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Biological Treatment of Produced Water: A Review of Microbial Processes, Bioelectrochemical Systems and Emerging Biotechnologies for Sustainable Management

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ABSTRACT

Produced water during oil and gas operations contains complex mixtures of organic and inorganic pollutants. Biological treatments are a sustainable way to reduce the concentration of pollutants contained within the produced water and assist with reuse. This review discusses traditional biological treatments including activated sludge, biofilm reactors, constructed wetlands, and anaerobic systems, and novel biological treatments such as bioelectrochemical systems, halophiles, and algae. The efficiency, drawbacks, and possible application of these technologies within Nigerian oil and gas industries has been evaluated. Fixed bed hybrid biological reactor systems have shown high chemical oxygen demand (COD) removal efficiencies up to 95%. Bioelectrochemical systems have shown to achieve approximately 90% contaminant removal of select pollutants. However, problems with high salinity levels, presence of toxic substances, complex produced water composition and lack of technical knowledge are a significant challenge. This is especially true within Nigeria as the produced water can contain up to 100,000 mg/L of salts. This review has identified ways that improvements can be made by developing salt tolerating cultures, combining biological treatments with physiochemical treatments and evaluating in pilot scale within local conditions. Full characterisation of produced water is also crucial. If biological treatment is properly designed it has a huge potential for sustainable produced water management within Nigeria's petroleum industry.

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INTRODUCTION

The management of produced water generated during oil and gas operations poses significant environmental challenges due to the complex composition of contaminants [1] [2] [3]. Biological treatment processes have been identified as a viable solution for managing produced water by providing an eco-friendly and cost-effective method for removing organic contaminants [4] [5]. These processes use the metabolic activity of microorganisms to decompose hydrocarbons and other organic contaminants into less harmful forms.

Produced water management has become an important aspect of sustainable oil and gas production due to increasing volumes of produced water and the complexity of its chemical composition. It contains a range of chemical characteristics that vary depending on the geological formation, extraction processes, reservoir maturity and chemicals used. The main chemical constituents include dissolved salts, dispersed and dissolved hydrocarbons, organic acids, phenols, heavy metals, suspended solids and residual production chemicals. This makes selecting the correct treatment technologies challenging [6] [7] [8].

There has been increasing interest in using produced water for beneficial purposes after treatment. This can help reduce the amount of

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freshwater required, reduce the amount of wastewater produced and improve resource efficiency in the petroleum industry. To achieve water of the correct quality, processes are required to remove both organic and inorganic contaminants. Biological treatment can offer a solution to this by reducing the amount of biodegradable organics in the water prior to desalination or advanced polishing [9] [10] [11].

Biological treatment of produced water has been of great interest in recent years. [12] reviewed the use of bioelectrochemical systems as innovative technologies for treating produced water from the oil and gas industry. These systems use a combination of biological and electrochemical processes to treat the wastewater providing an efficient and sustainable way of removing contaminants.

However, there are challenges associated with using biological treatment for produced water. Due to the high salinity levels, produced water can inhibit microbial activity [13]. The total dissolved solids can be very high with concentrations often above 100,000 mg/L. This causes osmotic stress which can inhibit the growth of microbes. The presence of hydrocarbons and other toxic compounds can also inhibit microbial growth meaning they require acclimation.

This review analysed biological treatment methods for produced water. These include traditional methods such as activated sludge and bioreactors. It also includes new technologies such as bioelectrochemical systems and microbial desalination cells. The paper also evaluates the performance of the different methods, factors affecting their performance and challenges and opportunities for implementation in Nigeria. The review will add to the growing body of knowledge on biological treatment of produced water and provide insight on how to develop sustainable treatment solutions for the Nigerian oil and gas industry.

BIOLOGICAL TREATMENT FUNDAMENTALS

Microbial Processes for Contaminant Removal

Biological treatment of produced water relies on metabolic processes of microorganisms to break down organic contaminants. Different biological treatments such as bioreactors and constructed wetlands have been described which use the natural ability of bacteria to degrade organic compounds [5]. Microorganisms will use organic compounds as a source of energy and carbon to create CO_2, water, and biomass.

Oxygen is used as a terminal electron acceptor in the aerobic treatment of organic contaminants. This process is effective at breaking down a wide range of hydrocarbons and other organic compounds to form CO_2 and water [14]. Oxygen must be provided via aeration which increases the amount of energy required. However, this treatment is faster and more complete. Anaerobic treatment does not require oxygen, and instead uses alternative electron acceptors such as nitrate, sulphate and CO_2. Methane and CO_2 are produced as end products. This can be captured and used as a source of energy [15]. However, this process is less energy intensive as it does not require aeration. It is slower than aerobic treatment.

The effectiveness of biological treatment is dependant on the variety of microorganisms and their metabolic capabilities. Different groups of microorganisms can contribute to the breakdown of organic contaminants derived from petroleum. Bacteria such as Pseudomonas, Bacillus, Acinetobacter and Rhodococcus have been studied for their ability to use petroleum hydrocarbons as a carbon and energy source. These bacteria will break down hydrocarbons through enzymatic reactions into intermediate products which can then be broken down into simpler compounds [16] [17].

Microbial consortiums may provide benefits when using bacteria. Different microorganisms can contribute to the breakdown of contaminants. Some will break down the complex hydrocarbons, whilst others will break down the intermediate products. This may improve the biodegradation of contaminants. The composition and stability of the microbial community in consideration for biological treatment of produced water is important. Recent studies have been carried out into microorganisms found in petroleum production environments to

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identify hydrocarbon degrading bacteria that are tolerant to stress [18] [19].

The type of microbial process will depend on the produced water being treated. The type and concentration of the organic compounds, salinity and presence of toxic compounds should be considered. To optimise biological treatment, the temperature, pH, nutrients and hydraulic retention time should be controlled to ensure active and stable microorganisms.

Factors Affecting Biological Treatment Performance

Several factors influence the performance of biological treatment systems for produced water. This includes salinity, temperature, pH, availability of nutrients and presence of toxic compounds. Biodesalination of raw hypersaline produced water samples has been investigated using native algal consortia from wastewater [13]. Salinity can greatly impact microbial activity during produced water treatment due to the osmotic stress caused. This can lead to reduced microbial growth and contaminant removal. However, halophilic and halotolerant microbes can adapt to high salinity making them suitable for treating hypersaline wastewaters [16] [17].

Moving bed biofilm and fixed bed hybrid reactors were evaluated at salinities between 1.5-20g/L. They showed high efficiency with >90% COD removal. However, salinity was shown to change the microbial species present which could impact long term stability [20]. Microbial adaptation and reactor type is an important consideration when treating produced water using biological methods [21] [22].

Table 1: Factors Affecting Biological Treatment of Produced Water [5], [13], *and* [14]

Factor	Optimal Range	Effect on Treatment	Management Strategies
Salinity (TDS)	< 35,000 mg/L	High salinity inhibits microbial activity, reduces treatment efficiency	Halophilic microorganisms, dilution, salt-tolerant strains
Temperature	25-35°C	Affects microbial growth rates and enzyme activity	Temperature control, thermophilic or psychrophilic organisms
pH	6.5-8.0	Affects enzyme activity and nutrient availability	pH adjustment using acids or bases
Dissolved Oxygen	2-4 mg/L (aerobic)	Essential for aerobic treatment, affects metabolic pathways	Aeration, oxygen supply systems
Nutrients (N, P)	COD:N:P = 100:5:1	Essential for microbial growth and metabolism	Nutrient addition, supplementation
Hydraulic Retention Time	1-10 days	Longer retention increases removal but requires larger systems	System design, flow rate optimization
Organic Loading Rate	Varies by system	High loading can overload system, reduce removal	Pre-treatment, loading optimization
Toxic Compounds	Minimize	Inhibit or kill microorganisms, reduce treatment	Pre-treatment, acclimation, resistant strains
Oil and Grease	< 50 mg/L	Coats microorganisms, inhibits mass transfer	Pre-treatment, oil-water separation

Table 1 provides information on the factors affecting biological treatment of produced water, ideal ranges of each factor, impact on biological treatment and ways to manage each factor. One of the biggest challenges in biological treatment is the high salinity of the produced

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water. This can be overcome by using halophilic or salt-tolerant microbes. Alternatively, the salinity can be reduced by diluting.

The presence of toxic compounds can also cause problems. These may be hydrocarbons, heavy metals or other contaminants. Microbial communities will need to be pre-treated or acclimated. [14] noted that the high salinity present in produced water can be an issue as it can inhibit microbial activity. This can make biological treatment ineffective for many produced waters. The presence of toxic compounds such as phenols and heavy metals can also cause issues and microbial communities will need to be pre-treated or acclimated.

Advantages and Limitations

Biological treatments have many benefits over physical and chemical treatments options. This includes being an environmentally friendly option and being cost effective. It can also ensure total removal of organic compounds [5]. Chemicals are not required so there is no risk of causing secondary pollution. Biological treatments can have a high removal of organic compounds. Using Fixed bed hybrid biological reactors can have removal rates of up to 95% for COD [14]. This means they can be a great option to reduce the organic compounds in produced water.

However, there are also many drawbacks to using biological treatment options. The high salinity can cause issues with the microorganisms. Toxic compounds can cause inhibition or death to the microorganisms. Retention times generally will be longer than physical/chemical options. This means larger treatment systems are required.

CONVENTIONAL BIOLOGICAL TREATMENT METHODS

Activated Sludge Systems

Activated sludge is one of the most common biological wastewater treatments. Here microorganisms suspended in aerated tanks are used to break down organic compounds and the biomass is recycled to create high concentrations of microorganisms [14]. Although activated sludge has high organic compound removal efficiency, the produced water can have high salinity and toxicity.

The success of the activated sludge system relies on an active and diverse community of microorganisms being maintained, which are able to break down the specific organic compounds in the produced water. A study was performed to compare the effectiveness of conventional activated sludge and fixed bed hybrid biological reactors for treating oilfield produced water. The effect of hydraulic retention time was studied and it was found that conventional activated sludge systems were less effective than hybrid systems [14]. This effect was more pronounced with shorter hydraulic retention times. Careful control of the system is required to ensure the correct running of an activated sludge system. Aeration rates, hydraulic retention times and sludge retention times must be controlled. The high salinity and toxicity of the produced water can cause problems such as foaming and bulking.

Biofilm and Fixed-Film Reactors

Biofilm reactors and fixed film reactors are an alternative to suspended growth systems. In these systems, microorganisms will attach to media and form biofilms, therefore creating a high concentration of active biomass [14]. Biofilm systems have several benefits when treating produced water as they can resist toxic compounds. Recent studies have shown that biofilm systems are suitable for treating difficult produced waters. An anaerobic/anoxic/moving bed biofilm reactor with microfiltration membranes has been developed to treat real produced water from a strong alkali ASP flooding system at a pH of 10.1-10.4 [23].

The system achieved removal efficiencies of 99% average for petroleum, 57% for COD, 66% for suspended solids, 40% for polymers and 44% for surfactants. Analysis by GC-MS showed that alkanes and olefins were being degraded. Analysis of the microbial community showed that Paracoccus, Synergistaceae and Trichococcus were the main functional bacteria responsible for degrading the pollutants. This study shows that a composite

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biofilm system can be used to treat extreme pH levels and complex pollutants.

A fixed bed hybrid biological reactor containing free activated sludge and biofilm was studied for treating produced water from the oilfield [14]. The fixed bed hybrid biological reactor treats synthetic produced water from the oilfield by using both free activated sludge and biofilm. The system allows for increased microbial diversity and high removal efficiencies of contaminants. Particularly at short hydraulic retention times compared to traditional activated sludge reactors. The system achieved high COD removal efficiencies of 95%. However, the system was expensive and required experts to run and maintain. Biofilm systems such as trickling filters, rotating biological contactors and moving bed biofilm reactors have the benefit of having high biomass concentrations and can resist toxic compounds. They can achieve high removal efficiencies of organics.

Constructed Wetlands

Constructed wetlands are natural biological treatment systems that utilise physical, chemical and biological mechanisms to remove contaminants from water. Wastewater is treated by using wetland vegetation and microorganisms to remove organic compounds, nutrients and some heavy metals [5]. Advantages of constructed wetlands include being low energy and requiring little maintenance. However, they have a large land footprint and can be affected by climatic conditions.

In recent years, life cycle assessments have shown that there is a good economic case for using constructed wetlands to treat produced water. A detailed review was carried out assessing the use of constructed wetlands to treat produced water in the oilfield industry [24]. This showed that constructed wetlands can reduce capital costs by approximately 50% and operating and maintenance costs by 90% compared to thermal, membrane, chemical and electrochemical technologies. It was also projected that the amount of conventional produced water generated from both onshore and offshore will double globally over the next decade (from approximately 158,900 to 243,000 million barrels per day). This supports the argument that constructed wetlands can be a good option to treat produced water due to them being low energy and requiring little maintenance. Provided they are not restricted by land availability.

However, the high salinity of produced water can cause problems when using constructed wetlands to treat produced water. Salt tolerant vegetation and halophilic microorganisms can be used to treat saline produced water. However, this can only remove some organic compounds and nutrients. This is a slow process and requires a large area. Constructed wetlands can be used as polishing systems to treat produced water. They can be a good option if low energy treatment is required. They use the interaction between wetland vegetation, microorganisms, sediments and substrates to remove or transform any remaining organic compounds and specific chemical additives. However, the efficiency of a constructed wetland depends on the influent water, flow rate, retention time, vegetation type and environmental conditions.

A study was carried out to investigate the use of constructed wetlands to polish produced water from the oil and gas industry [24]. This highlighted that constructed wetlands can be a relevant option to treat produced water that is released. However, the high salinity and potential toxicity of produced water must be considered when selecting vegetation types. Therefore, they may be more suitable as polishing systems after sufficient pretreatment.

Anaerobic Treatment Systems

Anaerobic systems utilise anaerobic microbes which can break down organic compounds and produce methane and carbon dioxide [15]. Advantages of using anaerobic systems include low energy use and biogas production. However, anaerobic systems do tend to be slower than aerobic systems and can also not fully break down complex organic compounds. A study was performed to investigate the effectiveness of anaerobic treatment of produced water using an anaerobic digester inoculum from

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a brewery wastewater treatment plant [15]. It was shown that produced water could be treated using anaerobic treatment but there were issues with keeping the microbial activity stable due to the changing composition and salinity of the produced water. The high salinity and toxic compounds can inhibit anaerobic microbes.

Anaerobic systems such as anaerobic digesters, upflow anaerobic sludge blanket reactors and anaerobic filters can be used to treat produced water but the conditions must be carefully controlled to keep the microbial communities stable. Sulfate present in produced water can cause hydrogen sulfide to be produced which is toxic and corrosive.

BIOELECTROCHEMICAL SYSTEMS

Principles of Bioelectrochemical Systems

Bioelectrochemical systems are an emerging treatment technology. [12] reviews a range of bioelectrochemical systems such as microbial fuel cells, microbial electrolysis cells, microbial desalination cells and microbial electro-synthesis cells for treating produced water. They work by using biological and electrochemical processes to treat wastewater. This makes them an efficient and sustainable way of removing contaminants from wastewater. They create useful products such as electricity or hydrogen.
There is a lot of energy in organic matter which can be wasted.

Conventional wastewater treatment uses a lot of energy. There is a lot of potential energy however it is often treated with high energy methods that could be optimised [12]. Bioelectrochemical systems make use of the energy released from the breakdown of organic matter. This lowers the amount of energy needed for treatment and can create useful products. Bioelectrochemical systems work by microorganisms metabolising and passing electrons onto the electrode. The microorganisms will oxidise organic molecules and pass electrons onto the anode. The electrons then travel to the cathode via an external circuit. This creates an electrical current which can be used or used to drive useful reactions.

Microbial Fuel Cells

Microbial fuel cells (MFCs) are bioelectrochemical systems that produce electricity through the breakdown of organic matter. A study carried out by [26] investigated the integration of electrochemical and bioelectrochemical systems to sustainably treat produced water. The study found that the removal efficiency of COD and total petroleum hydrocarbon was good at 90%. However, the removal efficiency of total dissolved solids and sulphates were not good at only 34.3% and 42.6%. MFCs depend on many factors such as the type of microbes, electrode material, membrane and process conditions. The high salinity of produced water may affect the conductivity and performance of MFCs. Toxic compounds can also inhibit the microbes. It is important to develop strong microbes and electrode materials to treat produced water using MFCs.

Combining MFCs with existing anaerobic treatments can be a good strategy to overcome the issues of using MFCs alone. A study was carried out at a lab scale to combine an up-flow anaerobic sludge blanket (UASB) reactor with sequential MFCs. The study found that the removal efficiency of COD was greater than 90% and removal of NH 3-N was 83% at a hydraulic retention time of 26 hours for treating oilfield wastewater [25]. Instrumental analysis showed a satisfactory level of biodegradation occurred for most hydrocarbons. The system was able to produce electricity and treat oily wastewater. This shows that MFCs can be incorporated into conventional treatments. An advantage of using MFCs is electricity is produced during treatment. This can reduce the cost of treating wastewater. However, the amount of electricity produced is generally low compared to conventional energy sources. Combining MFCs with other treatments can improve the overall performance of the system.

Microbial Electrolysis Cells

Microbial electrolysis cells (MEC) are bioelectrochemical systems that use electrical energy to produce hydrogen or other valuable products from the breakdown of organic

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compounds. [12] explains the principle and application of MECs for wastewater treatment. Hydrogen can be produced using this method providing a clean energy source. The process of MECs are similar to MFCs however, an external voltage is applied to cause hydrogen to form at the cathode. Microorganisms will break down organic compounds at the anode and transfer electrons to the cathode. This will produce hydrogen however extra energy is needed to produce this valuable product. Problems with using MECs for treating produced water include the high salinity and toxic nature of the produced water, which can cause inhibition of the microbes. Careful control of the process is required to produce hydrogen as the pH, temperature and voltage need to be controlled.

Microbial Desalination Cells

Microbial desalination cells (MDCs) are bioelectrochemical systems that can be used to desalinate water by using ion exchange membranes to transport ions. [12] described MDCs and their principles and applications for water desalination. The system consists of 3 chambers separated by anion and cation exchange membranes. Microorganisms in the anode chamber oxidise organic compounds producing an electrical potential which drives ion transport from the middle chamber into the external chambers. Water in the middle chamber is desalinated.

However, recent reviews have provided insight into how MDCs function and the limitations that still exist. [27] performed a detailed review of catalyst and electrode modifications for MDCs. They confirmed that the desalination occurs due to the electrical potential produced during microbial oxidation at the anode. This drives ion transport through the ion exchange membranes. However, there were limitations with the low proton mobility and slow oxygen reduction reactions. Low proton mobility caused a decrease in pH in the anolyte, which is detrimental to the microorganisms. Ion exchange membranes are expensive and so a limitation to scale-up for produced water applications. Produced water has high salinity and is toxic. However, MDCs could be applied to treat the water as it would remove organic contamination. There is a need to develop strong microbes and membranes to allow effective treatment of produced water using MDCs

Microbial Electro-synthesis Cells

Microbial electro-synthesis (MES) cells are an example of bioelectrochemical systems that use electrical energy to produce valuable products from CO_2 or other substrates [12]. The principles and potential applications of MES are discussed by [12]. MES uses microorganisms to utilise electrical energy to reduce CO_2 or other substrates to produce valuable products such as methane, acetate and other organic products. This process can help with capturing CO_2 and converting it into useful products. This can aid in carbon sequestration and sustainable production. Microbial electro-synthesis uses electroactive microorganisms to produce valuable products from CO_2 or other substrates. These products can include acetate, methane and other organic products.

This process has potential for resource recovery and sustainable wastewater treatment. However, the efficiency of this process is dependent on the properties of the electrodes, the microorganisms present, the availability of the substrates and electron transfer. This process has not been explored much for treating produced water and more experimentation is needed [12] [28]. Using MES for treating produced water has the potential to convert organic pollutants and CO_2 into valuable products. However, this technology is in its early stages of development and has issues such as low production rates and high energy demands.

EMERGING BIOTECHNOLOGIES AND INNOVATIONS

Halophilic and Extremophilic Microorganisms

The development of halophilic and extremophilic microorganisms has been explored as a method of treating high salinity produced water. A study has shown biodesalination and treatment of raw hypersaline produced water

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samples using native algal consortia from wastewater [13].

The use of halophilic microorganisms in produced water treatment offers advantages as they do not require dilution or desalination. These organisms have evolved to survive in high salinity environments by being able to perform metabolic processes in high salinity environments that would be inhibitory to conventional microorganisms. By isolating and characterising halophilic microorganisms found in produced water environments, produced water can be effectively treated using biological methods.

For halophilic microorganisms to be applied in produced water treatment, strong microbial communities must be developed to degrade the specific organic matter found within produced water. Operating conditions will need to be optimised to provide an environment suitable for halophilic microorganisms to thrive. This includes optimum temperature, pH, and nutrients.

Algal and Cyanobacterial Treatment

Treatment of produced water using algae and cyanobacteria can be used as a method to remove nutrients and break down organics via photosynthesis. In a study by [13] evalauted biodesalination and treating raw hypersaline produced water samples using indigenous algal consortia from wastewater. There are many benefits to using algae to treat produced water. Algae can be used to produce biomass, which can then be used for biofuel production. Algae can also remove nutrients and heavy metals from wastewater. However, due to the high salinity and toxic nature of produced water, salt tolerant species of algae will need to be used. The use of algae alongside other biological and physiochemical treatments may help to increase the overall efficiency of the treatment process. Algae could be used to remove nutrients and produce biomass, whilst other treatments could be used to remove organic contaminants and salts.

Enzyme-Based and Biocatalytic Approaches

Enzymatic and biocatalytic methods can be used to remove certain contaminants from produced water using isolated enzymes and whole-cell biocatalysts. This can be a highly efficient and specific method to degrade target compounds. However, enzymes can have issues with their stability.

Enzymes can be used to remove specific contaminants from produced water including hydrocarbons, phenols and other toxic compounds that cannot be removed using traditional biological methods. However, enzymes can have issues with their stability due to high salinity and variable conditions of produced water. By developing stable and robust enzymes using protein engineering and immobilisation, they could be used to effectively remove contaminants from produced water. Combined with other biological and physio-chemical treatments, enzyme treatment can provide a complete treatment of produced water.

APPLICATION IN THE NIGERIAN CONTEXT

Challenges and Opportunities

There are several challenges to using biological treatment for produced water in Nigeria. It has been noted that whilst there are many methods for treating produced water they are difficult to maintain in Nigeria due to the lack of access to original equipment manufacturers [29]. Biological treatment systems will require specialist equipment and expertise to operate. The high salinity levels in produced water from Nigerian oilfields make biological treatment challenging. The total dissolved solids can often be greater than 100,000 mg/L which causes osmotic stress, thus inhibiting microbial activity [30]. To overcome this issue halophilic microbes may be required, or dilution.

The characteristics of produced water from Nigerian oilfields show the need for systems to treat the actual water composition. It has been reported that after conventional treatment there are still heavy metals and organics present [31]. This means that simply removing the oil and greases may not be sufficient and polishing may be required. Treated produced water from facilities in the Niger Delta was analysed to see if it could be used for irrigation [32]. The study found that whilst it did partially meet Nigerian standards, it did

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not meet some international water quality requirements. This shows there is a need for further treatment and monitoring.

Toxic compounds are also present in produced water from Nigerian oilfields. This includes hydrocarbons, heavy metals and other contaminants. These can be inhibitory or lethal to microorganisms. Pre-treatment of the produced water or acclimating the microbes may be required. Resistant microbial communities can be developed by acclimating and enriching the microbes to allow effective treatment of toxic produced water. There are also many opportunities for using biological treatment in Nigeria. With the increasing awareness of the environmental and economic costs of discharging produced water there is a demand for sustainable treatment options. There is great potential for water reuse in the Nigerian oil and gas industry. Biological treatment can provide water that can be used for various reuses.

Potential Applications and Strategies

Biological treatment could be applied to produced water in Nigeria to help reduce the organic load. It has been shown that biological treatment can achieve high removals of COD and thus reduce the organic load of produced water [14]. This would reduce the environmental impact of produced water discharge and allow compliance to standards. By combining biological treatment with other treatments, full treatment of produced water can be achieved.

Pre-treatment such as physical chemical treatment could be used to remove oil and suspended solids followed by biological treatment. This could then be followed by membrane filtration or advanced treatment to provide highly treated effluent. Bioelectrochemical treatment could be used to treat produced water in Nigeria. This is effective at removing contaminants from produced water and also produces useful by-products. It has been noted that Bioelectrochemical treatment has been successfully used to remove different types of contaminants [12].

RECOMMENDATIONS

Based on the analysis presented in this review, some recommendations are:

1. An in-depth characterization of produced water from Nigerian oilfields needs to be carried out in order to design the right biological system for the treatment of produced water. This includes the characterization of organic compounds, salinity, toxic compounds, etc.
2. Halophilic and extremophilic microbial cultures need to be developed. Microorganisms can be isolated from produced water and enriched to develop strong cultures that can treat high salinity produced water.
3. Pilot scale studies need to be carried out to determine the performance of biological treatment systems. This will provide data on how well the system will perform, in terms of costs and maintenance.
4. Biological treatment systems can be integrated with other methods to provide a complete treatment. Combining biological treatment with physical chemical or membrane treatment can lead to high contaminant removal.
5. Training is needed to build up local expertise. Training should be provided on how to run the system, carry out maintenance and troubleshoot the system.

CONCLUSION

Biological treatment methods have great potential in removing the organic compounds present in produced water. Although conventional biological treatment methods such as activated sludge, biofilm reactors, constructed wetlands and anaerobic can achieve high levels of organic removal, problems occur due to the high salinity and toxicity of produced water. New technologies such as Bioelectrochemical systems and halophilic microorganisms can overcome these issues.

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There are several challenges with using biological treatment on produced water in Nigeria. These include the high salinity, toxic nature of produced water, lack of technical knowledge and lack of support from the original equipment manufacturers. However, there are also many opportunities for using biological treatment. These include treating the organic load, combining with other treatment methods and creating sustainable treatment methods.

Creating halophilic and extremophilic microorganisms that are specific to the produced water in Nigeria could allow effective biological treatment. Combining biological treatment with other treatment methods can provide a complete solution to produced water. This reduces the impact produced water can have on the environment and allows beneficial reuse. By overcoming these challenges and taking advantage of the opportunities identified in this review biological treatment can help provide sustainable solutions to produced water in the Nigerian oil and gas industry

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REFERENCES

[1] C. M. Cooper *et al.*, 'Oil and Gas Produced Water Reuse : Opportunities , Treatment Needs , and Challenges', *Am. Chem. Soc.*, 2021, doi: 10.1021/acsestengg.1c00248.
[2] A. Fakhru'l-Razi, A. Pendashteh, L. C. Abdullah, D. R. A. Biak, S. S. Madaeni, and Z. Z. Abidin, 'Review of technologies for oil and gas produced water treatment', *J. Hazard. Mater.*, vol. 170, no. 2–3, pp. 530–551, 2009, doi: 10.1016/j.jhazmat.2009.05.044.
[3] A. C. Klemz *et al.*, 'Oilfield produced water treatment by liquid-liquid extraction: A review', *J. Pet. Sci. Eng.*, vol. 199, no. July 2020, 2021, doi: 10.1016/j.petrol.2020.108282.
[4] K. T. Amakiri, A. R. Canon, M. Molinari, and A. Angelis-Dimakis, 'Review of oilfield produced water treatment technologies', *Chemosphere*, vol. 298, no. November 2021, p. 134064, 2022, doi: 10.1016/j.chemosphere.2022.134064.
[5] S. Ghafoori *et al.*, 'New advancements, challenges, and future needs on treatment of oilfield produced water: A state-of-the-art review', *Sep. Purif. Technol.*, vol. 289, no. November 2021, p. 120652, 2022, doi: 10.1016/j.seppur.2022.120652.
[6] F. Al-ajmi, M. Al-marri, F. Almomani, and A. AlNouss, 'A Comprehensive Review of Advanced Treatment Technologies for the Enhanced Reuse of Produced Water', *Water*, vol. 16, 2024, doi: 10.3390/w16223306 Academic.
[7] D. Yelatontsev, A. Mukhachev, and V. Shevchenko, 'Comprehensive utilization of mineral resources in produced water from oil and gas industry – A critical review', *Desalination*, vol. 619, no. October 2025, p. 119558, 2026, doi: 10.1016/j.desal.2025.119558.
[8] M. A. Al-ghouti, M. A. Al-kaabi, M. Y. Ashfaq, and D. Adel, 'Produced water characteristics, treatment and reuse : A review', *J. Water Process Eng.*, vol. 28, no. January, pp. 222–239, 2019, doi: 10.1016/j.jwpe.2019.02.001.
[9] O. L. Adepitan, O. O. C. D. Gbadeyan, and O. A. Joseph, 'Systems-Level Optimization of Hybrid Produced Water Treatment Systems for Sustainable Oil and Gas Production : A Review of Current Technologies', *Glob. Challenges*, pp. 1–21, 2026, doi: 10.1002/gch2.202500575.

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[10]C. Abdelhamid, A. Latrach, M. Rabiei, and K. Venugopal, 'Produced Water Treatment Technologies : A Review', *energies*, vol. 18, no. 63, 2025, doi: 10.3390/en18010063.

[11]A. Rajbongshi and S. Borgohain, 'A review on oil fi eld produced water and its treatment technologies', *Pet. Res.*, vol. 9, no. 4, pp. 640–656, 2024, doi: 10.1016/j.ptlrs.2024.06.003.

[12]J. Cabrera, M. Irfan, Y. Dai, P. Zhang, Y. Zong, and X. Liu, 'Chemosphere Bioelectrochemical system as an innovative technology for treatment of produced water from oil and gas industry : A review', *Chemosphere*, vol. 285, no. June, p. 131428, 2021, doi: 10.1016/j.chemosphere.2021.131428.

[13]S. Nadersha and A. Aly Hassan, 'Biodesalination and treatment of raw hypersaline produced water samples using indigenous wastewater algal consortia', *Desalination*, vol. 528, no. December 2021, p. 115638, 2022, doi: 10.1016/j.desal.2022.115638.

[14]N. Lusinier, I. Seyssiecq, C. Sambusiti, M. Jacob, N. Lesage, and N. Roche, 'A comparative study of conventional activated sludge and fixed bed hybrid biological reactor for oilfield produced water treatment: Influence of hydraulic retention time', *Chem. Eng. J.*, vol. 420, no. P2, p. 127611, 2021, doi: 10.1016/j.cej.2020.127611.

[15]Z. Huang, X. He, C. Nye, D. Bagley, M. Urynowicz, and M. Fan, 'Effective anaerobic treatment of produced water from petroleum production using an anaerobic digestion inoculum from a brewery wastewater treatment facility', *J. Hazard. Mater.*, vol. 407, no. June 2020, p. 124348, 2021, doi: 10.1016/j.jhazmat.2020.124348.

[16]L. C. Castillo-Carvajal, J. L. Sanz-Martín, and B. E. Barragán-Huerta, 'Biodegradation of organic pollutants in saline wastewater by halophilic microorganisms: a review', *Environ. Sci. Pollut. Res.*, vol. 21, 2014, doi: 10.1007/s11356-014-3036-z.

[17]M. T. Jamal and A. Pugazhendi, 'Degradation of petroleum hydrocarbons and treatment of refinery wastewater under saline condition by a halophilic bacterial consortium enriched from marine environment (Red Sea), Jeddah, Saudi Arabia', *3Biotech*, vol. 8, no. 276, 2018, doi: 10.1007/s13205-018-1296-x.

[18]I. I. Inoma and L. Evbuomwan, 'BIODEGRADATION OF TOTAL PETROLEUM HYDROCARBONS IN PRODUCED FORMATION WATER BY INDIGENOUS BACTERIAL ISOLATES FROM DELTA STATE, NIGERIA', *COAST J. Sch. Sci.*, vol. 7, no. 1, pp. 1243–1254, 2025, doi: 10.4314/coast.v7i2.3s Abstract.

[19]N. Mao *et al.*, 'Integrated Analysis of Paired Crude Oil and Produced Water Reveals Stress-Tolerant Hydrocarbon-Degrading Bacteria with Bioremediation Potential', *Microorganisms*, vol. 14, no. 1981, pp. 1–21, 2026, doi: Microorganisms 20210.3390/microorganisms14091981.

[20]N. Lusinier, I. Seyssiecq, C. Sambusiti, M. Jacob, N. Lesage, and N. Roche, 'Application of Moving Bed Biofilm Reactor and Fixed Bed Hybrid Biological Reactor for Oilfield Produced Water Treatment : Influence of Total Dissolved Solids Concentration', *Energies*, vol. 14, no. 7297, 2021, doi: 10.3390/en14217297 Abstract:

[21]M. A. Abujayyab, M. Hamouda, and A. Aly, 'Biological treatment of produced water : A comprehensive review and metadata analysis', *J. Pet. Sci. Eng.*, vol. 209, no. September 2021, p. 109914, 2022, doi: 10.1016/j.petrol.2021.109914.

[22]D. Asante-sackey, S. Rathilal, and E. K. Tetteh, 'Membrane Bioreactors for Produced Water Treatment : A mini-Review', *Membranes (Basel).*, vol. 12, no. 275, pp. 1–21, 2022, doi: 10.3390/membranes12030275.

[23]B. Sun *et al.*, 'Rheology and Oil – Water Emulsion Stability During Biodegradation of Hydrolyzed Polyacrylamide by Delftia lacustris EPDB-8', *Polymers (Basel).*, vol. 18, pp. 1–18, 2026, doi: 10.3390/polym18111268.

[24] Molly C McLaughlin *et al.*, 'Constructed wetlands for polishing oil and gas produced

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water releases', *Environ. Sci. Process. Impacts*, vol. 23, no. 12, 2021, doi: 10.1039/d1em00311a.

[25] D. Gong and G. Qin, 'Treatment of oilfield wastewater using a microbial fuel cell integrated with an up-flow anaerobic sludge blanket reactor', *Desalin. Water Treat.*, vol. 49, no. 1–3, pp. 272–280, 2012, doi: 10.1080/19443994.2012.719336.

[26] G. Mohanakrishna, R. I. Al-raoush, and I. M. Abu-reesh, 'Integrating electrochemical and bioelectrochemical systems for energetically sustainable treatment of produced water', *Fuel*, vol. 285, no. August 2020, p. 119104, 2021, doi: 10.1016/j.fuel.2020.119104.

[27] S. Mishra, A. Dhanda, B. K. Dubey, and M. M. Ghangrekar, 'Enhancing electrokinetics and desalination efficiency through catalysts and electrode modifications in microbial desalination cells', *J. Environ. Manage.*, vol. 366, no. July, p. 121719, 2024, doi: 10.1016/j.jenvman.2024.121719.

[28] A. Itopa *et al.*, 'Bioelectrochemical energy conversion and wastewater treatment in microbial fuel cells: a review of progress, limitations, and future developments', *Bioresour. Technol.*, vol. 443, no. December 2025, p. 133903, 2026, doi: 10.1016/j.biortech.2025.133903.

[29] A. G. Oreavbiere and E. G. Sadjere, 'Design, fabrication, and evaluation of produced water treatment system for effective removal of oil and salt', *Niger. J. Technol.*, vol. 40, no. 5, pp. 788–794, 2022, doi: 10.4314/njt.v40i5.4.

[30] T. Chikwe and F. Okwa, 'Evaluation of the physico-chemical properties of produced water from oil producing well in the Niger Delta Area, Nigeria', *J. Appl. Sci. Environ. Manag.*, vol. 20, no. 4, p. 1113, 2017, doi: 10.4314/jasem.v20i4.27.

[31] K. Tamunokuro, N. Amoni, A. Angelis-dimakis, and O. Albert, 'Physicochemical assessment and treatment of produced water : A case study in Niger delta Nigeria', *Pet. Res.*, vol. 8, no. 1, pp. 87–95, 2023, doi: 10.1016/j.ptlrs.2022.05.003.

[32] L. T. Popoola, S. G. Udeagbara, A. S. Yusuff, A. A. Adeyi, M. A. Lala, and I. A. Salaudeen, 'Oilfield produced water assessment from onshore treatment facilities in Niger Delta : Water quality susceptibility and suitability for soil irrigation', *South African J. Chem. Eng.*, vol. 45, no. September 2022, pp. 127–135, 2023, doi: 10.1016/j.sajce.2023.05.006.

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