consistent with the objectives, capacities, and requisites stipulated by the various International environmental protocols outlined above. These frameworks concern the conservation and sustainable use of marine and coastal; delving into the importance of the need for inter-regional cooperation, combating of pollution, and the preservation of ecosystems and similar. These also include broader environmental goals, which can be indebted to this study owing to the fact that, besides evaluating produced water and its treatment methods, the work in question tackles the problem of water pollution resulting from oil production, which is a universal concern despite the fact that it might be concentrated in several areas only.

Produced water is a byproduct in oil drilling, posing several issues in dealing with it due to the fluctuating chemical and biological qualities that it contains, making it damaging for ecosystems if not handled correctly. This research is associated with identifying the properties of produced water from Thar Jath due to its seasonal nature analyzed for an entire year to ensure accumulation of ample information. So, the study tries to find out the actual chemical and biological composition of this water and the level of pollutants that contains heavy metals, hydrocarbon, salts and microbial presence. This level of characterization is especially important to make informed decisions for the implementation of remediation measures depending on the content of the produced water in this region.

The comparison of different remediation methods, both physical, chemical, and biological, also correlates well with the tenets held by the outside frameworks regarding ensuring that pollution control and cleanup is integrated. Some physical treatment could include filtering and sedimentation and chemical treatment could include coagulating and oxidation which are made up of biological treatments that involved the use of microorganisms to breaking down pollutant. Cooperating with these methods, the study aims at identifying how effective they are not only individually but also when integrated together to improve the efficiency of the treatment process as a whole. This is in concordance with the principles of the integrated management promoted by the frameworks where different approaches are not limited or combined, but all possible means are considered appropriate for the local conditions.

The rationale for this research also lies in the lack of appropriate and effective remediation techniques that meet the mentioned criteria in the existing literature. As presented through the frameworks highlighted above, the promotion of sustainable development and the conservation of marine and coastal ecosystems, which are vulnerable to the effects of business development including oil exploration and extraction, is an influential concept. The research also directly contributes to the purpose of these frameworks through developing an efficient remediation technique that will assist in reducing pollution and preserving the environment. The detailed guidelines that are outlined in the study including the levels of pollutants, seasonal differences and ecosystem of the locality guarantee that the remediation measures which are being proposed will be efficient, Suitable and durable for the climate of Thar Jath.

In addition, the study of the produced water samples collected from the oil drilling in Thar Jath does not only contribute to the scientific literature on the environmental effects of oil exploration and production, but also provides insights and recommendations on how to manage the environmental impacts of such exploration in other parts of the world. As is evident, many regions of the world harbor similar issues with produced water and the conclusions and recommendations obtained in this research will be useful for other areas concerned with oil production and the environmental consequences that come with it. The research also gives a model that may be appropriately duplicated around the world, serving the international advancement in pollution control and efforts toward sustainable utilization to resources by means of a detailed chemical and biological evaluation of the produced water and examination of several remediation strategies.

The frameworks discussed also pay attention to the need for there to be regional collaborations and joint learning among the various organizations. This study – by presenting its observations and suggested intervention activities – may help promote the cooperation and sharing of information. The findings of this research will play an important role in improving the understanding of pollution issues within the regional level, thus enabling the governments, environmental organisations and the oil industry stake holders to align their approaches towards the efficient management of pollution and protection of the environment. This preventive and cooperative approach is instrumental in addressing environmental concerns that transcend international borders as well as the preservation of marine and costal environments.

The current research is carried out as a result of the increased awareness of the effects posed by the produced water resulting from the oil drilling activities and little efforts aimed at controlling the pollution rates. Knowledgeable about these environmental frameworks offers a robust background for this research since itunderline the value of pollution alleviation, ecosystem conservation, and sustainable development. The study's concern with the detailed characterization of produced water coupled with the assessment of potential remediation strategies is exactly aligned with these priorities and provides effective solutions on how to handle a significant environment concern.

Consequently, the reason for introducing these frameworks in the chapter is to stress the purpose that the objectives of the study serve toward the promotion of international environmental conservation and sustainable development. Thus, the frameworks offer a rich backdrop for appreciating the significance of the study and its potential implications on the practice of environmental management. In doing so, the study aligns with the principles of these frameworks, contributing new knowledge regarding produced water, and specific remediation techniques while aiding in combating pollution, conserving ecosystems and enhancing the sustainability the use of resources. This corroborates the method used in the study while equally stressing the role of the study in enhancing global environmental concerns and regional partnership. The study is, therefore, a significant progress towards identifying and realizing efficient, sustainable, and culturally appropriate ways of handling and containing additional environmentally detrimental aspect of oil drilling; produced water.

Chapter 6

Produced Water Management approach "Remediation Techniques and Applications"

6.1 Introduction

A major challenge in today's oil production industry is to minimize the amount of water produced. Fortunately, many strategies and solutions are currently available; some involve mechanical tools while others use chemicals to manage unwanted water production. Water influx from wells can be quickly pinpointed using common through-tubing production logging (PL) tools. These can be either the electrical wireline that provide real-time readouts, or memory tools that run on slickline and are de-programmed upon retrieval. One thing is certain, the water isn't going to suddenly go away, so time is not the most critical factor. Getting the right solution especially subsurface is the PL tools, in addition to pinpointing the water source, can quantify it in situ so the operator can see exactly how big a problem exists. Measurements include multiphase flow metering, and water-cut calculations. Some of the well-known and used techniques are discussed in this chapter.

6.1.1 *Sub surface* Management

Water Minimization

Downhole Minimization

- Mechanical Blocking Devices

Operators have used various mechanical and well construction techniques to block water from entering the well. Seright et al. (2001) offer several examples of these techniques.

Straddle Packers

Straddle Packer System (SPS) includes a pair of hydraulic-set packers. Simultaneous setting and releasing of these packers is controlled by a single hydraulic setting mechanism. This assembly, with various lengths of straddle tubing between the pair of hydraulic set packers, is used to straddle sections of well bore perforations to be treated. The SPS is connected to the coiled tubing and run to the desired depth. The packer is set and sealed automatically by increasing the pumping pressure in the coiled tubing, which above a threshold value allows fracturing treatments to be performed. Setting, releasing the packer, and circulating/reverse-circulating across the packer is controlled by the operator by changing the pressure/pumping rate inside the coiled tubing.

(http://www.freepatentsonline.com/6883610.html)

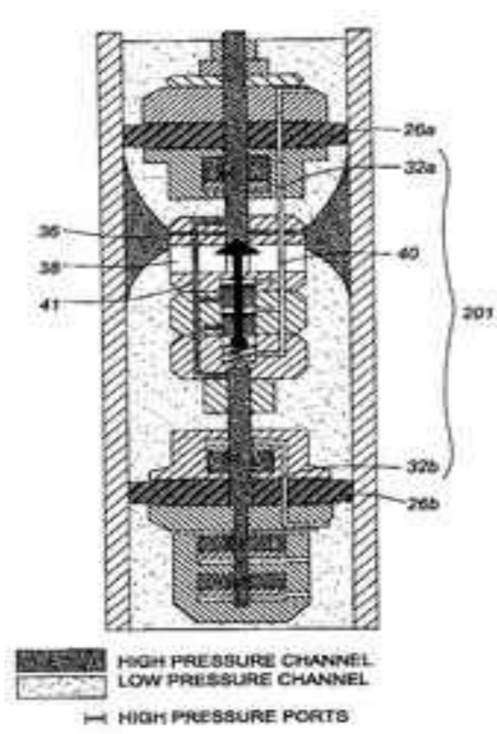


Figure 1

Bridge Plugs
The Bridge Plug normally run in hole using coiled tubing and then capped with cement as seen in the diagram. The jobs yielded excellent results in reducing water production and re-activating wells.

(http://www.onepetro.org/mslib/servlet/onepetropreview?id=SPE-93261-MS&soc=SPE).

This option of plugs was determined to be much cheaper than moving in a rig and doing a full-blown workover as stated by operators. (http://www.epmag.com/archives/features/2414.htm)

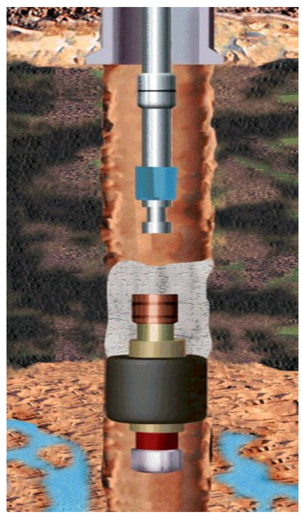


Figure 2

Tubing Patches
The tubing patch (sleeve) is a flexible Carbone fiber composite cylinder, thermosetting resins and rubber skin built around inflatable setting and then attached to a running tool. Then this runs through wireline into the well. This patch is positioned opposite the area to be treated and then inflate this patch using the well fluid then heated until fully polymerized and deflated leaving a hard, pressure sleeve sees the diagram below.

Cement squeeze technique
A method used in a cased well bore for placing cement in a vertical channel existing in the annulus between the casing and a well bore to seal off vertical channels in a prior cement job. In the method, where a vertical channel exists, the interval of the casing along the vertical channel is perforated circumferentially with the perforations at 15° angles with respect to one another about a vertical

axis. The perforations number can be as many as twenty-four over a six-foot interval. The interval of the casing is located near a water bearing formation and between permeable zones. A known volume of cement is then pumped through the perforations and into the vertical channel to seal off the annulus between the casing and the well bore and excess cement is reverse circulated out of the well bore.

(http://www.freepatentsonline.com/4531583.html)

Well bore sand plugs

Methods of isolating portions of a subterranean formation adjacent to a highly deviated well bore having a downstream end and an upstream end and substantially filling a first zone with a sand plug comprising lightweight particulates having a specific gravity of below about 1.25 so as to substantially isolate the first zone from the second zone wherein the first zone is located closer to the downstream end of the wellbore than the second zone.

(http://www.freshpatents.com/-dt20090910ptan20090223667.php)

6.2 Well abandonment

6.2.1 Infill drilling

This is a technique by which an infill drilling to be initiated for the fields that already producing with a high water cut. The main idea is to introduce an infill drilling program for new wells within the field through the workover program. This technique has already proven to have good results in South Umm Gudair oil field located between Sudia Arabia & Kuwait as stated by

(http://www.onepetro.org/mslib/servlet/onepetropreview?id=00036210&soc=SPE)

The Rühlermoor oil field has been producing for more than 45 years. Current production is characterized by low average oil rates, high water cuts, and increasing sand problems. Even with steam drive operations to mobilize the viscous oil, total recovery is less than 25%. Treatments such as frac packs and water shutoff were tested, with limited economic success. Cost-effective infill drilling was identified as the most economical means to accelerate production and increase reserves in the field. By upgrading a field workover rig, total drilling and completion costs were reduced by 60% compared with conventional-rig use.

(http://cat.inist.fr/?aModele=afficheN&cpsidt=1263175)

6.3 Pattern flow control

6.3.1 Horizontal wells

Applying horizontal well technology to improve oil recovery in reservoirs undergoing active water flooding. Development of remaining un swept oil reserves with horizontal wells as a method to improve conformance is a significant challenge. Evaluating and optimizing well conformance to achieve economic results in a waterflood setting is a critical step in maximizing the success of a horizontal well project. Horizontal laterals expose large amounts of productive reservoir rock, benefiting certain reservoir applications while adding a major risk component to well designs planned for heterogeneous, water flooded carbonate reservoirs. Long laterals increase potential of exposing undesirable geologic conditions such as water-filled fracture networks, zones of high water saturation and extreme permeability of thief zone intervals.

(http://www.jjcompanies.com/sitebuildercontent/sitebuilderfiles/locatingandproducinghoriwellsinpb.pdf)

6.4 Water shut-off Chemicals

Use of chemicals, that help shutting off water-bearing channels or fracture within the formation, to prevent water from making its way to the well. Most of water shut-off chemicals are polymer gels or their pre-gel forms (gelants). In the process of selectively entering the cracks and pathways that water follows, gel solutions displace the water. Once the gels set up in the cracks, they block most of the water movement to the well while allowing oil to flow to the well. The specifics of gel selection and deployment will be driven by the type of water flow being targeted.

(http://www.netl.doe.gov/technologies/pwmis/techdesc/shutoff/index.html).

6.5 Keeping the Water from Getting to the surface

6.5.1 Dual Completion wells

This technology entails drilling of an oil well through the oil-bearing zone to the underlying aquifer. Then, the well is dually completed both in the oil and water zones with two separate tubing strings and pumps, one at oil production depth, and the other at the lower water production depth. A packer separates the oil and water perforation zones. During production, oil flows into the upper completion being produced up the annulus between the tubing and the casing, while water is drained through the lowermost completion through perforations in the casing and then lifted up through the open tubing below the initial OWC. As a result, the produced oil is water free and the drained water is oil free. (Shirman, 1998). See the diagram below.

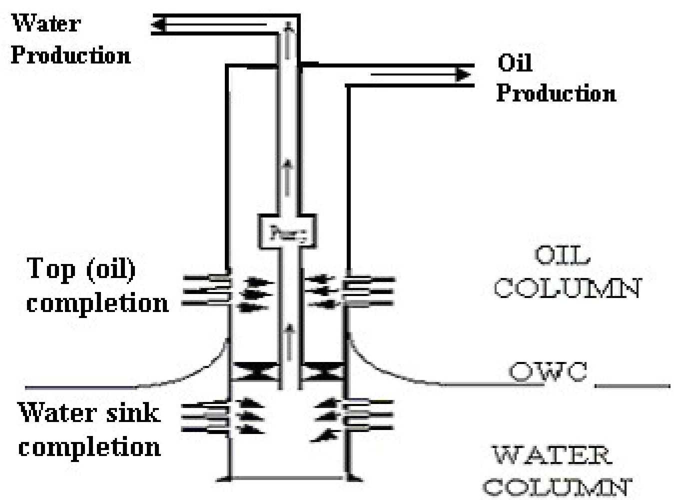


Figure 3

6.5.2 Downhole Oil/Water Separators
Separation technology for water downhole (hydro-cyclones). Used in Canada & USA such as:

- Downhole Gas/Water Separators
- Subsea Separation

6.6 Water Recycle and Reuse

6.6.1 Underground Injection for enhancing Oil Recovery

The most commonly used approach (onshore), which is re-injecting the water into underground formation. The safe injection should be to the deep aquifer within the oil-bearing zone. However, practically & economically is not feasible option and if practiced will be for maintaining reservoir pressure.

6.6.2 Injection for Future Use (Relatively used for Fresh water)

This water disposal option "Surface" is used for the fresh water that needs no or little treatment and can be stored and used later. This water can be injected immediately into the aquifer for future use.

6.6.3 Surface Management

Solid Separation

Primary produced water (Oil/ Water) separation

- Corrugated Plate Interceptors (CPI)
- API gravity separators
- Solid/ liquid hydro cyclones
- Liquid/ liquid hydro cyclones

6.6.4 Induced Gas Flotation (IGF)

- Secondary produced water separation
- Tertiary produced water separation

6.7 Advanced Produced water Treatment

6.7.1 Biological Treatment (Bio & Phyto remediation)

Bioremediation became known to a wider sector only in the late 1980s as a technology for decontamination of shorelines contaminated with spilled oil from supertankers like *Exxon Valdez.* Bioremediation is a spontaneous or managed process by which microbes (bacteria and other microorganisms) are used to degrade toxic chemical substances in contaminated sites. The process of transforming pollutants into non-toxic substances occurs naturally in soil and aquatic habitats though at a very slow rate. It is achieved by many bacteria, actinomycetes and fungi which occur naturally in soils, wetlands, pools and ponds. Some of them are known to use hydrocarbons in crude oil as sources of energy degrading the organic contaminants into harmless products like CO2.

6.7.2 Engineered Reed Bed Technology

Phytoremediation of Produced water

Phytoremediation is the direct use of living plants (Aquatic macrophytes) to remove or reduce pollutants in the produced water. The concept is based on the fact that the aquatic plants degrade, absorb, metabolize or destroy pollutants like hydrocarbons. This is achieved through different types of phytoremediation mechanisms. Phytoaccumulation/ Rhizofiltration; Plant absorb contaminants which are not destroyed but accumulate in shoots leaves and roots. And Phyto-stabilization by which plants produce chemical compounds like enzymes that immobilize contaminants rather than destroying them thus eliminating the bioavailability of these contaminants to other organisms. The third mechanism is Phytovolatalization; plants take up water containing organic contaminants and release the contaminants into the air through their leaves. Another mechanism is Phytodegradation: here plants destroys contaminants. This is achieved (a) direct degradation (b) indirect degradation. The latter known as rhizosphere degradation the plant releases root exudates to the advantage of microorganisms in the rhizosphere that enhance biological degradation of petroleum hydrocarbons.

- Reverse Osmosis System (RO)
- Natural Attenuation for produced water

6.7.3 Use of Produced Water after Treatment

Use by Animals

Some Produced water can be treated using some of the treatment options to be used after meeting the international standards as drinking water for livestock or Wildlife especially in areas that has scarce water resources:

Livestock Watering

Livestock has a certain level of tolerance for contaminants in their drinking water (ALL, 2003). However, in some cases they might show some sort of impairment. In general, animals can tolerate high (TDS) levels in water which is the case in most produced waters as stated by ALL, (2003). Water with elevated levels of TDS ranging between 1000 to 7000 ppm can be used for livestock with likelihood of diarrhea occurrence (ALL, 2003). The same source confirmed that there is an example of around 7 Ranch in Wyoming, in which livestock are using small reservoirs of produced water as drinking source.

Wildlife Watering and Habitat

John *etal.* (2004) described in his study that produced water from Coal Bed Methane in Rocky Mountain area have created a produced water collection points that retain large volume of this water to provide a source for drinking water for the wildlife as well as offering a habitat for fisheries. John *etal*. (2004) stressed the need to check that the quality of this water will not cause health concerns. These water points provide as well a source of additional recreational opportunities for the locals for hunting, fishing boating and bird watching.

Aquaculture and Hydroponic Vegetable culture

Jackson and Myers (2002) reported on a greenhouse experiments to raise vegetables and fish using produced water but not for animal consumption. He stated that quality of vegetables grown in produced water is different than the one grown in potable water; the size is smaller for the produced water Tomato. Whereas, the volume of Tilapia fish grown in produced water was larger than fresh water although some of the fish died. So, the study shows that produced water can be used in case that no other water sources are available.

6.8 Irrigation of Crops

Crop irrigation is the largest single use of fresh water in the United States, making up to 39% of all fresh water withdrawn (USGS 1998). All (2003) described produced water quality used for crop irrigation as their critical parameters are salinity that affects the crop itself, Sodicity that affects the soil (excess sodium can damage soil; high SAR values lead to soil dispersion and loss of soil infiltration capability and make soil sticky when wet and crusty impermeable when dry) and toxicity that affects the crop as well. Trace elements in produced water cause crop toxicity when present in sufficient quantities. All (2003) suggest that most common source of plant toxicity are chloride, sodium and boron.

Texas University established a program to develop portable produced water treatment system that can be moved into oilfields to convert produced water to potable water or water that can be used for crop irrigation. Their goal was to reduce the TDS for less than 500 mg/l and hydrocarbon to less than 0.05 mg/l. such system not only augments scarce water resources in arid regions but also provide an economic payback to operators that could allow the well to produce longer (Burnett et al. 2002).

6.9 Industrial Uses

This could be considered as well where fresh water resources are scarce the produced water may be substituted in various industrial processes. This as well needs to meet the industrial water quality. Produced water has already been used for some industrial activities all over the world. Some are discussed in this section:

Dust Control

In most of the oil fields worldwide as the case for Sudan, they used unpaved all weather or dry weather roads. These lease roads can create substantial dust that may lead to other hazards i.e accident and respiratory infections. So, some regulators allow oil companies to use produced water to be sprayed on roads to suppress dust. This practice is generally controlled in a way that produced water is not applied beyond the road boundaries. Murphree (2002) confirmed the use of produced water for road watering for dust suppression at the locations where regulators allow.

6.10 Vehicle and equipment washing

In the United States; some states recommend operators to wash vehicles leaving production sites to control the possibility of transporting seeds of undesirable weed species (ALL, 2003).

6.10.1 Oil filed Use

A program in New Mexico is treating produced water by removing hydrogen sulfide and then using this water in drilling operations and this used saves 4 million bbl per year of local groundwater (Peacock, 2002).

6.10.2 Power Generation

About 360,000 bpd of produced water from Chevron Texaco facility in California is softened and sent to a cogeneration plant as a source of boiler feed water (Brost, 2002). Another potential use is cooling water: it has been stated that the electric power generation industry is the second largest user of freshwater in the United States, making up 38% of all freshwater withdrawn (USGS, 1998). Theses conventional sources of water are scarce due to high demands and there should be alternatives for such purposes. Produced water nowadays represents a large volume that could potentially serve this purpose of power generation.

6.10.3 Fire Fighting

In areas where groundwater and surface water resources are limited produce water can serve as source for firefighting. The use of produced water (Saline water) in firefighting might have negative impact on soil. However, that can be justified comparing the devastating impacts of fire. ALL (2003) reported that firefighters in Colorado used produced water impoundments as sources for water to fill air tankers for helicopters that spray water onto fire during the summer of 2002.

6.10.4 Other Uses

There could be other future uses for this produced water considering the scarce of surface and ground water resources.

Chapter 7 Results and Discussion

7.1 Primary Data Overview

This chapter was about the results obtained from the Thar Jath oil fields in Unity State, Southern Sudan where bio-remediation was studied to treat the produced water with high oil content. Monthly readings indicated oil content at various treatment stages: Drainage & Treatment, FWKO or Free Water Knock Out, IGF or Induced Gas Flotation, Pond A & Pond B, and EVP or Evaporation. These percentages were calculated regarding the efficacy of the treatments provided at FWKO and at the successive stage of EVP through the analysis of decreased oil content at each stage.

Observations made were that there was appreciable cut down of oil following the IGF test which proved the efficiency of bioremediation especially in Pond B where the mature age of bacteria helped decrease the entitlement of oil condiment. Carrying capacity trends were found to be the most significant at Ponds A and B as well as between Pond B and EVP. Seasonal and operational effects were also observed and fluctuations in the oil concentrations may be attributed to production fluctuations or bacterial activity during certain seasons. While the sample FWKO values for April were observed to be considerably high compared with levels recorded in the same month of the previous year, EVP values were generally low, affording further support to the treatment's efficacy.

Simplifying fluctuations in oil content, carried out to test the response to load changes, proved that resilience of mature bacteria in Pond B. While exploring examples of bioremediation, its sustainability advantage was highlighted due to its ability to use small amounts of chemicals in the process. All these observations pointed to the possibility of a relationship between the volume of oil treated and volume of water produced; therefore, the report suggested a Pearson correlation test to determine the relationship further. It also revealed cases where it recorded high contents of oil that were surprisingly high in specific months, for example August and September and then dramatically reduced the following month. This implied that the bioremediation system was capable of tolerating fluctuating loads and that mature bacteria population in Pond B was largely responsible for that.

Possible reasons for monthly variation for oil content included change in production, bacterial activity concerning the whole month and the diversity of oil-water mixtures. Nevertheless, these swinging were successfully capped by progressions in bioremediation where limited oil content was seen as a sign of health. The research has demonstrated that bioremediation possesses great efficacy in decreasing the concentration of oils in water in terms of Pond B. This helped to support the principles of bioremediation as an environment=s friendly and efficient treatment method in accordance with environmental and sustainability policies.

Table 1 Primary Data

Month	FWKO	IGF Induced Gas Flotation Stage	Bioremediation POND A	Bioremediation POND B	EVP Pond
April	92.02	32.63	30.54	18.02	2.19
May	86.53	38.12	36.64	19.82	3.81
June	67.44	35.97	32.25	20.38	3.29
July	68.26	34.51	25.34	15.87	2.62
Aug.	171.13	37.2	23.45	14.09	2.34
Sept	182.6	95.8	43.98	22.19	3.16
Oct.	96.66	62.56	40.68	30.12	5.55
Nov.	75.86	45.45	30.93	23.72	6.03
Dec.	109.84	77.73	35.51	26.28	5.97
Jan .	76.15	53.96	30.97	21.73	4.13
Feb.	127.74	54.88	38.41	20.56	2.73
March	132.8	65.03	41.04	33.08	4.31
April	120.62	63.47	32.45	21.91	3.59

7.2 Reduction Analysis in Oil Content

The data table represents values of oil content in water samples taken each month at various step in the process of water treatment by bioremediation. These include FWKO (Free Water Knock Out) for the first phase of separation, IGF (Induced Gas Flotation) for the second phase to get rid of smaller oil droplets, POND A and POND B as the final refining phase and the EVP (Evaporation) stage where the gas minimally contains oil.

7.2.1 FWKO (Free Water Knock Out)

FWKO stands for 'Free Water Knock Out,' and it is another useful stage that signifies the first step in the water treatment process with the main aim of separating oil-water mixtures. This stage is strategic because the major proportion of the oil is handled at this stage according to theWP-150 report. The main purpose of the FWKO is gravity separation that ensures that oil, water, and gas content in the reservoir different based on densities. On the bottom of the vessel the heavier water accumulates; on the top – the lighter oil products and, if any, gases escape through the top of the component.

At this stage, the primary goal is to get rid of a major portion of the free oil and gas from the water so that it is ready to undergo additional treatment processes in the next few stages. From how effective or ineffective this FWKO stage turns out, the efficiency of other stages is influenced for the simple reason that any oil that has not been segregated in this stage is going to require other techniques that may be even more complex and costly. Hence, the determination of oil content at FWKO stage is important since it also provides a check point that defines the initial level of oil present in the produced water thereby enabling an approximate measure of the efficiency of the initial separation operations.

The problems that may be encounter in this stage of the process includes fluctuation in the rate and quality of the produced water which influences the operation of the separation equipment. Moreover, there may be a situation where the samples contain such tiny droplets of oil that they cannot be separated in layers; these may also need to be treated. Knowledge of these dynamics is important for increasing the effectiveness of the FWKO stage, because improvements here can dramatically affect the costs associated with the processes and improve the efficiency of further treatment processes.

7.2.2 IGF (Induced Gas Flotation)

The IGF or Induced Gas Flotation stage is an important stage in the water treatment that is used to separate small oil droplets from water that could not be separated from water during the FWKO stage. In this method, gas bubbles are injected into the water where they surround and coat the oil droplets and hence float to the surface where they can be easily harvested. The gas employed is the air or the natural gas and the bubbles are produced mechanically or hydraulically.

Some of the problems with gravity separation are solved or reduced through the IGF process, thus improving separation efficiency. Regarding the FWKO stage it means that water with little oil droplets is produced where large droplets are more or less eliminated but the small ones are normally left behind in the water. The flow of gas bubbles at the IGF stage enhances the effectiveness of these droplets to rise or to float to the surface as they combine with the other droplets. Effectiveness of a system in this stage could be measured by the amount of oil reduction from the FWKO output to the post IGF water. Thus, when high performance is attained, IGF systems have the potential of producing large reductions and thereby off-loading other treatment processes downstream. There are some parameters that plays a role for the IGF step, including the size of bubbles, the rate of gas flow through the water, and the chemical composition of the water. Achievement and fine-tuning of these parameters are important for getting the best possible results and constant attainment of high removal efficiency of the oil droplets.

Issues arising at the IGF stage include how stable emulsions can be formed as well as the influence of surfactants which actually interferes with the folding of gas bubbles to the oil droplets. Potential solutions to these problems may require the use of chemicals in preparing the material to be floated or changing the conditions of the flotation process. Therefore, the IGF stage plays a critically important role in enhancing the efficiency of water clarification since fine oil droplets cannot be easily separated at the initial stage. Its function is to filter the water through removing most of the oil particles before it gets to the other treatment steps, namely Pond A and Pond B, hence increasing the efficiency of the biological degradation process.

7.2.3 POND A & POND B

Pond A and Pond B are the phase_ of the water treatment step in which the water will be purified naturally and by engineered bioremediation methods. These ponds are normally shallow basin that is either uncovered or covered with a lagoon which allows water to stay for a long time in order to be subjected to natural quick processes which breaks down other forms of petroleum oil.

In Pond A, the primary bioremediation process focuses on the microbial degradation of the remaining oil content in water. This pond is an enclosed one and particular types of bacteria that are known to break down the hydrocarbons are seeded and enriched. The performance of Pond A is evaluated in terms of its ability to remove oil from the water by comparing the IGF stage output and the water that leaves Pond A, with factors like the water residence time in a pond, the concentration and types of microbes involved and the prevailing conditions of temperature pH. However, Pond B is the second or third stage in treatment of water where A was the first, meaning that, water treated in Pond B is already characterized by low oil content and therefore what Pond B does is refine the quality of the water. The higher level of bacteria species makes Pond B beneficial in breaking any of the remaining hydrocarbons further lowering the level of oils. This pond sometimes functions optimally to support the abundance and activity of microorganisms which enhances their bioremediation activities.

Some of the issues that may be encountered at Pond A and Pond B include microbial ability to effectively metabolize contaminants and dealing with any changes in influent water quality and concentrations of contaminants. This means that; Although bioremediation is an effective way of managing pollutants, it should be noted that changes in the seasons as well as operational changes may affect the efficiency with which contaminants are eliminated and therefore, constant monitoring and variation in management procedures must be made. About the end oil levels in the treated water, the performance of Ponds A and B is very important in attaining low outcomes. These stages do not only decrease the volume of produced water that affects the environment but also increase the sustainability of tackling this issue through application of natural bio- processes. When it gets to Pond B, water is generally more purified prior to going through the final process of purification.

7.2.4 EVP (Evaporation)

The last stage of water treatment is the EVP (Evaporation) stage which aims at attaining the least amount of oil in the treated water. This stage applies several physical processes that are focused on washing and use principles of evaporation, with other form of purification being common in a bid to produce the best water quality. During evaporation, water is subjected to conditions that favours change of phase of the water molecules from liquid phase to vapor phase and in the process, the contaminants amongst them oil are concentrated and leaves behind. This can be done through direct exposure to the sun where the water is spread in a large reservoir called ponds or through the aid of engineering equipment such as evaporators or distillation units. The purpose is to make it such that any oil which has survived after passing through Pond B should be eradicated or at least minimized to the highest extent possible.

In regard to the EVP stage, the degree of efficiency is determined by the residual oil content of the treated water – this should be the lowest of the totals recorded in the preceding stages. The efficiency of this process depends on the parameters such as the temperature and humidity of the water, surface area of the water for evaporation, and other additional purging systems that may include filters or adsorber beds for holding any remnants of the oil. Some issues of the EVP stage are; power demand when working Conditioned engineered evaporation systems and disposing or handling of concentrated solid residuals that contain elevated levels of oil and other foul substances. Furthermore, the process of natural evaporation is also affected by factors like weather conditions prevailing in the environment.

The function of the EVP stage is crucial in guaranteeing that water treated is fit to meet the recommended standards as required by the water regulation agencies besides being safe to the environment. This particular stage facilitates the continual attainment of the lowest possible quantity of oil content thus enabling the water to be fit for discharge or reutilization which completes the bioremediation process. The effectiveness of the last, the EVP stage is a clear indication of success of the entire treatment process in eradicating oil content and purifying the produced water while experiencing the cumulative effect of each prior stage.

7.3 Reduction Analysis in practice

In particular, it is possible to isolate the constant reduction analysis from FWKO to EVP as the essential evaluation factor of the general outcome of the bioremediation treatment. The actual amount of oil loss is then obtained by deducting the oil content of the sample taken in the final stage from the oil content of the one taken in the initial stage. When many people are involved, efficiency is determined by a specific percentage that is achieved during the course of a month. From this analysis one gets to know quantitatively the amount of oil content that is treated out as water gets to the different treatment stages.

The percentage reduction formula $(\text{Initial}-\text{Final})/\text{Initial}\times 100$ is another robust instrument in establishing performance shift. This evaluation enables the determination of operational patterns, strengths, and weaknesses and helps in discovering emerging patterns as the days progress. Through these constant reductions, one is able to revisit the severities of the specific bioremediation and be able to make appropriate adjustments because of oil content changes or fluctuations in environmental conditions. The sum of the data gathered in reviewing this plant support each stage of the complete treatment plan while reviewing the FWKO stage gravity and FB stage sand and organic material before making a complete effluent water quality in the EVP zone.

7.4 Trends and Observations

7.4.1 April Start to April End (Year-over-Year Comparison)

A comparative study from April of the previous year to the next year provided deeper understanding into the variability and success of bioremediation process. Initially the specific gravity of the oil and water mixture was taken at 92.02 and ending with 120. 62 in the FWKO stage indicating that there could be seasonal or operational factors that affected the initial oil content at the start. These differences could be as a result of fluctuation in the production rate of oil, climate change, or changes in the management of the oil firm. Nevertheless, a reduction of the oil content for every stage of the experiment indicates that the bioremediation process is a worthy effort at every month. Notably, the flow regime of the lowest oil content value was identified at the EVP stage, which therefore suggests high efficiency in the removal of residual oil. This pattern shows that the system could maintain high oil content cutting effectiveness regardless of initial setting and discharge the treated water to the needed quality.

7.5 Consistency Across Stages

The data also revealed a decline in the amount of oil each month from FWKO through to the EVP stage of the bioremediation process, though each stage showed an obvious step down in the quantity. This consistency demonstrates that each of the steps impacts a large extent to the remaining oil content within the produced water. The first coarse separation in the FWKO stage eliminates the bulk of the oil, with the IGF stage lowering minute oil inclusions even more. Spent from oil, ponds A and B are specific for the microbial degradation of the remaining oil wherein Pond B is ideal because of the developed mature bacteria. The last stage in the EVP is designed to cut off the last bar of the oil content and refine the quality of the water for its discharge into the environment. Such stepwise reduction helps underline the significance of each stage for reaching the set treatment objectives and offers one more perspective on how the several bioremediation approaches are interconnected and function in concert in the process of produced water treatment.

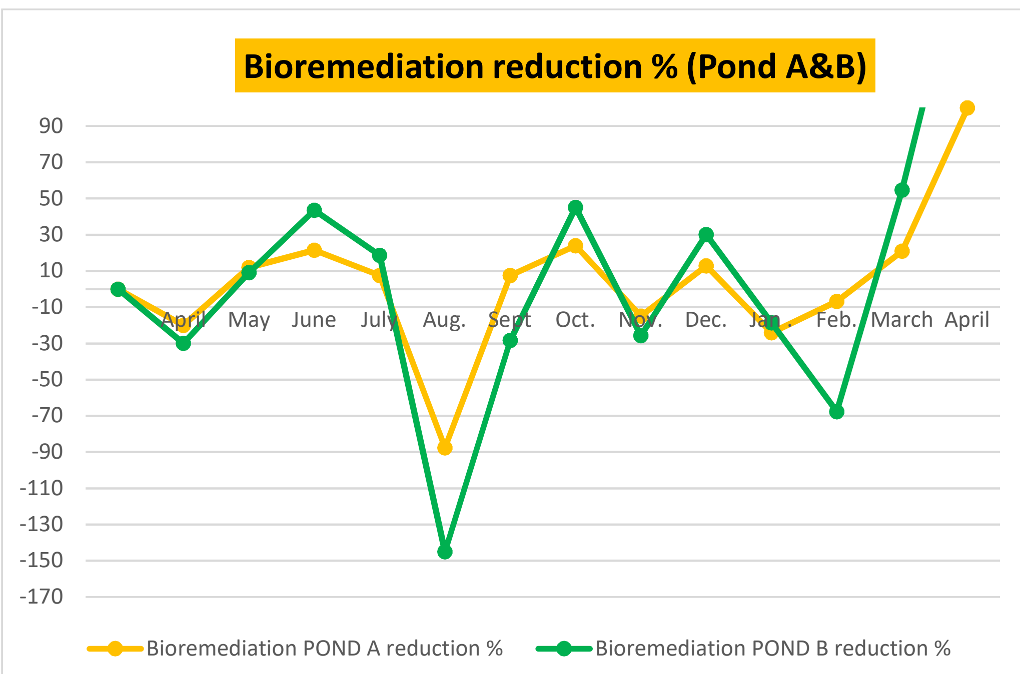
7.6 Effectiveness of POND B and EVP

It is also evident that the Pond B showed low levels of oil content throughout the experiment and the EVP stage particularly had the least oil content as compared to the previous stages to prove how they played significant roles in bioremediation process. Pond B, which has developed mature bacterial structure, quickly decodes the remaining even small pieces of complex hydrocarbons that were not cleared out in the initial stage. This stage makes certain that a better portion of the remaining oil is broken down before the water continues to the last stage of treatment. The stage of the EVP then minimizes water content of oil to eliminate any traces of oil that may be remaining in the treated water. These stages play a significant role in the achievement of the necessary goal, which is the meeting of environmental standards in treated water ready for discharge or reuse. The signal of decrease in the density of oil in Pond B as well as the rapid decrease of fish's EVP also support the steady efficiency of the bioremediation process. This functionality is particularly significant when considering their ability to adapt to fluctuations in the oil content, which would otherwise greatly diminish the overall efficiency of the treatment.

7.7 Samples Analysis

7.7.1 Interpreting the Bioremediation Pond Reduction Graph

The below graph illustrates the amount of contamination in terms of percentage that was eliminated by two bioremediation ponds, namely Pond A and Pond B, in the span of 14 months. The horizontal axis is in terms of the months while the vertical axis is in terms of percentage decrease in contamination.



Graph 1:Bioremediation reduction % (Pond A&B). Source: Self-generated.

Table 2: Bioremediation reduction % (Pond A&B).

Month	Bioremediation POND A reduction %	Bioremediation POND B reduction %
April	-19.97380485	-9.988901221
May	11.98144105	-2.82542886
June	21.42635659	22.12953876
July	7.458563536	11.21613106
Aug.	-87.54797441	-57.48757984
Sept	7.503410641	-35.73681839
Oct.	23.96755162	21.24833997
Nov.	-14.80763013	-10.7925801
Dec.	12.78513095	17.31354642
Jan.	-24.0232483	5.38426139
Feb.	-6.847175215	-60.89494163
March	20.93079922	33.76662636
April	100	100

Concerning the two ponds, a negative reduction of contamination is evident in the early months of civilisation, especially April and May, which suggest more contamination as opposed to less contamination. While the two ponds were being studied, Pond A has a higher percent reduction in purity (-19. 97%) than Pond B (-9.99%). Yet, both the ponds exhibit an improvement in June reducing contamination for the initial time since April. It can be observed that the percentage of wild fish that was stocked in Pond A improved by 21.43% compared to Pond B 22.13%.

Indeed, July remains a month in which the remediation continues but in the form that is somewhat less effective compared to June. A reduction of 20% decreases Pond A to 7. 42%, Pond C has a reduction of 6% only, and at last, Pond B gets only 11% reduction. 22%. Further, it is observed that in August, there is a prominent decline in the quality of both the ponds those adversely affect the contamination level. This implies that, Pond A significantly highly contaminated by 87. 55% and may results from either overloading of the contaminant or disruption of the bioremediation process. Comparing the results, the contamination of Pond B increases (-57. 49%) but with lesser extent compared with Pond A Reduction occurs in pond A in the month of September it has shown a progress of 7. 50% while Pond B continuously increases in contamination (-35. 74%). Additionally, it shows changes and reveals new values for both ponds: October becomes positive again. Pond A reduces 23% of the total population of the MHSs on average to their optimal level. Pond A resolves contamination to as low as 0.0032 percent or 97% while Pond B reduces contamination by 21 percent or 0.0688. 25%. In September, October and the beginning of November both ponds return to negative reduction values but in the month of November and December have more reduction values than the previous months. The results indicate that the concentration of contamination in Pond A rises (- 14. 81%) followed by Pond B at a slightly lower rate (- 10.7%). Later in the month of December provides a ray, of hope with reduced rate of contamination for both the ponds. Several factors, Pond A eased pollution by 12. 72%, whereas Pond A records 79% effluent reduction, and pond B only 17.31%.

From graph 1 and table 2 it is cleared that in winter season from month January it starts bringing negative reduction value for Pond A -24. 02% which is sign of increase in contamination. Though contamination at Pond B had continued to increase for the past five months, beginning from October, the statistics jumps to a positive figure for the first time indicating that contamination has been cut by 5. 38%. February also experiences such a pattern of performance. Pond A has a higher contamination level (-6. 85%) while Pond B have a lower contamination level (-60. 9%). This is the largest decrease that was noted for the Pond B for the whole studied period, and there is quite a strong indication that the reduction might have been even deeper if the study was done during the other seasons. Luckily, March comes back positive reduction values for both ponds. It was evident that Pond A effectiveness was enhanced because contamination level was reduced by 20%. 94% A B Pond reduces sedimentation to 33%. 77%. The percent change for contamination for both Pond A and Pond B is 100% reduction in contamination for the final month (April) The 100% reduction of contamination could a sign that the contaminant has been eradicated or that data collection was terminated at this stage.

- **Possible Explanations for the Fluctuations**

Several factors could explain the fluctuations observed in the bioremediation process:

Seasonal Variations: One of the fundamental aspects of bioremediation entails microbial activity, which is affected by fluctuating temperature that is characteristic of seasons. The warm temperatures in June and October might also lead to higher microbial growth rates resulting in **Higher reduction rates.** On the other hand, lower temperature, moisture, and sunlight in winter may slow down the rate of microbial growth which could be a reason for negative reduction values in the winter period.

Nutrient Availability: Some of the compounds that help grow microorganisms include nitrogen and phosphorus. Sudden or frequent changes in nutrient content in the ponds could impact on the microbial load and its ability to achieve slated purification levels.

Contaminant Influx: More to the point, the presented graph does not provide knowledge about the kind or quantity of the contaminant that gets into the ponds. The contamination rates would increase, and it could be because when there were infiltrations of the contaminants in specific months such as August, the bioremediation was unable to cope with the extra load thereby resulting in the increase.

Microbial Population Shifts: Bioremediation is a process in which microorganisms are used to degrade environmental pollutants, and such microorganisms may live as single species or in diverse and shifting communities. Long term fluctuations in the efficiency of the reduction might be attributed to changes in the composition of microbial community residing in the ponds.

7.2.2 Analysis of Reduction % in Oil Content

The given data contains information about the changes in the value of FWKO, IGF, and EVP Pond reduction on a monthly basis with the respected percentage decrease for each. These reductions indicate alterations to the effectiveness of oil and gas separation, which has periods displaying variations due to seasonal fluctuations and system operations per month as shown in table 3.

Table 3: Reduction Analysis in Oil Content

Month	FWKO Reduction %	IGF Reduction %	EVP Pond reduction %
April	5.966094327	-16.82500766	-73.97260274
May	22.0617127	5.640083945	13.64829396
June	-1.215895611	4.058938004	20.36474164
July	-150.7031937	-7.794842075	10.6870229
Aug.	-6.702506866	-157.5268817	-35.04273504
Sept	47.06462212	34.69728601	-75.63291139
Oct.	21.51872543	27.34974425	-8.648648649
Nov.	-44.79303981	-71.02310231	0.995024876
Dec.	30.67188638	30.58021356	30.82077052
Jan .	-67.74786605	-1.704966642	33.89830508
Feb.	-3.961171129	-18.49489796	-57.87545788
March	9.171686747	2.398892819	16.70533643
April	100	100	100

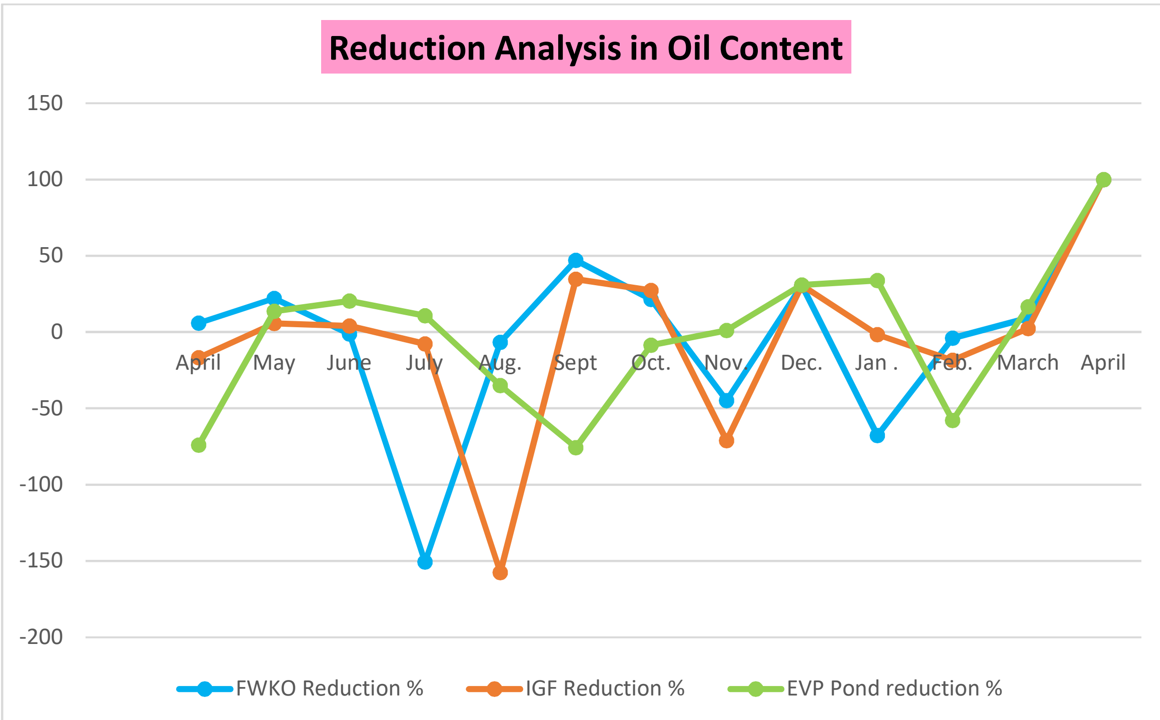
Starting with FWKO reduction percentages, April has a 100% reduction which implies maximum separation efficiency of LWCO from FWKO. The effects may be due to better environmental conditions, operating procedures or systems put in place by the company. But June shows a shocking -150, in July again thisratio worsends again to -150. There is a gross swallow fall of about 70% and this may suggest inefficiency when separation mechanisms are compromised more, maybe by higher oil or water influx. From this perspective, these oscillations might be due to changes in crude oil properties or production speeds, which could be worse during warmer months, known for exacerbating separation issues.

Turning to identify and quantify the IGF reduction percentages, one can see April having a 100% which reflects efficiency in gas flotation. On the other hand, in August the level significantly decreases to a -157. As seen from the Table above, the conversion efficiency has decreased with 53%, which can be attributed to some operational losses or environmental barriers limiting the separation of gas. These variations might be attributed to changes in the composition of gases in the field or the rate of injection resulting from seasonal variation in demand or the reservoir characteristics.

As with call center costs, percentages of reduction in EVP Pond also present significant fluctuation as illustrated by the figures: The provided data shows that April has a 100% improvement thereby indicating that there is proper management of evaporation ponds. However, in August the above index experiences a -35. the amounts may have been diluted by 04% possible because evaporation rates are low especially in cooler temperatures or low rainfall. Seasonally, these post-impoundment fluctuations have illustrated the vulnerability of an evaporation pond in the area, whereby changes in temperature and humidity will determine the rate of evaporation of water.

Reading information depending on seasonal changes provides rather interesting data in terms of month's comparison. The separation efficiencies across all the parameters are discovered to be at their best during such season or the months of April and May in particular as temperatures are usually mild and production is consistent. On the other hand, the calendar months are problematic especially July and August experience higher levels of separation in efficiency perhaps due to increased production rates or environmental conditions. Specifically, the data of the overall scores reveals a 'C 'shaped partially declined tendency in the fall months, specifically September and October regardless of the separation processes.

As for comparison, December appears to be quite extraordinary in terms of displaying the same level of the decline across all the indicators, which may indicate a solid operational performance given improving, if not optimal, winter conditions. July, on the other hand, have shown a fairly sizable level of inefficiency, pointing to operational risks or environmental adversity in July when generating the summer production peak. Evaluating the non-steady FWKO, IGF and EVP Pond reduction percentages, the authors concluded that reserves contain cyclical and trend variations reflecting seasonal influence, other operational issues and environmental factors related to oil and gas separation. Such factors can be utilized to understand how operators can use appropriate production patterns to avoid or minimize adverse effects and improve general performance throughout various seasons.



Graph 2: Reduction Analysis in Oil Content. Source: Self-generated

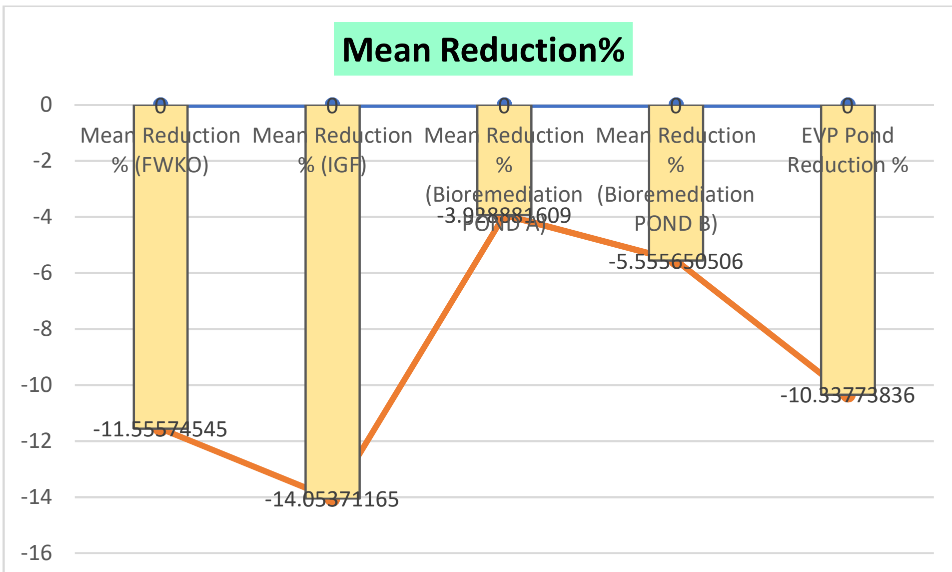
The variation can be attributed to; a change in seasons hence a factor that influences microbial action, the change in nutrient concentration within the ponds, alteration in input load of contamination into the ponds and change in abundance of microbes that restore the ponds. One limitation with the graph. 2 is that it does not present information on the initial concentrations of contamination or even the type of contamination that is being addressed. Possessing this information would enable a more judicious assessment of the efficacy of the bioremediation ponds. Also, acquiring more information on the additional parameters of ponds such as water temperature, nutrient inputs, and contaminant inputs, together with the reduction data, would help identify more definite connections between them and the changes in the rate of bioremediation performance.

7.2.3 Mean Reduction

The mean reduction percentages of different activities involved in the oil and gas production have been represented in the table 4 and graph 3 FWKO, IGF, POND A, POND B & EVP.

Table 4: Mean Reduction

Mean Reduction % (FWKO)	Mean Reduction % (IGF)	Mean Reduction % (Bioremediation POND A)	Mean Reduction % (Bioremediation POND B)	EVP Pond Reduction %
-11.55574545	-14.05371165	-3.928881609	-5.555650506	-10.33773836



Graph 3: Mean Reduction. Source: Self-Generated

Thus, further reduction percentages of FWKO mean are −11. 56 % shows a little deviation from 100 % that mean there is slightly less efficiency in the separation of the free water from the crude oil. This indicates that, on the average, we may have a very small proportion of water contaminated in the separated oil stream. Some of the potential causes for this could stem from changes in the feed flow rates of the oil-water mixture to the separator, or presence of problems in the various separation equipment such as pumps, valves,ortex nozzles, among others, or sub-optimal conditions in the separator.

Likewise, the mean reduction compared to basal levels for IGF is -14.05% which is slightly higher than the international efficiency of 95% in the gas flotation processes. This may, in turn, indicate that the average efficiency of the induced gas flotation system in separate of the gas may still remain an issue, and may not attain the expected level of efficiency. The causes that could have led to this could be changes in the type of gas used or rates at which it is injected into the flotation vessel, or may be, conditions under which flotation is done could have been unfavorable.

As for the mean reduction percentages for bioremediation ponds, it can be seen that POND A and POND B performed as follows: POND A has a mean reduction of -3. 93% and -5.56%, respectively. These values indicate moderately efficient in the bioremediation processes and conditions that prevail in these ponds. Bioremediation ponds used for the treatment of wastewater generally require the microbial breakdown of the organic pollutants in the produced water. Although FWKO and IGF have significantly higher mean reduction percentages it's important to know that with relatively lesser mean reduction percentages it could be deduced that on an average these ponds offer a means of reduction of organic contaminants although the efficiency may not be optimum. Some of the factors that could have resulted in these values could be the difference in microbial turnover, nutrient concentration and time taken by water in the ponds before being treated and leaving the ponds.

Lastly, on average, the percentage reduction of the EVP pond is at -10%. 34% which per cent say described a moderate level of efficiency the pond in evaporating water in the evaporation pond. Some ways are the evaporation ponds which involves containing the produced water and allowing it to evaporate to reduce the volume and leave behind substances such as salts. Using the mean reduction percentage information, it is inferred that the specific pond efficiency of evaporation might be below optimal. Because evaporation happens depending on the temperature differences, wind speed, and the type and design of the pond put in place, then its efficiency will be affected.

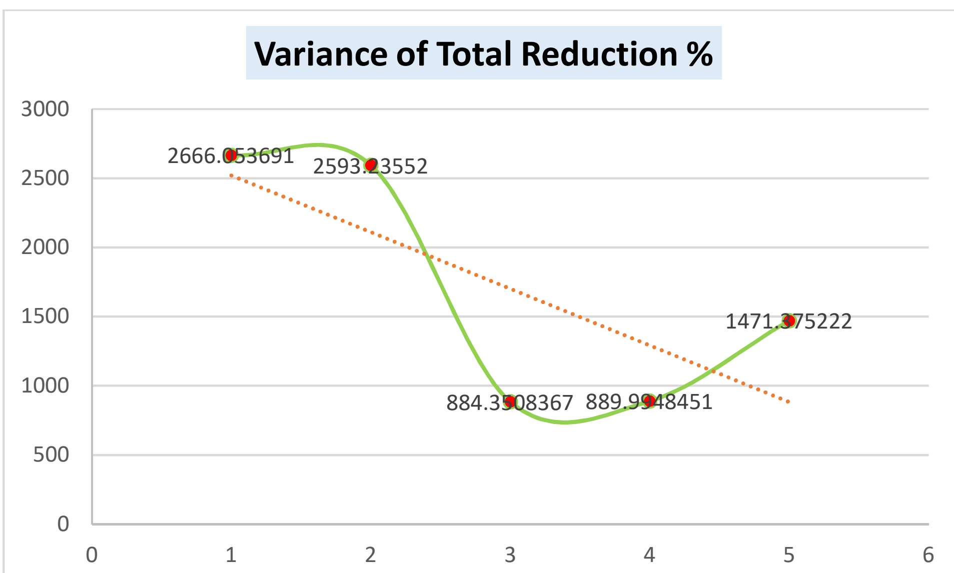
From these values, one would be in a position to compare the two in terms of efficiency and possible difficulties of the two processes. Although certain processes may seemingly achieve higher levels of efficiency than the others, issues such as variability in feed make-up, process conditions and the impact of environmental factors are general issues that would affect the overall efficiency of all these processes. Calculating these mean reduction percentages, the procedures of process facilitators and defining better strategic goals to enhance mean efficiency of every procedure in oil and gas production operation.

7.2.4 Variance Interpretation

The table 5 and graph 4 below gave FWKO reduction, IGF reduction, Reduction in bioremediation pond A and bioremediation pond B, EVP pond reduction; variance gives an understanding of how widely data include the extent to which the values in the figure diverge from the average.

Table 5: Variance

Variance (FKWO Reduction)	**Variance (IGF Reduction)**	**Variance (Bioremediation POND A reduction)**	**Variance (Bioremediation POND B reduction)**	**Varinace (EVP Pond Reduction)**
2666.053691	2593.23552	884.3508367	889.9948451	1471.375222



Graph 4: Variance of Total Reduction. Source: Self-generated

Analyzing the FWKO reduction beginning with the variance, the value amounts to 2666. 05 explains the high level of variability in the data points in relation to the reduction percentage defined by the mean. This implies that for different instances/tranche, the level of efficiency in adhering to the FWKO separation process is highly variable. Possible causes for effect variability could be variations in the properties of crude oil, alterations in field conditions or instability in the performance of tools and equipment.

Likewise, the variance regarding IGF reduction is 2593.24, which suggests that the distribution of the points should stand away from the mean by a significant margin in terms of the percentage decrease. This implies that the efficiency of the induced gas flotation process is rather inconsistent, and may be influenced by some elements such as changes in the composition of the generated gas, changes in the conditions within the system or differences in the performance of the flotation apparatus.

Continuing with the variances for bioremediation ponds A and B they bear slightly smaller fluctuation marks than those of FWKO and IGF reduction at 884. 35 and 889. 99, respectively. This can be inferred to mean that the reduction efficiencies in these bioremediation ponds are relatively shorter with lesser variability than the FWKO and IGF processes. Some of the potential reasons for this could be constant, better, and stable microbial community in the ponds, constant nutrient supply, or moderate hydraulic condition in the pond.

And lastly, the variance for reduction of EVP pond is calculated as 1471. 38, demonstrating average volatility of outcomes and reflecting the effectiveness of water evaporation from the evaporation pond. Even though the magnitude of variance is relatively low as compared to the reductions in FWKO and IGF, it means that evaporation can be affected by factors such as: temperature difference, wind speed, and the design of the ponds in which the condensations occurs.

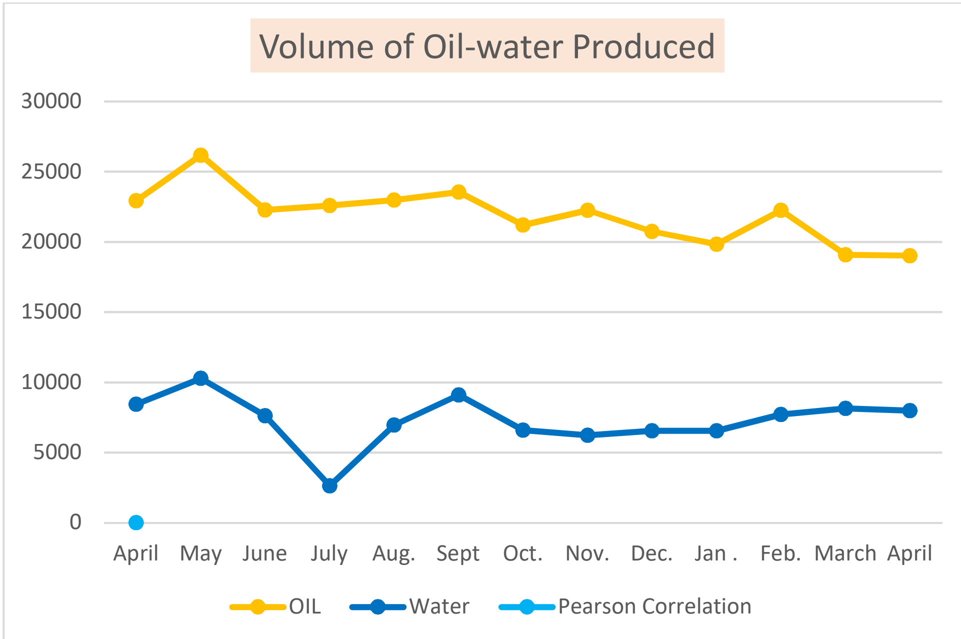
Looking at these dissimilarities, it is possible to compare that FWKO and IGF processes show variations in reduction efficiency in relation to bioremediation ponds and EVP pond. This may be due to the fact that oil-water or gas-liquid separators are technically challenging and even emotionally charged as a result of numerous factors affecting their performance. Biologically, bioremediation ponds and EVP pond will have lower variations because they are almost environmental/physical systems which are less influenced by outside environment or parameters. Altogether, it is possible to gain certain understanding of the stability and efficiency of various operations pertaining to the oil and gas production taking within the framework of such company when it addresses these variances. Understanding the root causes of variance can enable operational personnel to improve control of processes, efficiency of operations, and managing potential negative outcomes from variability in reduction efficiencies.

7.2.5 Pearson Correlation Coefficient

The table 6 and graph 5 explains monthly production volumes of oil and water, and the corresponding Pearson's correlation coefficient of the volumes of oil and water production for each month. Should to become familiar with how to interpret and compare these values. The volumes of oil and water produced as shown below indicate marked differences occurring across the months. The indicated two months namely April and May register slightly higher oil production volumes with the figures showing 22,925 and 26,181 barrels in the two months respectively. On the other hand, the average daily production of oil in December and January is still lower with the production volume being 20,737 and 19,835 barrels respectively. Likewise, the volumes of water production differ with May topping the charts with a throughput of 10,277 barrels and July coming out as the worst with a throughput of only 2,631 barrels.

Table 6: Volume Reduction (Pearson Correlation)

Month	OIL	Water	Pearson Correlation
April	22925	8445	0.273260298
May	26181	10277	
June	22286	7615	
July	22587	2631	
Aug.	22987	6952	
Sept	23540	9096	
Oct.	21206	6589	
Nov.	22259	6220	
Dec.	20737	6550	
Jan.	19835	6549	
Feb.	22242	7720	
March	19082	8151	
April	19026	7983	



Graph 5: Volume of Oil-water Produced (Pearson Correlation). Source: Self-gennerated

Contrasting the two types of production in terms of volumes presented for different months shows different patterns. For instance, while the level indicates that oil production reaches its maximum figure in May, the same can be said of the graph that shows that the production of water also increases in the same month. This would only imply that oil and water are produced simultaneously, where high oil production could mean a corresponding high-water production based on the reservoir characteristics and other causes.

Pearson's Coefficient of correlation indicates the extent of the positive linear relationship between oil and water production measures. A positive value of correlation coefficient shows that products have a positive linear relationship, which implies that in the process of increasing the overall production of oil there is also a tendency of increasing the overall production of water. On the other hand, when the correlation is negative it suggests that an increase in one correlates with the decrease of the other and therefore when the production of oil increases the production of water decreases.

In this case they obtained the Pearson correlation coefficient that lies in the interval of 0. 273 and -0. 273. When the coefficient is positive, as in April (0.273), it means that the increase in the amount of oil production is associated with a small increase in the volume of water production, indicating a positive correlation with a low degree of relation. As with negative coefficients like the one shown above in May (-0. 273), clearly points out a weak negative direct linear relationship between oil and the water produced.

It is important to note that these correlation coefficients tell us that although there is a reasonably clear association between oil and water production totals, the relationship is not very strong. This could be caused by numerous factors like reservoir heterogeneity, characteristics of the fluids, production methodology employed or methods of managing and operating the oil well. Furthermore, fluctuations in the correlation coefficient, depending on the selected months, also indicate that the investigations of oil and water production processes are characterized by significant volatility. Therefore, the study of both the volumes of oil and water production and the value of the Pearson correlation coefficient offers useful information on the relationship between the two factors, which can be beneficial in production forecasting, management of the reservoir, and operational decision-making within the framework of the oil and gas industry.

7.3 Summary of Results

According to the results of the current study raising an evidence it is established that the bioremediation techniques apply in the water treatment process in the Thar Jath oil fields in Unity state Sudan are effective in the removal of oil content. Altogether, the breakdown of average monthly readings conducted using statistical analysis showed the progressive decline of oil levels from FWKO stage to the EVP stage. This reduction analysis determined based on the simple mathematical subtraction equation betwixt the initial and final concentration of oil afforded profound information respecting the efficiency of the treatment. The details drawn out in the year on year comparison included element variability which pointed to consistent differences in oil content, the reasons for which could have been seasonal or purely operational. However, the oscillatory trend in the final six-soak oil content was not alarming because there was a progressive decrease in the oil content at all the stages each month, as characterized by the bioremediation process.

When analyzed in more depth, it was noted that both Pond B and the EVP stage had the lowest values of the oil content as compared to the previous stages, thus highlighting the crucial importance of these stages in order to obtain the required level of product purification. This was so because Pond B has matured bacterial populations that exploited the complex hydrocarbons hence a shorter Curve was achieved through the EVP stage to minimize oil contents in the treated water. This stepwise reduction brought out the fact that each stage was absolutely crucial in striving towards the overall set goals in Bioremediation hinting at the fact that most of the techniques used in this process work in a synergistic manner.

Altogether, the present investigation supplied significant information to support the efficiency of bioremediation specifically in Pond B with established bacteria in minimizing the oil concentration in the water. The fact that both the Pond B and EVP managed to have less final oil content at the end proved the sound and effectiveness of the treatment system. Through this knowledge, the study does not only provide insights into bioremediation techniques but also provides idea solutions for enhancement of water facilities in oil fields. Thus, using natural ways in combination with specially designed steps of treatment, bioremediation appears as efficient and environmentally friendly approach allowing for efficient management of water contaminated with oil, thus corresponding to environmental and sustainable development objectives.

There was an apparent documentation of two ponds ‘A & B’, that went through a bioremediation exercise for 14 months alongside other parameters such as FWKO, IGF, and EVP. Firstly, in both ponds increases during the period of April and May due to contamination. It was then attended by a phase of increased stability and enhancement (June to July). They note that while in September they realized a slight improvement in the level of contamination of both ponds, in August they registered a severe blow with a significant deterioration of results. The remaining months that is between September and December were largely characterized by fluctuations which included some forward movements, (progression) and backward movements (regression). It is worthy to note that the contamination level in Pond B in January was comparatively lower than in the previous month whereas that of Pond A show a tendency to rise again. The same trend was continued through February, and Pond B recorded an appreciable drop. For both ponds, an increase of 15.86% and improvements in water quality in March were recorded again.

The last month (April) had 100% of the specifications for both ponds; it may mean that the ponds were fully rehabilitated or the sampling was over. Possible reasons for the variation include: variations in microorganisms due to seasonal changes, changes in nutrient concentrations, changes in load rates of contaminants, among others. Nevertheless, the initial levels of contamination, and the nature of contaminants largely remain unknown, which would in turn make the understanding of the efficiency of the bioremediation ponds limited if not for these factors. The first gap that could have been avoided is lack of clarity of how various factors such as pond temperature, nutrient concentration, and contaminant inputs affected the reduction data that was collected Introduction of these various factors and association with observed variations in bioremediation efficiency would have been more clarified if assessed alongside the data of reduction.

Based on the evaluation of monthly oil and water production and the introduction of the Pearson indexes, a number of important factors in the production processes in the oil and gas segment can be identified. Heavy–to–light ratios of oil and water are also observed that depicts the nature of reservoirs and their performances in terms of operation during one month as compared to another month. The Pearson correlation coefficients presented below, we can observe that there is indeed a very slight relationship between oil and water production volumes both in well and field levels, therefore, the null hypothesis, has been partly rejected. This clearly shows how it is difficult to isolate the production regime for any one reservoir characteristic, fluid type, or production method when analyzing production rates. These aspects are vital for the management of reservoirs, productivity enhancement, and strategic planning for the businesses in the oil and gas sector since it provides insight into future trends, potential danger that may occur, and measures that needs to be taken to enhance the yield of production.

Chapter 8 Conclusion

This dissertation comprehensively explored the frameworks and conventions established to protect marine and coastal environments worldwide, with a particular focus on produced water from oil drilling and its remediation. These frameworks, ranging from the Nairobi Convention in Eastern Africa to the OSPAR Convention in the North-East Atlantic, collectively emphasize the critical need for regional cooperation, pollution control, and sustainable development. Each framework provides a robust legal and operational foundation for addressing the diverse and complex environmental challenges associated with marine pollution and resource management. By aligning the study's objectives with these international principles, the chapter underscores the importance of a comprehensive approach to environmental protection.

The study at hand focused on the characterization of produced water from oil drilling in Thar Jath (Block 5A) and the evaluation of various remediation techniques. Produced water, a byproduct of oil extraction, poses significant environmental risks due to its complex chemical and biological composition. The study's year-long sampling period ensures a thorough understanding of seasonal variations in produced water characteristics, providing a robust dataset for analysis. This detailed characterization is essential for identifying specific pollutants, such as heavy metals, hydrocarbons, salts, and microbial content, which are crucial for designing effective remediation strategies.

The evaluation of remediation techniques—physical, chemical, and biological—addresses the core principles advocated by the international frameworks. Physical techniques, such as filtration and sedimentation, offer immediate solutions for removing particulate matter and some dissolved substances. Chemical methods, including coagulation, oxidation, and advanced oxidation processes, can effectively reduce the concentration of harmful contaminants. Biological treatments, through bioremediation and phytoremediation, utilize natural processes and organisms to degrade pollutants, offering a sustainable and eco-friendly approach. By assessing these methods, the study aims to determine the most effective techniques for treating produced water in the specific context of Thar Jath, considering local environmental conditions and pollutant profiles.

The study's contribution to designing a proper remediation technique based on the identified criteria is a significant step towards sustainable environmental management. The specific criteria, of pollutant concentrations, seasonal variations, and local ecosystem characteristics—ensure that the proposed remediation strategies are both effective and adaptable. This approach aligns with the integrated management strategies promoted by the international frameworks, emphasizing the need for tailored solutions that address local environmental challenges while adhering to global best practices.

Moreover, the study highlights the importance of regional cooperation and knowledge sharing, as emphasized by the frameworks. By documenting its findings and proposed remediation strategies, the study facilitates collaboration among regional stakeholders, including governments, environmental organizations, and the oil industry. This collaborative approach is essential for addressing transboundary environmental issues and ensuring the long-term sustainability of marine and coastal ecosystems. The study's findings can serve as a model for other regions facing similar challenges, contributing to global efforts in pollution control and sustainable resource management.

Therefore, the study underscores the critical importance of aligning local environmental studies with international frameworks to enhance the effectiveness and sustainability of pollution management strategies. The detailed characterization of produced water and the comprehensive evaluation of remediation techniques provide valuable insights for designing effective treatment solutions. By contributing to the broader goals of marine and coastal protection, the study not only addresses the specific environmental challenges of Thar Jath but also supports global efforts in sustainable development and environmental conservation. This alignment not only validates the study's approach but also emphasizes its significance in contributing to regional and international environmental objectives. The study is a critical step towards developing effective, sustainable, and locally adapted solutions for managing produced water and protecting marine and coastal environments from the impacts of oil drilling.

References

Abbas, A.J., Gzar, H.A. and Rahi, M.N., 2021, February. Oilfield-produced water characteristics and treatment technologies: a mini review. In IOP Conference Series: Materials Science and Engineering (Vol. 1058, No. 1, p. 012063). IOP Publishing.

Abdelfattah, I. and El-Shamy, A.M., 2024. Review on the escalating imperative of zero liquid discharge (ZLD) technology for sustainable water management and environmental resilience. Journal of Environmental Management, 351, p.119614.

Abdelgadir, M., 2021. Life Cycle Assessment of Crude Oil Processing Plant in Sudan (Doctoral dissertation, Marmara Universitesi (Turkey)).

Abdullah, A.N., Rahman, S., Essex, S. and Benhin, J., 2020. Economic contributions of mega-dam infrastructure as perceived by local and displaced communities: a case study of merowe dam, sudan. Agriculture, 10(6), p.227.

Abiola, O.N., 2019. Polymers for coagulation and flocculation in water treatment. Polymeric materials for clean water, pp.77-92.

Abou Khalil, C., Prince, V.L., Prince, R.C., Greer, C.W., Lee, K., Zhang, B. and Boufadel, M.C., 2021. Occurrence and biodegradation of hydrocarbons at high salinities. Science of the Total Environment, 762, p.143165.

Adam, A.H., 2020. The Insecure Investment Climate & It's Impact on Foreign Direct Investment Flows in SUDAN.

Ahmad, A. and Azam, T., 2019. Water purification technologies. In Bottled and Packaged Water (pp. 83-120). Woodhead Publishing.

Ahmed, H.A.M., 2003. Studies of Some Physical Properties of Sudanese crude oil (Doctoral dissertation, University of Khartoum).

Ahmed, M.B., Zhou, J.L., Ngo, H.H., Guo, W., Thomaidis, N.S. and Xu, J., 2017. Progress in the biological and chemical treatment technologies for emerging contaminant removal from wastewater: a critical review. Journal of hazardous materials, 323, pp.274-298.

Ahmed, Q.A., Nimir, H.B., Hussien, M.A., Zomrawi, M.M., Babiker, E.M. and Fadul, I., 2018, December. Evaluation of seepage from evaporation ponds of produced water in some sudanese oilfields. In Conference Proceedings Civil Engineering 2018.

Ahmed, S.F., Mofijur, M., Nuzhat, S., Chowdhury, A.T., Rafa, N., Uddin, M.A., Inayat, A., Mahlia, T.M.I., Ong, H.C., Chia, W.Y. and Show, P.L., 2021. Recent developments in physical, biological, chemical, and hybrid treatment techniques for removing emerging contaminants from wastewater. Journal of hazardous materials, 416, p.125912.

Akhtar, N., Syakir Ishak, M.I., Bhawani, S.A. and Umar, K., 2021. Various natural and anthropogenic factors responsible for water quality degradation: A review. Water, 13(19), p.2660.

Al-Ameri, W., Elhassan, A. and Maher, R., 2023. Optimization of electro-oxidation and electro-Fenton techniques for the treatment of oilfield produced water. Water and Environment Journal, 37(1), pp.126-141.

Al-Ghouti, M.A., Al-Kaabi, M.A., Ashfaq, M.Y. and Da'na, D.A., 2019. Produced water characteristics, treatment and reuse: A review. Journal of Water Process Engineering, 28, pp.222-239.

Ali, S., Abbas, Z., Rizwan, M., Zaheer, I.E., Yavaş, İ., Ünay, A., Abdel-Daim, M.M., Bin-Jumah, M., Hasanuzzaman, M. and Kalderis, D., 2020. Application of floating aquatic plants in phytoremediation of heavy metals polluted water: A review. Sustainability, 12(5), p.1927.

Alkhadra, M.A., Su, X., Suss, M.E., Tian, H., Guyes, E.N., Shocron, A.N., Conforti, K.M., De Souza, J.P., Kim, N., Tedesco, M. and Khoiruddin, K., 2022. Electrochemical methods for water purification, ion separations, and energy conversion. Chemical reviews, 122(16), pp.13547-13635.

Allaire, M., Wu, H. and Lall, U., 2018. National trends in drinking water quality violations. Proceedings of the National Academy of Sciences, 115(9), pp.2078-2083.

Al-Mutaz, I.S., 2022. Thermal processes. In A Multidisciplinary Introduction to Desalination (pp. 95-153). River Publishers.

Al-Shayji, K.A., Al-Wadyei, S. and Elkamel, A., 2005. Modelling and optimization of a multistage flash desalination process. Engineering optimization, 37(6), pp.591-607.

Altinbilek, D. and Hatipoglu, M.A., 2020. Water resources development. Water Resources of Turkey, pp.61-84.

Amakiri, K.T., Canon, A.R., Molinari, M. and Angelis-Dimakis, A., 2022. Review of oilfield produced water treatment technologies. Chemosphere, 298, p.134064.

Asante-Sackey, D., Rathilal, S., Tetteh, E.K. and Armah, E.K., 2022. Membrane bioreactors for produced water treatment: A mini-review. Membranes, 12(3), p.275.

Asante-Sackey, D., Rathilal, S., Tetteh, E.K. and Armah, E.K., 2022. Membrane bioreactors for produced water treatment: A mini-review. Membranes, 12(3), p.275.

Asante-Sackey, D., Rathilal, S., Tetteh, E.K. and Armah, E.K., 2022. Membrane bioreactors for produced water treatment: A mini-review. Membranes, 12(3), p.275.

Azuazu, I.N., Sam, K., Campo, P. and Coulon, F., 2023. Challenges and opportunities for low-carbon remediation in the Niger Delta: towards sustainable environmental management. Science of the Total Environment, p.165739.

Babatunde, B.B., Sikoki, F.D., Avwiri, G.O. and Chad-Umoreh, Y.E., 2019. Review of the status of radioactivity profile in the oil and gas producing areas of the Niger delta region of Nigeria. Journal of environmental radioactivity, 202, pp.66-73.

Barimah, R., 2019. Geochemical Feasibility of Brine Exchange Between Arbuckle and Lansing-Kansas City Formations as a Produced Water Management Alternative (Doctoral dissertation, University of Kansas).

Baza, J., Chard, S., Dunkel, M., Kell, S., Harris, K. and Saunders, N., 2019. Groundwater Protection Council Produced water report: Regulations, current practices, and research needs. In WEFTEC 2019-92nd Annual Water Environment Federation's Technical Exhibition and Conference.

Bellefontaine, N., Donner, P., Hildebrand, L. and Johansson, T., 2018. Oil spill intervention in the Mediterranean Sea. Oil Pollution in the Mediterranean Sea: Part I: The International Context, pp.79-103.

Benansio, J.S., Funk, S.M., Lino, J.L., Balli, J.J., Dante, J.O., Dendi, D., Fa, J.E. and Luiselli, L., 2022. Perceptions and attitudes towards climate change in fishing communities of the Sudd Wetlands, South Sudan. Regional Environmental Change, 22(2), p.78.

Bhojwani, S., Topolski, K., Mukherjee, R., Sengupta, D. and El-Halwagi, M.M., 2019. Technology review and data analysis for cost assessment of water treatment systems. Science of the Total Environment, 651, pp.2749-2761.

Bianchi, C.N., Azzola, A., Cocito, S., Morri, C., Oprandi, A., Peirano, A., Sgorbini, S. and Montefalcone, M., 2022. Biodiversity monitoring in Mediterranean marine protected areas: Scientific and methodological challenges. Diversity, 14(1), p.43.

Boxer, B., 1979, March. Mediterranean Oil Pollution Monitoring and Control: Technical and Policy Issues. In *International Oil Spill Conference* (Vol. 1979, No. 1, pp. 283-285). American Petroleum Institute.

Bundhoo, Z.M., 2018. Solid waste management in least developed countries: current status and challenges faced. Journal of Material Cycles and Waste Management, 20, pp.1867-1877.

Capodaglio, A.G., 2020. Critical perspective on advanced treatment processes for water and wastewater: AOPs, ARPs, and AORPs. Applied Sciences, 10(13), p.4549.

Carpenter, A. and Johansson, T., 2018. The Barcelona Convention and its role in oil pollution prevention in the Mediterranean Sea. *Oil Pollution in the Mediterranean Sea: Part I: The International Context*, pp.129-166.

Chandra, P., Mudgal, A. and Patel, J., 2024. Effect of feed water temperature on the performance and economics of thermal energy driven multiple effect distillation system for water treatment. Hybrid Advances, p.100179.

Chang, H., Li, T., Liu, B., Vidic, R.D., Elimelech, M. and Crittenden, J.C., 2019. Potential and implemented membrane-based technologies for the treatment and reuse of flowback and produced water from shale gas and oil plays: A review. Desalination, 455, pp.34-57.

Charcosset, C., 2016. Ultrafiltration, microfiltration, nanofiltration and reverse osmosis in integrated membrane processes. Integrated membrane systems and processes, pp.1-22.

Chatterjee, S., Kumari, S., Rath, S. and Das, S., 2022. Prospects and scope of microbial bioremediation for the restoration of the contaminated sites. In Microbial Biodegradation and Bioremediation (pp. 3-31). Elsevier.

Chen, G.Q., Gras, S.L. and Kentish, S.E., 2019. Separation technologies for salty wastewater reduction in the dairy industry. Separation & Purification Reviews, 48(4), pp.325-353.

Christodoulou, A. and Stamatelatou, K., 2016. Overview of legislation on sewage sludge management in developed countries worldwide. Water Science and Technology, 73(3), pp.453-462.

Coady, L., Lister, J., Strandberg, C. and Ota, Y., 2013. The role of corporate social responsibility (CSR) in the international shipping sector. A phase, 2.

Coha, M., Farinelli, G., Tiraferri, A., Minella, M. and Vione, D., 2021. Advanced oxidation processes in the removal of organic substances from produced water: Potential, configurations, and research needs. Chemical Engineering Journal, 414, p.128668.

Convention for the Protection of the Marine Environment and Coastal Area of the South-East Pacific. (1981, November 12). Retrieved from https://www.ecolex.org/details/treaty/convention-for-the-protection-of-the-marine-environment-and-coastal-area-of-the-south-east-pacific-tre-000741/

Cooper, C.M., McCall, J., Stokes, S.C., McKay, C., Bentley, M.J., Rosenblum, J.S., Blewett, T.A., Huang, Z., Miara, A., Talmadge, M. and Evans, A., 2021. Oil and gas produced water reuse: Opportunities, treatment needs, and challenges. ACS ES&T Engineering, 2(3), pp.347-366.

D. Atoufi, H. and Lampert, D.J., 2020. Impacts of oil and gas production on contaminant levels in sediments. Current pollution reports, 6, pp.43-53.

D. Atoufi, H., Lampert, D.J. Impacts of Oil and Gas Production on Contaminant Levels in Sediments . Curr Pollution Rep 6, 43–53 (2020). https://doi.org/10.1007/s40726-020-00137-5

da Silva Gonçalves, A.H., de Andrade, F.P., De Farias Silva, C.E., Medeiros, J.A., Santos, G.K.S., do Nascimento, M.A.A., Tonholo, J. and Almeida, R.M.R.G., 2023. Biological treatment of petroleum produced water ex situ using microorganisms: an overview, main developments and challenges. Energy, Ecology and Environment, 8(4), pp.289-303.

Darabinia, M. and Nagafi Asfad, M., 2012. Performance of Kuwait regional convention on Persian Gulf marine environment. *Journal of Mazandaran University of Medical Sciences*, *22*(96), pp.71-78.

Di Sacco, A., Hardwick, K.A., Blakesley, D., Brancalion, P.H., Breman, E., Cecilio Rebola, L., Chomba, S., Dixon, K., Elliott, S., Ruyonga, G. and Shaw, K., 2021. Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits. Global Change Biology, 27(7), pp.1328-1348.

Doreen, S., 2021. Oil Production Activities and Community Well-Being in Upper Nile (Melut) and Unity State (Koch) in South Sudan (Doctoral dissertation, Institute of Petroleum Studies-Kampala).

Doreen, S., 2021. Oil Production Activities and Community Well-Being in Upper Nile (Melut) and Unity State (Koch) in South Sudan (Doctoral dissertation, Institute of Petroleum Studies-Kampala).

Eaton, W.M., Brasier, K.J., Burbach, M.E., Whitmer, W., Engle, E.W., Burnham, M., Quimby, B., Kumar Chaudhary, A., Whitley, H., Delozier, J. and Fowler, L.B., 2021. A conceptual framework for social, behavioral, and environmental change through stakeholder engagement in water resource management. Society & Natural Resources, 34(8), pp.1111-1132.

Echchelh A., Hess, T., Sakrabani, R., Prigent, S. and Stefanakis, A.I., 2021. Towards agro-environmentally sustainable irrigation with treated produced water in hyper-arid environments. Agricultural Water Management, 243, p.106449.

El Mquirmi, N., 2021. The Sudan at a Crossroads: Multi-layered Fragility. Policy Center for New South", November, pp.2022-01.

Elbrir, F.A., 2018. The Effect of Produced Water from Heglig Oil Field on Chemical Additives for Fracturing Fluids. J Environ Anal Chem, 5(237), pp.2380-2391.

Emeka-Okoli, S., Nwankwo, T.C., Otonnah, C.A. and Nwankwo, E.E., 2024. Environmental stewardship and corporate social responsibility: A review of case studies from the oil and gas sector. World Journal of Advanced Research and Reviews, 21(3), pp.069-077.

Esmaeilion, F., Ahmadi, A., Hoseinzadeh, S., Aliehyaei, M., Makkeh, S.A. and Astiaso Garcia, D., 2021. Renewable energy desalination; a sustainable approach for water scarcity in arid lands. International Journal of Sustainable Engineering, 14(6), pp.1916-1942.

Etikala, B., Adimalla, N., Madhav, S., Somagouni, S.G. and Keshava Kiran Kumar, P.L., 2021. Salinity problems in groundwater and management strategies in arid and semi-arid regions. Groundwater geochemistry: pollution and remediation methods, pp.42-56.

Fakhru'l-Razi, A., Pendashteh, A., Abdullah, L.C., Biak, D.R.A., Madaeni, S.S. and Abidin, Z.Z., 2009. Review of technologies for oil and gas produced water treatment. Journal of hazardous materials, 170(2-3), pp.530-551.

Fallet, M.G., 2010. The impact of the oil industry on local communities in South Sudan (Master's thesis).

Farooq, U., Patil, A., Panjwani, B. and Simonsen, G., 2021. Review on application of nanotechnology for asphaltene adsorption, crude oil demulsification, and produced water treatment. Energy & Fuels, 35(23), pp.19191-19210.

Folkerts, E.J., Goss, G.G. and Blewett, T.A., 2020. Investigating the potential toxicity of hydraulic fracturing flowback and produced water spills to aquatic animals in freshwater environments: a North American perspective. Reviews of Environmental Contamination and Toxicology Volume 254, pp.1-56.

Gamwo, I.K., Azam, H.M. and Baled, H.O., 2022. Produced Water Treatment Technologies: An Overview. Solid–Liquid Separation Technologies, pp.1-24.

Gamwo, I.K., Azam, H.M. and Baled, H.O., 2022. Produced Water Treatment Technologies: An Overview. Solid–Liquid Separation Technologies, pp.1-24.

Gathuoy, P.L.D., 2022. A Critical Evaluation of The Petroleum Regulatory Framework in The Context of Environmental Issues of South Sudan (Doctoral dissertation, Institute of Petroleum Studies-Kampala).

Ghafoori, S., Omar, M., Koutahzadeh, N., Zendehboudi, S., Malhas, R.N., Mohamed, M., Al-Zubaidi, S., Redha, K., Baraki, F. and Mehrvar, M., 2022. New advancements, challenges, and future needs on treatment of oilfield produced water: A state-of-the-art review. Separation and Purification Technology, 289, p.120652.

Ghafoori, S., Omar, M., Koutahzadeh, N., Zendehboudi, S., Malhas, R.N., Mohamed, M., Al-Zubaidi, S., Redha, K., Baraki, F. and Mehrvar, M., 2022. New advancements, challenges, and future needs on treatment of oilfield produced water: A state-of-the-art review. Separation and Purification Technology, 289, p.120652.

Ghafoori, S., Omar, M., Koutahzadeh, N., Zendehboudi, S., Malhas, R.N., Mohamed, M., Al-Zubaidi, S., Redha, K., Baraki, F. and Mehrvar, M., 2022. New advancements, challenges, and future needs on treatment of oilfield produced water: A state-of-the-art review. Separation and Purification Technology, 289, p.120652.

Ghafoori, S., Omar, M., Koutahzadeh, N., Zendehboudi, S., Malhas, R.N., Mohamed, M., Al-Zubaidi, S., Redha, K., Baraki, F. and Mehrvar, M., 2022. New advancements, challenges, and future needs on treatment of oilfield produced water: A state-of-the-art review. Separation and Purification Technology, 289, p.120652.

Hadzihafizovic, D., 2024. Production Operations in Oilfield. Available at SSRN 4741926.

Hakim, S., Naqqash, T., Nawaz, M.S., Laraib, I., Siddique, M.J., Zia, R., Mirza, M.S. and Imran, A., 2021. Rhizosphere engineering with plant growth-promoting microorganisms for agriculture and ecological sustainability. Frontiers in Sustainable Food Systems, 5, p.617157.

Hale, S.E., Neumann, M., Schliebner, I., Schulze, J., Averbeck, F.S., Castell-Exner, C., Collard, M., Drmač, D., Hartmann, J., Hofman-Caris, R. and Hollender, J., 2022. Getting in control of persistent, mobile and toxic (PMT) and very persistent and very mobile (vPvM) substances to protect water resources: strategies from diverse perspectives. Environmental Sciences Europe, 34(1), p.22.

Hornstein, D.T. and Hornstein, E.D., 2023. Climate Change and Biotechnology. NCJL & Tech., 25, p.109.

Jabbo, J.N., Isa, N.M., Aris, A.Z., Ramli, M.F. and Abubakar, M.B., 2022. Geochemometric approach to groundwater quality and health risk assessment of heavy metals of Yankari Game Reserve and its environs, Northeast Nigeria. Journal of Cleaner Production, 330, p.129916.

Jasim, N.A., 2020. The design for wastewater treatment plant (WWTP) with GPS X modelling. Cogent Engineering, 7(1), p.1723782.

Jiang, W., Lin, L., Xu, X., Wang, H. and Xu, P., 2022. Analysis of regulatory framework for produced water management and reuse in major oil-and gas-producing regions in the United States. Water, 14(14), p.2162.

Jiménez, S.M., Micó, M.M., Arnaldos, M., Medina, F. and Contreras, S., 2018. State of the art of produced water treatment. Chemosphere, 192, pp.186-208.

Kabyl, A., Yang, M., Abbassi, R. and Li, S., 2020. A risk-based approach to produced water management in offshore oil and gas operations. Process safety and Environmental protection, 139, pp.341-361.

Kang, Z., Zhao, Y. and Yang, D., 2020. Review of oil shale in-situ conversion technology. Applied Energy, 269, p.115121.

Kebede, G., Tafese, T., Abda, E.M., Kamaraj, M. and Assefa, F., 2021. Factors influencing the bacterial bioremediation of hydrocarbon contaminants in the soil: mechanisms and impacts. Journal of Chemistry, 2021, pp.1-17.

Kennedy, A.R., 2022. Does it pay to pay for success? Stakeholder perceptions of costs and benefits of PFS feasibility studies. Public Performance & Management Review, 45(5), pp.1088-1111.

Kesari, K.K., Soni, R., Jamal, Q.M.S., Tripathi, P., Lal, J.A., Jha, N.K., Siddiqui, M.H., Kumar, P., Tripathi, V. and Ruokolainen, J., 2021. Wastewater treatment and reuse: a review of its applications and health implications. Water, Air, & Soil Pollution, 232, pp.1-28.

Kiefer, J.R., 2009. Wastewater treatment and disposal. ENGINEERING, SIXTH, p.283.

Koppel, D.J., Kho, F., Hastings, A., Crouch, D., MacIntosh, A., Cresswell, T. and Higgins, S., 2022. Current understanding and research needs for ecological risk assessments of naturally occurring radioactive materials (NORM) in subsea oil and gas pipelines. Journal of environmental radioactivity, 241, p.106774.

Kumar, L., Chugh, M., Kumar, S., Kumar, K., Sharma, J. and Bharadvaja, N., 2022. Remediation of petrorefinery wastewater contaminants: A review on physicochemical and bioremediation strategies. Process Safety and Environmental Protection, 159, pp.362-375.

Kuran, C.H.A., Morsut, C., Kruke, B.I., Krüger, M., Segnestam, L., Orru, K., Nævestad, T.O., Airola, M., Keränen, J., Gabel, F. and Hansson, S., 2020. Vulnerability and vulnerable groups from an intersectionality perspective. International Journal of Disaster Risk Reduction, 50, p.101826.

Lado, F.E.S., 2021. Thermal Enhanced Oil Recovery and Potential Benefits for Use of Produced Water for Agriculture and Food Security: A Case Study of Oil Fields in South Sudan (Doctoral dissertation, Virginia Tech).

Lado, F.E.S., 2021. Thermal Enhanced Oil Recovery and Potential Benefits for Use of Produced Water for Agriculture and Food Security: A Case Study of Oil Fields in South Sudan (Doctoral dissertation, Virginia Tech).

Li, C., Gao, X., Li, S. and Bundschuh, J., 2020. A review of the distribution, sources, genesis, and environmental concerns of salinity in groundwater. Environmental Science and Pollution Research, 27, pp.41157-41174.

Longxin, M.U., Yaqiang, C.H.E.N., Anzhu, X.U. and Ruifeng, W.A.N.G., 2020. Technological progress and development directions of PetroChina overseas oil and gas field production. Petroleum Exploration and Development, 47(1), pp.124-133.

Löw, F., Stieglitz, K. and Diemar, O., 2021. Terrestrial oil spill mapping using satellite earth observation and machine learning: A case study in South Sudan. *Journal of Environmental Management*, *298*, p.113424.

Manu, D.A.K., 2011. The emerging oil industry in Ghana: Socio-economic and environmental impact on the people of Cape Three Points (Master's thesis, Norwegian University of Life Sciences, Ås).

Mao, H., Yang, Y., Zhang, H., Zhang, J. and Huang, Y., 2020. A critical review of the possible effects of physical and chemical properties of subcritical water on the performance of water-based drilling fluids designed for ultra-high temperature and ultra-high pressure drilling applications. Journal of Petroleum Science and Engineering, 187, p.106795.

M'Arimi, M.M., Mecha, C.A., Kiprop, A.K. and Ramkat, R., 2020. Recent trends in applications of advanced oxidation processes (AOPs) in bioenergy production. Renewable and Sustainable Energy Reviews, 121, p.109669.

Martínez, R., Vela, N., El Aatik, A., Murray, E., Roche, P. and Navarro, J.M., 2020. On the use of an IoT integrated system for water quality monitoring and management in wastewater treatment plants. Water, 12(4), p.1096.

Mathelemusa, A., 2021. Challenges of nation building in the 21st Century Africa: Experiences from South Sudan, 2011-2013 (Doctoral dissertation).

McGregor, N. and Yeung, G., 2022. Strategic coupling, path creation and diversification: Oil-related development in the 'Straits Region'since 1959. The Extractive Industries and Society, 11, p.101085.

Meng, X., Tan, X., Wang, Y., Wen, Z., Tao, Y. and Qian, Y., 2019. Investigation on decision-making mechanism of residents' household solid waste classification and recycling behaviors. Resources, Conservation and Recycling, 140, pp.224-234.

Mohamed, E.H.A., 2001. Evaluation of some chemical and physical parameters of Sudanese crude oil.

Mohammad, J., 2021. Assessment of the geothermal resources of the Republic of the Sudan (Doctoral dissertation, Prince of Songkla University).

Mohammadi, M.H., Kulakhmetovna, Y.A. and Joia, R., 2024. An Overview of Oil Recovery Techniques: From Primary to Enhanced Oil Recovery Methods. Journal for Research in Applied Sciences and Biotechnology, 3(1), pp.291-301.

Mohebi, Z. and Nazari, M., 2021. Phytoremediation of wastewater using aquatic plants, A review. Journal of Applied Research in Water and Wastewater, 8(1), pp.50-58.

Moradi, M., Vasseghian, Y., Arabzade, H. and Khaneghah, A.M., 2021. Various wastewaters treatment by sono-electrocoagulation process: a comprehensive review of operational parameters and future outlook. Chemosphere, 263, p.128314.

Mukherjee, S., Sikdar, P.K. and Pal, S., 2021. Sustainable governance of groundwater as drinking water in the post-COVID-19 world: An urban water security perspective. In Legacy, Pathogenic and Emerging Contaminants in the Environment (pp. 311-338). CRC Press.

Mukhopadhyay, A., Duttagupta, S. and Mukherjee, A., 2022. Emerging organic contaminants in global community drinking water sources and supply: A review of occurrence, processes and remediation. Journal of Environmental Chemical Engineering, 10(3), p.107560.

Murashko, K., Nikku, M., Sermyagina, E., Vauterin, J.J., Hyppänen, T., Vakkilainen, E. and Pyrhönen, J., 2018. Techno-economic analysis of a decentralized wastewater treatment plant operating in closed-loop. A Finnish case study. Journal of Water Process Engineering, 25, pp.278-294.

Mushtaq, F., Raza, Z.A., Batool, S.R., Zahid, M., Onder, O.C., Rafique, A. and Nazeer, M.A., 2022. Preparation, properties, and applications of gelatin-based hydrogels (GHs) in the environmental, technological, and biomedical sectors. International journal of biological macromolecules, 218, pp.601-633.

Nair, N.V. and Nayak, P.K., 2023. Exploring Water Quality as a Determinant of Small-Scale Fisheries Vulnerability. Sustainability, 15(17), p.13238.

Naorem, A., Jayaraman, S., Dang, Y.P., Dalal, R.C., Sinha, N.K., Rao, C.S. and Patra, A.K., 2023. Soil constraints in an arid environment—challenges, prospects, and implications. Agronomy, 13(1), p.220.

Nasiri, M., Jafari, I. and Parniankhoy, B., 2017. Oil and gas produced water management: a review of treatment technologies, challenges, and opportunities. Chemical engineering communications, 204(8), pp.990-1005.

Neff, J.M., 2002. Bioaccumulation in marine organisms: effect of contaminants from oil well produced water. Elsevier.

Ni, L., Tian, J., Song, T., Jong, Y. and Zhao, J., 2019. Optimizing geometric parameters in hydrocyclones for enhanced separations: a review and perspective. Separation & Purification Reviews, 48(1), pp.30-51.

Nikbeen, T. and Nayab, A.K., 2023. Transformation of Traditional Wastewater Treatment Methods into Advanced Oxidation Processes and the Role of Ozonation. Journal of Ecological Engineering, 24(6).

Nweke, I.A. and Ilo, G.E., 2019. Cultivation and land use changes their implications in soil productivity management and crop yield. Agriculture and Agribusiness, 4(1), pp.35-62.

Oetjen, K., Chan, K.E., Gulmark, K., Christensen, J.H., Blotevogel, J., Borch, T., Spear, J.R., Cath, T.Y. and Higgins, C.P., 2018. Temporal characterization and statistical analysis of flowback and produced waters and their potential for reuse. Science of the Total Environment, 619, pp.654-664.

Ogunbiyi, O., Al-Rewaily, R., Saththasivam, J., Lawler, J. and Liu, Z., 2023. Oil spill management to prevent desalination plant shutdown from the perspectives of offshore cleanup, seawater intake and onshore pretreatment. *Desalination*, p.116780.

Omer, A., 2019. Water resources management and sustainable development in Sudan. LAP LAMBERT Academic Publishing.

Omer, A.A.E., 2017. Structural Style and Its Impact on Trap Formation and Hydrocarbon Distribution in Muglad Rift Basin, Sudan (Doctoral dissertation, University of Malaya (Malaysia)).

Osman, A.K. and Ali, A.M., 2021. Sudan–Land, Climate, Energy, Agriculture and Development: A Study in the Sudano-Sahel Initiative for Regional Development, Jobs, and Food Security.

Panagopoulos, A., Haralambous, K.J. and Loizidou, M., 2019. Desalination brine disposal methods and treatment technologies-A review. Science of the Total Environment, 693, p.133545.

Pandey, P. and Yadav, R., 2018. A review on volatile organic compounds (VOCs) as environmental pollutants: fate and distribution. International Journal of Plant and Environment, 4(02), pp.14-26.

Paustenbach, D.J., Langenbach, B.T. and Wenning, R.J., 2024. Primer on human and environmental risk assessment. Human and ecological risk assessment: theory and practice, 1, pp.1-69.

Pessôa, L.C., Cruz, E.P., Deamici, K.M., Andrade, B.B., Carvalho, N.S., Vieira, S.R., da Silva, J.B.A., Pontes, L.A.M., de Souza, C.O., Druzian, J.I. and de Jesus Assis, D., 2022. A review of microalgae-based biorefineries approach for produced water treatment: Barriers, pretreatments, supplementation, and perspectives. Journal of Environmental Chemical Engineering, 10(4), p.108096.

Puttasrinivasa, C.S., Yogarajachari, R.M., Gurusiddappa, L.H., Kachintaya, C.K. and Kalikeri, S., 2023. Advance oxidation processes for wastewater treatment: A crucial tool for sustainability. In Concept of Zero Liquid Discharge (pp. 163-185). Elsevier.

Quteishat, M.A.K., 2020. Hydrocyclone flow characteristics and measurements. Flow Measurement and Instrumentation, 73, p.101741.

Rahman, A., Agrawal, S., Nawaz, T., Pan, S. and Selvaratnam, T., 2020. A review of algae-based produced water treatment for biomass and biofuel production. Water, 12(9), p.2351.

Raiter, K.G., Prober, S.M., Possingham, H.P., Westcott, F. and Hobbs, R.J., 2018. Linear infrastructure impacts on landscape hydrology. Journal of Environmental Management, 206, pp.446-457.

Rathi, B.S., Kumar, P.S. and Vo, D.V.N., 2021. Critical review on hazardous pollutants in water environment: Occurrence, monitoring, fate, removal technologies and risk assessment. Science of the Total Environment, 797, p.149134.

Regional Organization for the Protection of the Marine Environment (ROPME). (1998). *Protocol Concerning Marine Transboundary Movements and Disposal of Hazardous Wastes and Other Wastes*. Retrieved from https://ropme.org/wp-content/uploads/2019/12/Hazardous_Wastes_Protocol.pdf

Ruach, N.T., 2015. The Traumatic Past and Uncertain Future of South Sudan: Perspective from Social Responsibility on Local and Global Issues & the Relentless Struggle for Education. AuthorHouse.

Rugland, E., 2021. Integrating Land and Water: Tools, Practices, Processes, and Evaluation Criteria. Cambridge: Lincoln Institute of Land Policy. https://www. lincolninst. edu/sites/default/files/pubfiles/rugland_wp21er1_1. pdf.

Sadeghfar, F., Ghaedi, M. and Zalipour, Z., 2021. Advanced oxidation. In Interface Science and Technology (Vol. 32, pp. 225-324). Elsevier.

Saeed, M.U., Hussain, N., Sumrin, A., Shahbaz, A., Noor, S., Bilal, M., Aleya, L. and Iqbal, H.M., 2022. Microbial bioremediation strategies with wastewater treatment potentialities–A review. Science of the total environment, 818, p.151754.

Saha, S. and Saha, S., 2020. Toward Sustainable Conservation Plan for Fragile Ecosystem in Indian Sunderban. In Urban and Transit Planning: A Culmination of Selected Research Papers from IEREK Conferences on Urban Planning, Architecture and Green Urbanism, Italy and Netherlands (2017) (pp. 193-202). Springer International Publishing.

Salem, F. and Thiemann, T., 2022. Produced water from oil and gas exploration—problems, solutions and opportunities. Journal of Water Resource and Protection, 14(2), pp.142-185.

Samuel, O., Othman, M.H.D., Kamaludin, R., Sinsamphanh, O., Abdullah, H., Puteh, M.H., Kurniawan, T.A., Li, T., Ismail, A.F., Rahman, M.A. and Jaafar, J., 2022. Oilfield-produced water treatment using conventional and membrane-based technologies for beneficial reuse: A critical review. Journal of Environmental Management, 308, p.114556.

Sánchez-Pastor, P., Obermann, A., Reinsch, T., Ágústsdóttir, T., Gunnarsson, G., Tómasdóttir, S., Hjörleifsdóttir, V., Hersir, G.P., Ágústsson, K. and Wiemer, S., 2021. Imaging high-temperature geothermal reservoirs with ambient seismic noise tomography, a case study of the Hengill geothermal field, SW Iceland. Geothermics, 96, p.102207.

Sanchez-Rosario, R. and Hildenbrand, Z.L., 2022. Produced water treatment and valorization: A techno-economical review. Energies, 15(13), p.4619.

Sanchez-Rosario, R. and Hildenbrand, Z.L., 2022. Produced water treatment and valorization: A techno-economical review. Energies, 15(13), p.4619.

Santos, E., Carvalho, M. and Martins, S., 2023. Sustainable Water Management: Understanding the Socioeconomic and Cultural Dimensions. Sustainability, 15(17), p.13074.

Santos, R.G.D., Loh, W., Bannwart, A.C. and Trevisan, O.V., 2014. An overview of heavy oil properties and its recovery and transportation methods. Brazilian Journal of Chemical Engineering, 31, pp.571-590.

Saravanan, A., Kumar, P.S., Jeevanantham, S., Karishma, S., Tajsabreen, B., Yaashikaa, P.R. and Reshma, B., 2021. Effective water/wastewater treatment methodologies for toxic pollutants removal: Processes and applications towards sustainable development. Chemosphere, 280, p.130595.

Saravanan, A., Kumar, P.S., Jeevanantham, S., Karishma, S., Tajsabreen, B., Yaashikaa, P.R. and Reshma, B., 2021. Effective water/wastewater treatment methodologies for toxic pollutants removal: Processes and applications towards sustainable development. Chemosphere, 280, p.130595.

Seyyedi, M. and Sohrabi, M., 2020. Oil reservoir on a chip: Pore-scale study of multiphase flow during near-miscible CO2 EOR and storage. Transport in Porous Media, 134(2), pp.331-349.

Sheehan, D. (Ed.) (1997). Bioremediation protocols.

Sheng, Y., Zhang, L., Wang, Y. and Miao, Z., 2020. Exploration of a novel three-dimensional knitted spacer air filter with low pressure drop on cooking fume particles removal. Building and Environment, 177, p.106903.

Shi, J., Huang, W., Han, H. and Xu, C., 2021. Pollution control of wastewater from the coal chemical industry in China: Environmental management policy and technical standards. Renewable and Sustainable Energy Reviews, 143, p.110883.

Shmeis, R.M.A., 2018. Water chemistry and microbiology. In Comprehensive analytical chemistry (Vol. 81, pp. 1-56). Elsevier.

Silva, T.L., Morales-Torres, S., Castro-Silva, S., Figueiredo, J.L. and Silva, A.M., 2017. An overview on exploration and environmental impact of unconventional gas sources and treatment options for produced water. Journal of environmental management, 200, pp.511-529.

Sørbø, G.M., 2020. Sudan's transition: Living in bad surroundings. Sudan Working Paper.

Sun, Y., Iris, K.M., Tsang, D.C., Cao, X., Lin, D., Wang, L., Graham, N.J., Alessi, D.S., Komárek, M., Ok, Y.S. and Feng, Y., 2019. Multifunctional iron-biochar composites for the removal of potentially toxic elements, inherent cations, and hetero-chloride from hydraulic fracturing wastewater. Environment international, 124, pp.521-532.

Tai, U.M., Fan, L.Y., Sun, C.Z., Cheng, X.D. and Ran, H.J., 2021, October. Study and Application of Complex Fault Block Reservoir Characterization in TM Oilfield, South Sudan. In International Field Exploration and Development Conference (pp. 4580-4595). Singapore: Springer Nature Singapore.

Thor, B.Y., 2019. Effects of oil production activities on the socioeconomic wellbeing of communities living in greater unity, South Sudan (Doctoral dissertation, Africa Nazarene University).

Thor, B.Y., 2019. Effects of oil production activities on the socioeconomic wellbeing of communities living in greater unity, South Sudan (Doctoral dissertation, Africa Nazarene University).

Tomomewo, O.S., 2021. Reducing Produced Water Disposal Via Effective Treatments Methods And Re-Use: Proposed Sustainable Application For Bakken, North Dakota (Doctoral dissertation, The University of North Dakota).

Totowa New Jersey:Humana Press. Hatzikioseyian, A. (2010). Principles of bioremediation processes. Research Signpost 37/661 (2), 695-723.

Tree, C., 2020. Scholars Academic Journal of Biosciences.

UNEP. (n.d.). Cartagena Convention. Retrieved from https://www.unep.org/cep/who-we-are/cartagena-convention

UNEP. (n.d.). Convention for Cooperation in the Protection and Sustainable Development of the Marine and Coastal Environment of the Northeast Pacific. Retrieved from https://www.unep.org

UNEP. (n.d.). Convention for the Protection of Natural Resources and Environment of the South Pacific Region (Noumea Convention). Retrieved from https://www.unep.org

UNEP. (n.d.). Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention). Retrieved from https://www.unep.org

UNEP. (n.d.). Convention for the Protection, Management and Development of the Marine and Coastal Environment of the Eastern African Region (Nairobi Convention). Retrieved from https://www.unep.org

UNEP. (n.d.). Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). Retrieved from https://www.unep.org

UNEP. (n.d.). Convention on the Protection of the Black Sea Against Pollution (Bucharest Convention). Retrieved from https://www.unep.org

UNEP. (n.d.). Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention). Retrieved from https://www.unep.org

UNEP. (n.d.). Framework Convention for the Protection of the Marine Environment of the Caspian Sea. Retrieved from https://www.unep.org

United Nations Terminology Database. (n.d.). *Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol)*. Retrieved from https://unterm.un.org/unterm2/en/view/UNHQ/e7ee3673-5095-42c0-b5e6-a839984eda1e

University of the West Indies, Cave Hill. (n.d.). SPAW Protocol factsheet. Retrieved from https://www.cavehill.uwi.edu/cermes/research-projects/ebm-dss/docs/spaw_factsheet.aspx

VAJPAYEE, S. and BHALALA, V., 2023. A COMPARATIVE STUDY OF THERMAL ENHANCED OIL RECOVERY METHOD. I-Manager's Journal on Material Science, 10(4).

Vallabhan, M.K., 2022. Produced water treatment using hydrocyclones-Theoretical and experimental studies of novel control schemes.

Viaene, N., Hallmann, J. and Molendijk, L.P., 2021. Methods for nematode extraction. In Techniques for work with plant and soil nematodes (pp. 12-41). Wallingford UK: CABI.

Wang, L.K., Wang, M.H.S., Shammas, N.K. and Hahn, H.H., 2021. Physicochemical treatment consisting of chemical coagulation, precipitation, sedimentation, and flotation. Integrated natural resources research, pp.265-397.

Witchell-Chibber, A., 2020. From a Policy of Non-Interference to Proactive Engagement (Doctoral dissertation, Utrecht University).

Yacovitch, T.I., Daube, C. and Herndon, S.C., 2020. Methane emissions from offshore oil and gas platforms in the Gulf of Mexico. Environmental science & technology, 54(6), pp.3530-3538.

Yousef, R., Qiblawey, H. and El-Naas, M.H., 2020. Adsorption as a process for produced water treatment: A review. Processes, 8(12), p.1657.

Zhang, H., Gao, C., Zhang, H., Song, N. and Cao, Q., 2024. Recent advances on the treatment of oilfield-produced water by advanced oxidation processes: A review. Water Reuse, p.jwrd2024003.

Ziganshina, E.E., Mohammed, W.S. and Ziganshin, A.M., 2023. Microbial Diversity of the Produced Waters from the Oilfields in the Republic of Tatarstan (Russian Federation): Participation in Biocorrosion. Applied Sciences, 13(24), p.12984.

Zooalnoon, M.O. and Musa, A., 2019. Evaluation of produced water quality by using water quality indices in Heglig area, Sudan. Journal of Water Supply: Research and Technology—AQUA, 68(7), pp.607-615.