Water Practice & Technology

Water Practice & Technology Vol 17 No 10, 2171 doi: 10.2166/wpt.2022.104

Effects of oil exploration on surface water quality – a review

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ABSTRACT

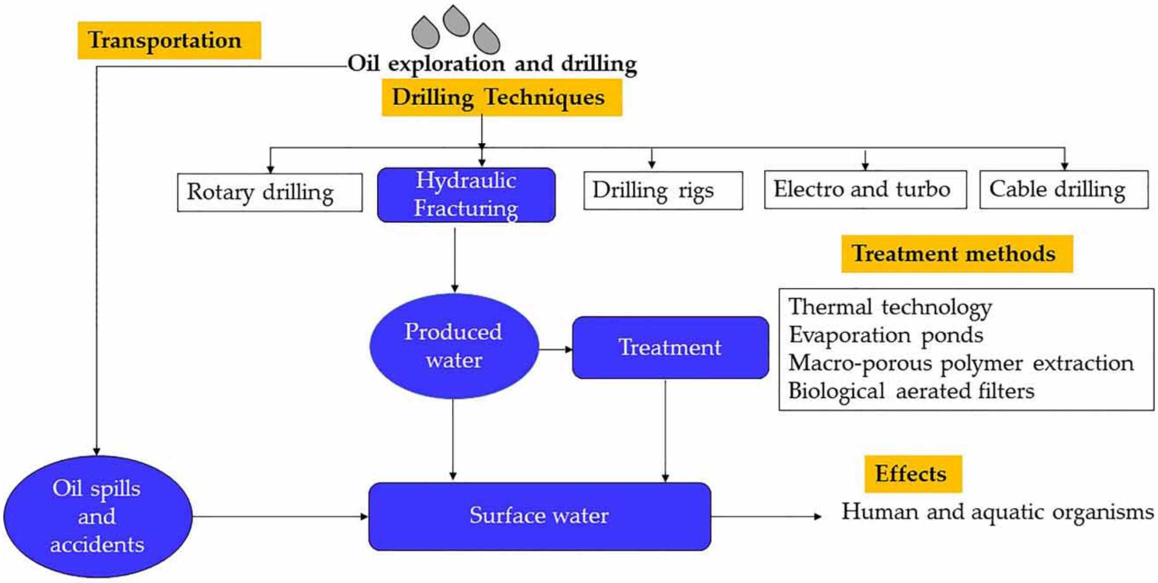
The oil industry is a source of revenue and foreign exchange for an economy. Nevertheless, oil exploration is an inherent risk to the environment due to the pollution of water resources, especially surface water resources. The main waste is produced water, which is increasing around the world. As a consequence, water pollution resulting from normal oil drilling, refining, distribution, and accidents is the principal concern of oil exploration in the environment. Oil pollution is associated with ecological contaminants such as heavy metals and organic compounds which are the primary contaminant of surface water resources. Often this results in toxicity accretion in the food chain, and their non-biodegradable nature is of great concern to both human and aquatic life. Therefore, this review evaluates existing knowledge on the effect of oil exploration on surface water quality, hydraulic fracturing technique/chemicals, and composition of produced water. This review also recommends further research on the physicochemical characteristics, analysis of heavy metals in water/sediments, and characterization of hydro-chemical facies of surface water resources around oil exploration sites to enable effective policy development.

Key words: hydraulic fracturing, oil spill accidents, produced water, treatment technologies

HIGHLIGHTS

- Potentially unknown chemicals are used in oil exploration.
- Paucity of information exists on health risk associated with oil-exploration contaminants.
- Combination of treatment methods is desirable for produced water.
- Insufficient legislation and policies on standards for produced water pollutants.

GRAPHICAL ABSTRACT



INTRODUCTION

The oil and gas sectors play a significant role in the economy of oil-producing countries while holding the potential for major disasters to the environment. According to Johnston *et al.* (2019) there are around 40,000 oil fields globally and 6 million people that live or work nearby. Most countries rich in petroleum resources depend on their sales for revenue and economic development (Graham & Ovadia 2019). Oil and gas are essential to the global economy for electricity production, transportation, plastics and chemicals manufacturing and heating. However, the extraction and processing of oil and gas have immense impact on the environment thus contaminating soil, water, air and human health. (Plänitz & Kuzu 2015). Oil and gas mining has been in existence since 2000 BC (Bainomugisha *et al.* 2010). However, the first commercial oil and gas exploration was done in Tutsivilee Pennyslavia in 1859 which triggered other explorations activities worldwide (Mugendi 2020).The major producers of oil globally include Russia, United States of America (USA), Saudi Arabia and China (Al-Ghouti *et al.* 2019).

There are sixteen countries in Africa, including Nigeria, Libya, Angola and Algeria, which are oil-producing and exporting countries (ADB 2009). In East Africa, oil was first discovered in Uganda in 2006, and before then, the region was dependent on agriculture as the backbone of its economy. Commercial oil exploration was discovered in Kenya in 2012 in Lokichar Basin in Turkana County. However, exploration activities have been taking place since 1960 (Heya 2011; Purcell 2014). Later in December 2017, 38 wells at the Tertiary Rift Valley Oil Block 13 T South Lokichar Basin were drilled (TullowPLC 2018).

Several oil and gas processes are improved via the injection of hydraulic fracturing (HF) fluids into the formation to enhance oil and gas production. Produced water is the principal waste stream associated with oil and gas extraction and contains organics, salts, metals and radioactive material (Azetsu-Scott *et al.* 2007). According to Dickhout *et al.* (2017) approximately 70 billion barrels of produced water are generated annually out of which 21 billion barrels is produced by USA alone. The major constituents that are present in produced water include: salt content (measured salinity), total dissolved solids (TDS) or electrical conductivity; oil and grease; polyaromatic hydrocarbons (PAHs): benzene, toluene, ethylbenzene and xylenes (BTEX): phenols, organic acids; natural organic and inorganic compounds that cause hardness and scaling (Al-Ghouti *et al.* 2019).

All through the numerous stages of oil exploration, fluids are discharged into the environment. The discharge might come from activities such as drill cuttings, drilling mud, and produced fluids such as oil and water along with other chemicals injected to enhance the separation of oil from water (Bayode & Adewunmi 2011; Ite *et al.* 2013).

The possible environmental impacts as a result of inappropriate disposal and treatment of oil exploration and mining waste include land degradation, water and air pollution to adverse effects on the community's sources of livelihood. In addition, health issues due to water and air contamination may lead to insecurity challenges due to resource scarcity (Kadafa & Ayuba 2012).

The numerous challenges faced by communities living in oil and gas exploration sites are due to the ineffective policy and legal framework in developing countries such as Nigeria (Agbonifo 2015). This include lack of technical legislation on the permissible levels of many pollutants on the practices for the management of production water drilling muds and gas flaring. Thus, proper management of environmental resources such as water, land and vegetation is key (Opiyo *et al.* 2015).

Few studies have been carried out to determine the impacts of oil exploration on the community's social and economic activities, sustainable environmental management, and chemical composition of drill cuttings (Opiyo *et al.* 2015; Mutua 2016; Mugendi 2020). In addition, there is a lack of systematic analyses of the environmental or health impacts from oil exploration, drilling and extraction (Lave & Lutz 2014). Therefore, this review aims to leverage on existing scientific literature to assess the potential impact of oil and gas production on surface water by identifying the chemicals used in HF, the characteristics and effects of produced water, and treatment technologies for wastewater management.

METHODOLOGY

The study adopted the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA-P) (Moher *et al.* 2015) in conducting the review. The information was sourced from online databases such as Scopus, Web of Science, Google Scholar, Directory of Open Access Journals (DOAJ), and databases of organizations such as the United States Environmental Protection Agency (EPA), United Nations Environment Programme (UNEP), and the World Bank for peer-reviewed articles, books, and grey literature.

The search strategy was executed using Boolean operators 'AND & OR'. It was also completed using words and phrases such as water pollution and oil exploration, produced water, oil exploration, oil spills, water treatment, oil pollution, water quality and oil exploration, oil exploration techniques, oil pollution and hydraulic fracturing. All articles were searched without limitation on the year of publication.

Literature screening was conducted in three stages; firstly, the title, abstract, keywords and finally, the full article. Articles were included or excluded based on the SPICE (Setting, Perspective, Intervention, Comparison, and Evaluation) framework (Booth 2006), as summarized in Table 1.

Table 1 | Inclusion and exclusion criteria

Item	Included	Excluded
Intervention	– Oil explorations that affect water quality – Water treatment technologies for oil-polluted surface water – Oil exploration processes that affect water quality – Transportation of oil which results in oil accidents	– Oil exploration practices unrelated to water pollution
Article type	Reviews, journal articles, communications, reports, grey literature and books	– Articles with no full texts – Journal articles not peer-reviewed
Geographical	All articles in oil-producing and exporting countries	
Language		– Articles not published in English

RESULTS

The search resulted in 223 articles, out of which 104 were included in qualitative synthesis (Figure 1). 19 out of the 104 articles were for the oil drilling techniques, 35 (7 and 24) covered produced water and its effects on water quality, human and aquatic life, 23 articles covered oil spills and accidents while 27 articles covered water treatment technologies. These are discussed in detail in the subsequent sections.

Oil drilling techniques

Oil drilling is determined by the geologic formation leading to low oil recovery as a result of poor permeability of the local bedrock. This is particularly real bedrock such as shales, tight sands, oil sands, and coal beds (Pichtel 2016). There are various drilling methods each possessing its benefits. They include drilling rigs, electro and turbo, vertical/horizontal, hydraulic fracturing, cable and rotary drilling (Speight 2011; Adeola *et al.* 2022).

Rotary drilling technique was developed mainly to improve operational efficiencies; however, it does cater for complex wells such as directional well and horizontal wells (Lyons & Plisga 2011).

The horizontal wells are usually used to develop the tight oil and gas, shale oil and gas, mainly due to the drainage area can be enlarged and it's good for multi-stage fracturing, as a result, enhanced oil and gas recovery (Ma *et al.* 2015).

Vertical drilling technique is important because it reduces the down-hole accidents and exploits unconventional petroleum resources such as deep geothermal energy and geo-resources. (Elders *et al.* 2014).

The most common drilling method is HF because it is an economically viable oil drilling technique. It also promotes gas production from shale and other low-permeability reservoirs in sandstones, siltstones, and carbonate formations. This technique also produces low greenhouse gas emission (Koplos *et al.* 2014). HF is discussed in detail in the following subsection.

HF

HF is a drilling technique whose purpose is to stimulate wells in low and moderate permeability reservoirs and create natural fractures in the bed formation (Kondash *et al.* 2017). Generally, more than 90% of fracturing fluids

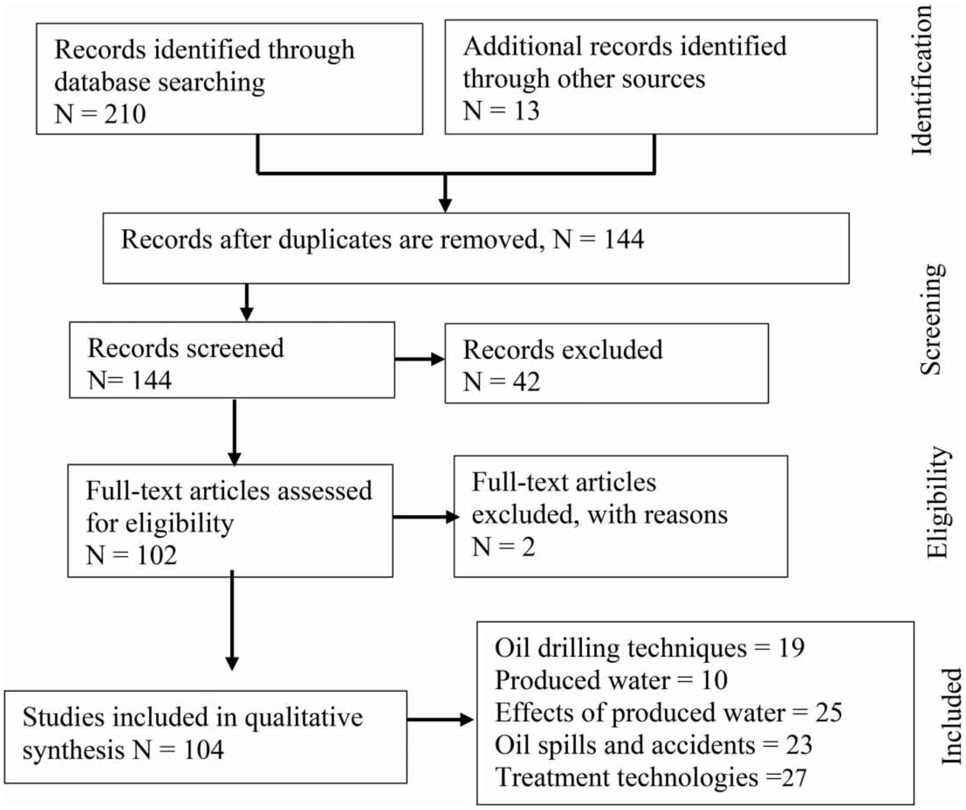


Figure 1 | PRISMA chart for the literature review.

are water-based because aqueous fluids are cheaper and provide a wide range of physical properties (Fink 2003; Koplos *et al.* 2014).

This drilling technology is also known as 'fracking.' It consists of a mixture of fluids injected into recovery wells under high pressure to fracture low permeability formations and enhance gas and oil production (Britt, 2012). HF involves many processes, including rock failure, fracture generation, proppant transport and fracture closure. All these processes affect the performance of fractured wells (Wu *et al.* 2021). It is done at an estimated depth of 3,000 meters and encompasses around 16,000 m^3 of water per well (Theodori *et al.* 2013). The water is mixed with almost 1,000 chemical additives to increase water flow and improve deposition efficiency (Xu *et al.* 2019).

The basic environmental concern associated with fracking is the use of a large amount of freshwater that becomes contaminated and therefore a health threat if used by humans, animals, and plants. In addition, there is a need to protect ground and surface water resources from contamination by the fracking fluid. In December 2014 fracking was banned in New York out of the concern of water contamination and high water consumption (Hauter & Gladstone 2020).

Whereas HF involves rock failures, complex fracture generation, proppant transport and fracture closure. There is a lack of models for calculating complex fracture conductivity such as the effect of proppant placement and proppant distribution in fractures, fracture surface roughness and dissolution (Wu *et al.* 2021).

HF components (Table 2) may pose a threat to public health and the environment as some are known to be acutely toxic, and others carcinogenic (Kassotis *et al.* 2016).

Produced water

The amount of water injected into rocks that instantly returns to the surface or infiltrates into rocks is referred to as produced water. Produced water consists of naturally occurring salts, radioactive materials, heavy metals, and other compounds from the formation, such as polycyclic aromatic hydrocarbons, alkenes, alkanes, and other volatile and semi-volatile organics (Guerra *et al.* 2011; Elliott *et al.* 2017).

Table 2 | Composition of hydraulic fracturing compounds and purpose (Hamed 2016)

Compound	Purpose	Examples
Corrosion inhibitor	To eliminate oxygen and reduce the risk of corrosion of equipment	Ethoxylated octylphenol nonylphenol, isopropanol
Crust inhibitor	Limits deposits of the mineral crust	
Biocide compounds	Reduce bacterial fouling	Glutaraldehyde, 2-Bromo-2 Nitro-1 2-propanediol
Coagulants, flocculants, and purifiers	To remove solids	Iron chloride, alum
Solvent	To reduce paraffin deposit	Methanol
Emulsion, destroyer/ Purifier	Destroy water emulsion in oil	Polypropylene
Proppants	Hold fissures open and allow gas to flow out of the formation	Sand, ceramic beads and graphite
Gellants	Increase viscosity and suspended sand during proppant transport	Propylene glycol, guar gum and petroleum distillate
Iron control	Prevents carbonate and sulphate compounds from precipitating in the formation plugs	Ethylene glycol, sodium chloride
Clay stabilizers	Block clay from swelling to block the open channels created in the mining operation	Sodium chloride, tetra methyl ammonium chloride

Produced water is a mixture of injected water, formation water, HF chemicals, and hydrocarbons (Bakke *et al.* 2013). Oil fields are responsible for more than 60% of produced water generated worldwide (Fakhru'l-Razi *et al.* 2009). The composition of the produced water (Table 3) may vary from one geographic location to another due to

Table 3 | Characteristics of produced water (Igunnu & Chen 2014)

Parameter	Range	Parameter	Range
Density (kg/m^3)	1,014-1,140	Calcium (mg/l)	13–29,222
Conductivity (μS/cm)	4,200–58,600	Sodium (mg/l)	132–97,000
Surface Tension (Dyn/cm)	43–78	Potassium (mg/l)	24–4,300
Turbidity (NTU)	182	Magnesium (mg/l)	8–6,000
pH	4.3–10	Iron (mg/l)	<0.1–100
TDS (mg/l)	267,581	Aluminium (mg/l)	310–410
Total organic compounds (mg/l)	1–1,500	Boron (mg/l)	5.95
Total suspended solids (mg/l)	1.2–10,623	Barium (mg/l)	1.3–650
Dissolved oxygen (mg/l)	8.2	Cadmium (mg/l)	<0.005
Total oil (mg/l)	2–565	Copper (mg/l)	<0.02–1.5
Volatiles (mg/l)	0.39–35	Chromium (mg/l)	0.02–1.1
Chloride (mg/l)	80–200,000	Lithium (mg/l)	3–50
Bicarbonate (mg/l)	77–3,990	Manganese (mg/l)	<0.004–175
Sulfate (mg/l)	<2–1,650	Lead (mg/l)	0.002–8.8
Sulfite (mg/l)	10	Strontium (mg/l)	0.002–2,204
Ammonia nitrogen (mg/l)	10,300	Titanium (mg/l)	<0.001–7
Phenol (mg/l)	0.009–23	Zinc (mg/l)	0.01–35
Volatile fatty acid (mg/l)	2–4,900	Arsenic (mg/l)	<0.005–0.3
		Silver (mg/l)	0.001–0.15
		Beryllium (mg/l)	<0.001–0.004
		Nickel (mg/l)	0.001–1.7
		Mercury (mg/l)	<0.005–0.3

its contact with hydrocarbon-bearing formations. It may contain some of the chemicals and hydrocarbon characteristics of the formation (Veil 2015). According to Isehunwa & Onovae (2011), about one billion barrels of produced water are discharged yearly during oil and gas production in Nigeria. Continued production of a large amount of produced water discharges is estimated to increase because the ratio of the relative amount of water to oil escalates with the age of the production wells (Da Silva *et al.* 2015). However due to increased oil exploration produced water from a specific reservoir does not remain constant. Produced water production increases with the age of the reservoir (Nasiri & Jafari 2017). Hence, specific studies for each region should be done as its characteristics varies from region to region which assist in investigating the environmental risks of its discharge.

Major oil spills and accidents

An oil spill is the release of oil into the environment, which degrades the environment's physical, chemical and biological components. These spills/accidents may lead to fire outbreaks when oil is ignited claiming human animal life, choking plants and degradation of water quality (Lawson *et al.* 2012). There are two types of oil spills; sea oil spills and land oil spills (Mulaku 2019), with the latter subsequently ending up in receiving water bodies through runoff. Globally, accidental oil spills into the marine environment account for less than 10% of total oil spills (Farrington 2013). The location of offshore oil spill is an important factor than the amount of oil spilled since some areas have higher absorption capacity than other areas (Chen *et al.* 2019).

The fate and behaviour of onshore oil spills are governed by the following main processes: evaporation, spreading, oxidation, dissolution, biodegradation, dispersion and sedimentation (Figure 2). These processes are affect the extent and severity of the oil spills. Evaporation is the most important process which affects oil spill mass balance (Rogowska & Namiesnik 2010). Evaporation in open waters account for 20–40% of oil spilled mass balance (Afenyo *et al.* 2016). The nature of crude oil, with thousands of compound with varying evaporation rates, makes prediction of evaporation after oil spill difficult to predict (Zhao *et al.* 2021).

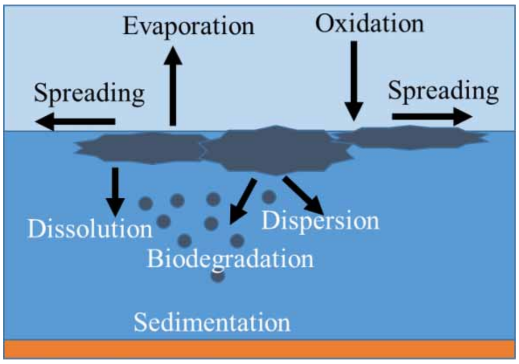


Figure 2 | Fate of oil spills in marine environment. Modified from (Rogowska & Namiesnik 2010).

Oil spilled on water spreads out in a relatively thin layer on the surface while lighter components gradually evaporate, and some water-soluble ones dissolve (dissolution) and wave action will break up the oil, creating oil droplets in the water and water droplets in the oil transforming it into emulsion (Jernelöv 2010). Oil emulsification is the process where small water droplets are trapped in an oil continuous phase to form a water-in-oil emulsion and consequently change the oil physical properties such as viscosity (Zhao *et al.* 2021).

Biodegradation, due to presence of oxidising micro-organisms, helps in self-cleaning of waters after oil spills (Rogowska & Namiesnik 2010). Biodegradation process depends on the oil-water interface where microbes access food and since the interfacial area of a slick is much smaller than the dispersed oil droplets, the biodegradation of surface slicks are considerably slower compared to the biodegradation of small droplets dispersed into the water column and therefore, dispersion plays a key role in this process (Zhao *et al.* 2021). The physical process of sedimentation after oil spill is poorly researched and the available literature is fragmented (Afenyo *et al.* 2016).

The largest oil spill in history was in 2010 in the Gulf of Mexico where 500,000 tonnes of oil was released to the Gulf, which destroyed the coast's ecosystem (Mulaku 2019). Such destruction led to the interference of shrimping and fishing industries which downplayed the region's economy dependent on tourism and seafood. In addition, it affected the natural beauty of the coast. It is worth noting that to repair the effects of the oil spill an amount of US$200,000 million was used (Mulaku 2019).

In the African continent, several cases of the oil spill have led to the degradation of the environment and claimed human lives. For example, in Nigeria, the largest spill was an offshore well blow-out in January 1980 when an estimated 200,000 barrels of oil spilled into the Atlantic Ocean from an oil industry facility that damaged 340 hectares of mangrove (Nwilo & Badejo 2005). The spread of oil spills depends on several factors such as topography, mode of transportation, and the type of oil among others. For example, the topography of the Niger Delta area can cause oil spills to spread rapidly through freshwater swamps, mangroves, and lagoons (Obasi 2019).

In Kenya, some of the oil spill incidences include KenGen's oil spill that occurred in 2012 at Kipevu diesel power station, where at least 10,000 litres of oil was released, and it spread into the sea, soaking beaches and killing animals near the port of Mombasa (Ringa 2012). Also, in the 1998 oil spill, 15,000 tonnes of oil gushed out of storage tanks at the Mombasa harbour, which destroyed hectares of mangroves, leading to an ecological disaster (UNEP 2010). The oil spill from Kenya Pipeline Company Nairobi Terminal on 12 September 2011 claimed the lives of 100 people and badly injured around 160 people (Shileche 2012).

Measures to address oil spillages include enforcement of international and local policies and legal and institutional mechanisms. The *Environmental, Health, and Safety (EHS) Guidelines for Crude Oil and Petroleum Product Terminals* (World Bank 2007) have created regulations to be observed to control and manage oil spills/accidents. The International Maritime Organization is tasked with setting global standards setting for safety, security and environmental performance of international shipping through various conventions (Carpenter 2019). However, governance of marine transportation is complex due to the freedom of the high seas and difficulties in monitoring compliance in this area unlike in the exclusive economic zone where countries have legal mandate to enforce their regulations (Hassler 2011).

African countries have developed governance mechanisms for oil spills. The traditional oil-producing countries have elaborate legislations for the management of oil spills and accidents. For example, Nigeria established the Oil in Navigable Water Act 1968, National Oil Spill Detection and Response Agency Act 2006, Associated Gas Re-injection Act 1979, Federal Environmental Protection Agency Act 1988 among others to deal with environmental aspects of oil production and distribution (Atanda 2015; Kingston & Nweke 2018). In emerging oil producing countries have also developed legislations to govern oil spills. For example, in Kenya, management and response mechanisms of oil spills and accidents is regulated by several legislations such as the Environmental Management and Co-ordination Act 1999 and its amendment of 2015 (GOK 2015) and the Petroleum Act, 2019 (GOK 2019), among others. The National Environment Management Authority (NEMA) and the Kenya Maritime Authority are the key institutions responsible for enforcing offshore and onshore oil spills regulations, respectively. In Uganda, the key legislation is the National Evironment Act, 2019 which establishes the National Environment Management Authority (GOU 2019). The Act also established the Petroleum Authority with mandate to implement the national oil spill contingency plan (GOU 2020).

The preparedness, response and management of oil spills especially in developing economies such as those in Africa is hampered by a myriad of challenges. These include weak government regulation and the exploitation of this weak regulations by the oil companies, lack of technologies for monitoring (Ikporukpo 2020), lack of monitoring data, lack of co-ordination among agencies and inadequate rapid response strategies (Asif *et al.* 2022). Another important bottleneck is the inability to control operational discharges such as tank washing and fuel-oil sludge spill (Jernelöv 2010). Therefore, there is need for strengthening the legal and institutional framework governing oil spills.

Effects of produced water on surface water resources

Environmental hazards have been attributed to crude oil exploration and processing in Africa, mostly from the discharge of wastes, including drilling fluids, oil drill cuttings, oil spills, gas flares, well treatment fluids, and deck drainage (Adeola *et al.* 2022). The effect of produced water in an environment is dependent on the physical, chemical, and biological composition of the formation environment. Water poses a risk of being contaminated by discharges of petroleum hydrocarbons and related chemical wastes if they find their way into the freshwater environment, especially during heavy rainfall (Fatoba *et al.* 2016).

Produced water from oil and gas industries usually is acceptable to be discharged into the environment (Durell *et al.* 2000). Produced water in offshore drilling is often discharged into the close aquatic environment. Discharge of this wastewater to the freshwater environment affects agricultural resources and destroys aquatic life (Ayotamuno *et al.* 2002; Obire & Amusan 2003). According to Obire & Amusan (2003), the organic and inorganic compounds in produced water tend to have higher toxicity than crude oil. Research has proven that produced water effluents have a high level of biological oxygen demand (BOD) and chemical oxygen demand (COD) created from compounds of fatty acids. Isehunwa & Onovae (2011), stated that the concentration of salinity is higher in produced water than in some seawater, which may destroy freshwater resources. Salinity in produced water can range from 1,000 to 400,000 mg/L (Guerra *et al.* 2011) whereas for sea water is 35,000 mg/L (Durack 2015).

In Western Siberia, a river basin that hosts over 112 oil fields measured high concentrations of chloride and elevated salinity in the surface water, suggesting the release of oil-related wastewater through leakage and dumping (Moskovchenko *et al.* 2020). According to Neff *et al.* (2011) heavy metals and naturally occurring radioactive material associated with the produced water could pollute the environment. Inorganic ions such as sodium, potassium, calcium, and chloride are concern in produced water discharges, especially when discharged to the land, surface, and brackish (Neff *et al.* 2011). Sodium is a major dissolved constituent in most produced waters and leads to significant soil degradation through changing clays and soil textures and consequent erosion. Raised sodium levels can also cause poor soil structure and inhibit water infiltration in soil (Guerra *et al.* 2011).

The nature of produced water has the latent to cause damage to the environment via the organic material. Organic matter in produced water exists in two forms: dispersed oil and non-hydrocarbon organic material. Dispersed oil and droplets do not precipitate at the bottom of the sea but float on the water's surface.

The volume of produced water discharged to the environment is increasing despite the threat to the receiving water bodies. Produced water has been identified as the largest water stream generated during the oil production process and the volume of produced water can be larger than the hydrocarbons produced (Fakhru'l-Razi *et al.* 2009). Annual produced water volumes made by the oil and gas industry are around 3,000 billion litres, equal to a volume of 8.2 billion litres generated daily (Bybee 2011).

Impacts of oil exploration on human health and aquatic organisms

Oil exploration and oil spills have adverse impacts on the surrounding environment, causing both short and long-term hazards to the adjacent vegetation, animals, and humans (Barron *et al.* 2020; Bebeteidoh *et al.* 2020). Barium is a compound released to surface water resources due to drilling waste discharges and the erosion of weathered rock. Uptake of excess barium may cause a person to experience vomiting, abdominal cramps, diarrhoea, difficulties in breathing, increased or decreased blood pressure, numbness around the face and muscle weakness (Zabbey & Olsson 2017). A study in a small community in the Amazon region of Ecuador assessed the association between cancer and oil extraction and it was found that there were excess cases and mortality for all types of cancer (Johnston *et al.* 2019). An earlier study using a structured questionnaire among women living near oil wells in Ecuador identified a higher prevalence of skin fungi, nasal irritation, and throat irritation (San Sebastián *et al.* 2001). In Nigeria, significantly higher rates of neurological symptoms, including headache, dizziness, eye and skin irritation, and anaemia, after adjusting for age, sex, and smoking status were observed among community members (Kponee *et al.* 2015). Exposure to high concentrations of volatile organic compounds (VOCs) such as xylenes benzene and polycyclic aromatic hydrocarbons (PAHs) can cause central nervous system problems resulting in dizziness, fatigue, and headache (Ite *et al.* 2013). For example, many residents in the Niger Delta had complained of asthma, breathing difficulties and pain, headaches, nausea, throat irritation, throat irritation, and chronic bronchitis (Chijioke *et al.* 2018).

Pollutants can cause adverse effects on human health from early life such as cardiovascular disorders, mental disorders, allergies, and respiratory disorders (Kelishadi 2012). For instance, Polycyclic aromatic hydrocarbons found in crude oil have been documented to cause cancer and cardiovascular problems in aquatic life (Brette *et al.* 2017; Dubansky *et al.* 2018). Short-term exposure of the fish *Achirus lineatus* to water contaminated with light crude oil led to changes in the normal bacterial composition of the gut (Améndola-Pimenta *et al.* 2020; Cerqueda-García *et al.* 2020).

The most common acute effects reported after exposure to oil spills among clean-up workers are respiratory, eye and skin symptoms, headache, nausea, dizziness and fatigue. Chronic effects include psychological disorders, lower respiratory tract symptoms and reduction of lung function (O'Callaghan-Gordo *et al.* 2016).

Treatment alternatives and technologies for produced water

The basic aim for the treatment of produced water is to remove dispersed oil, suspended solids, naturally occurring radioactive material, desalination and water softening (Arthur *et al.* 2005). Recycling produced water can reduce the demand for fresh water and change the waste into a usable water resource. Therefore, treatment technologies would need to be customized for each area according to the water quality and quantity (Arthur *et al.* 2005).

A large amount of the produced water can be used for numerous purposes, such as an underground injection to increase oil production, irrigation, livestock or wildlife watering and habitats, and various industrial uses such as dust control, vehicle washing, power plant make-up water, and fire control (Ekins *et al.* 2007; Fakhru'l-Razi *et al.* 2009). Alternatively, it may be injected into a nearby non-producing well (Payne *et al.* 2011). Reinjection is not always possible due to the geography of the area and cost considerations (Sullivan *et al.* 2004). In addition, the produced water can be used to solve problems created by near-record drought conditions, develop wildlife habitats and provide water for agriculture, industry, and other uses (UNEP 2007).

There are many options for the treatment of produced water before disposal or reinjecting (Veil 2008) such as evaporation ponds, aerated biological filters, membrane processes, hydro-clones, macro-porous polymer extraction, freeze-thaw technology, and thermal technology. These methods vary greatly in efficiency and cost. The biological method is one of the cheapest and easiest available options. Both mixed and pure bacterial and fungal cultures have been used successfully to degrade hydrocarbons (Okoh 2006).

Biological aerated filters are a type of biological waste treatment method. It requires a media not more than 10 cm in diameter to enhance biochemical oxidation and to remove organic components in the wastewater (Igunnu & Chen 2014). This method can eliminate oil, ammonia, suspended solids, nitrogen, COD, BOD, and heavy metals from produced water (Delin *et al.* 2007). The water recovery process is almost 100% since waste generated is removed in solid form (Igunnu & Chen 2014).

Evaporation ponds are also used as an artificial treatment technology for produced water. The ponds are designed to evaporate water using solar energy (Velmurugan & Srithar 2008). The ponds are constructed to prevent soil infiltration and are favourable in arid and semi-arid regions (Consulting 2003). The ponds are usually covered with netting to avoid water flow due to contaminants in produced water.

Membranes are micro-porous films with precise pore grades, which selectively isolate a fluid from its components. There are four types of membrane separation processes. These approaches include microfiltration (MF), ultrafiltration (UF), reverse osmosis (RO), and nanofiltration (NF) (Xu & Drewes 2006). They are effective in removing oil, suspended solids, and non-dissolved organic carbon (Faibish & Cohen 2001; He & Jiang 2008). The disadvantage of this technology is that the membranes are prone to scaling and fouling, and the life span of the membranes is less than 10 years (Mark 2007). It is recommended for produced water that has already undergone pre-treatment (Mondal & Wickramasinghe 2008).

Hydro-clones is a pre-treatment technology that removes solids from liquids with a range of about 15 mm (Igunnu & Chen 2014). It is the most recommended technology since it does not involve the use of chemicals, and has a long life span though it is disadvantaged by the amount of sludge generated. Macro-porous polymer extraction technology is one of the recommended technologies with the best environmental practices for produced water management on offshore oil and gas platforms (Meijer & Madin 2010). Its water recovery is almost 100%, can adapt to a wide range of water quality and quantity, and does not need maintenance (Meijer *et al.* 2004).

Freeze-thaw evaporation (FTE) technology is an established and robust for produced water treatment and disposal. It involves freezing thawing, and conventional evaporation for produced water management. FTE technology creates a substantial amount of concentrated brine and oil hence, waste management and disposal must be addressed (Boysen & Boysen 2007).

Thermal technology is employed in regions where the cost of energy is quite cheap. Thermal separation was selected for water desalination before the development of membrane technology. Major thermal desalination technologies include multi-stage flash (MSF) distillation, vapour compression distillation (VCD), and multi-effect distillation (MED) (Boysen & Boysen 2007). The advantage of this technology is that it is a relatively cost-effective method with a plant life span of greater than 20 years (Darwish *et al.* 2003).

Enhancement of treatment of produced water in environmentally friendly chemical agents coupled with technology should be recommended in the future to enhance green efficient oil exploration (Liu *et al.* 2021). In addition, single treatment methods are not able to meet all re-use and disposal requirements. Therefore, technology integration is pointed out as the approach to treat and re-use produced water (Nasiri *et al.* 2017).

Some technologies for advances of Produced water management include alternative technologies for reducing the water production and water discharge such as down -hole oil-water separation and sub-sea (Du *et al.* 2005).

DISCUSSION

The review has established that oil exploration affects water quality through drilling technologies adopted, produced water and oil spills, and accidents during oil transportation and handling. Oil exploration and oil spills/accidents have negative impacts on the environment causing hazards, to water human health, and aquatic species. Some of the incidences are avoidable such as oil spillage, gas flaring, and improper waste management (Pathak & Mandalia 2012). There are still a large number of known and potentially unknown chemicals used and produced in oil exploration. Hence more research needs to be conducted especially to determine their effects on human health. An upfront consequence of the oil exploration on surface water, is the socio-economic issue that may lead to loss of livelihood due to a contaminated water ecosystem.

The major compounds used in HF that are of environmental concern include corrosion and crust inhibitors, biocide compounds, coagulants, flocculants, purifiers, solvents, emulsion, destroyer/purifier proppants, gellants, iron control and clay stabilizers (Table 2). However, there is a potential research gap in the components used in hydraulic fracturing, especially in Africa (Table 4). Therefore, further research is required to form a basis for policy formulation, especially in waste treatment and technologies.

The composition of produced water varies from one geographic location to another (Fakhru'l-Razi *et al.* 2009). There is little knowledge on the effects /composition of produced water on surface water resources in Africa due to the inaccessibility of the oil exploration area. Hence, detailed research should be undertaken to understand the change of water quality in surface resources when the produced water is discharged and also its effect on sediments.

The effects of produced water on the environment have been established by literature sources. Produced water from oil and gas industries usually is acceptable to be discharged into the environment (Durell *et al.* 2000). Nevertheless, the discharge of this wastewater into the freshwater environment affects agricultural resources and destroys aquatic life due to the toxic nature of produced water (Ayotamuno *et al.* 2002; Obire & Amusan 2003). The evidence is from the USA and China, where a detailed analysis of the effects has been done. Some of the articles are from Nigeria, one of the top producing oil countries in Africa they generally concentrate on the effects of oil exploration on the environment. Therefore specific and detailed research on the effects of oil exploration on environmental aspects such as water, soil, and vegetation is required and especially in emerging and new oil producing countries whose legal and institutional framework is less developed.

Oil exploration spills and accidents have become an issue in society. Some oil spills are due to negligence or just accidents but it has a detrimental effect on vegetation, loss of life, water quality deterioration, and also the livelihood of the people living around the affected areas (Lawson *et al.* 2012). Therefore, regulations governing transporation of oil should be enacted and enforced to prevent environmntal damage due to oil spills and accidents. Understanding the fate and transport of oil in the environment after oil spill is important in designing managememt strategies including clean up. This could be achieved by modelling the various processes such as dispersion, sedimentation, evaporation and biodegradation among others as illustrated in Figure 2.

Recycling treated produced water can help in reducing the pressure on freshwater sources. The recycled water can be used for numerous purposes such as underground injection to increase oil production, irrigation, livestock or wildlife watering and habitats, and various industrial uses. The end use of the recycled water depends on the treatment technology adopted and its efficiencies. The treatment technologies are customized for each area according to the water quality and quantity (Arthur *et al.* 2005). Therefore, there is a need for research on area-specific treatment technology, especially for developing countries considering the cost of operations, necessity of pre and post treatment and technology capability.

Table 4 | Summary of existing knowledge and research gaps

Subtopic	Findings/existing knowledge	Gap
Oil drilling techniques	– Drilling rigs, electro and turbo, vertical/horizontal, hydraulic fracturing (HF), cable, and rotary drilling – HF is commonly used – HF uses a lot of water	– Components of HF in use especially In Africa – Research on strategies of minimizing water consumption in HF
Produced water	– It contains both organic and inorganic compounds – Characteristics varies from region to region	– Little information on characteristics of produced water in emerging oil producers – Region/country-specific characterization of produced water is needed
Effects of produced water on water resources	– Produced water has negative effect on water quality – Re-use of produced water in HF helps in reducing pressure on fresh water resources but it is complicated by complex legal processes	– Large number of known and potentially unknown chemicals used and produced in oil exploration – There is dearth of information around socio-economic issues due to a contaminated water ecosystem – Policies on produced water re-use in HF
Impacts of oil exploration on human and aquatic life	– Oil exploration and associated activities have short and long term effects on humans, animals and plants – Some of the diseases and ailments associated with oil exploration activities include gastro-intestinal, nervous disorders, cancer, allergies and respiratory problems	– Due to complexity of compounds generated during oil exploration, there is need to undertake detailed investigation on effects of oil exploration activities particularly on aquatic life (plant and animals) – Country or region-specific risk assessment needs to be undertaken in oil producing areas
Treatment technologies for produced water	– The common technologies are evaporation ponds, aerated biological filters, membrane processes, hydro-clones, macro-porous polymer extraction, freeze-thaw technology, and thermal technology – Treatment technologies need to be customized based on the quality of water desired – A combination of technologies is desirable than single technology	– Nearly all technologies involve significant amounts of water hence leading to management challenges related to water. – Onsite testing technology to ensure the discharge requirements are met. – Desalination technologies capable of reliable recoveries to cut down the use of brackish water and capital operating cost associated with construction of disposal wells.
Oil spills and accidents	– Oil spills and accidents are environmental disasters – Fate and behaviour of oils spills in the marine environment is governed by weathering and transport processes of evaporation, spreading, oxidation, dissolution, biodegradation, dispersion and sedimentation – Oil spill on land is determined by the location rather than volume of oil – Weak disaster preparedness and response mechanism increases the severity of oil spills and accidents to the environment	– There is inadequate knowledge on some of the physical processes such as sedimentation – workable legal and institutional mechanisms for disaster preparedness and response is needed especially in developing countries – Control mechanisms for operational discharges is inadequate

Oil-producing countries do not form a homogenous group especially extent of oil dependence. Some countries accounts for the vast majority of fiscal revenue and exports, while in others it is less significant for the economy. The main policy issues include duplication of agencies and policy inconsistency such as corporate governance have contributed to weakening the level of integration and optimization of resources within the petroleum industry (Oyewunmi & Olujobi 2016). In addition, The existing oil and gas laws are weak in terms of provisions for transparency and hence most of the laws and policies are outdated and not in tune with the contemporary realities in the global oil and gas sector (Oyewunmi *et al.* 2017).

The adoption of an open door policy approach will provide a good starting point for necessary adjustments, to provide long-term benefits to the stakeholders that are dependent on the oil and gas revenues.

CONCLUSION AND RECOMMENDATION

This review has described the composition of oil-produced water, including common fracking additives, effects on surface water quality and possible treatment technologies. The findings showed variations in the characteristics of produced water and the chemical components of the HF process. Therefore site specific test should be carried out to determine the composition of the produced water.

The components of the produced water are determined by the physical, chemical and biological environment in which the exploration is carried out. Surface water contaminated by oil exploration activities affects humans, plants, and aquatic organisms. There is need for research through conducting individual exposure assessment such as biomarkers of exposure to test blood/urine for presence of PAHs and evaluation of chromosomal damages. This will promote understanding of health risk associated with exposure oil related contaminants.

The sustainability of the environment in the oil mine regions is anchored on disposal and treatment techniques. Hence more research is recommended to influence policy dialogues in water quality management. It should noted there is no discreet method for treating produced water, so a composite/integrated process should be developed.

Also, the hydro-chemical characterisation of surface water resources requires further research on the heavy metal analysis in water and sediments. This will provide more knowledge and the ability to recommend suitable waste disposal and treatment strategies. There is also a need for a holistic approach in research between government agencies and government institutions to facilitate information and data provision oil exploration and their associated impacts.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 3 November 2021; accepted in revised form 18 August 2022. Available online 27 August 2022