Chapter

Environmental Challenges Associated with Processing of Heavy Crude Oils

Samuel O. Sojinu and Onome Ejeromedoghene

Abstract

The petroleum industry is one of the largest industries in the world and plays a pivotal part in driving a nation's economy. However, the exploration and exploitation of heavy crude oil have raised series of environmental challenges and caused increased concern for the communities where the oil refineries are cited. Activities such as gas flaring and oil spillage have led to the release of toxic organic and inorganic pollutants, which has resulted in acid rain, climate change, and contamination of soil, water, and air. These environmental hazards have caused adverse effects directly or indirectly to the ecosystem. This chapter offers a general overview of the processes involved in the processing and some of the potential environmental challenges associated with heavy crude oil processing.

Keywords: heavy crude oil, toxic pollutants, oil refinery, environment

1. Introduction

Heavy oil has been part of the natural environment for centuries. It is a substance believed to have formed over the years by the death and decomposition of plant and animal remains that have become incorporated in the sediments of shallow seas and later overlaid by a succession of strata of sedimentary rocks for millions of years. These organic residues are acted upon by intense heat and pressure into petroleum, migrating upwards, sometimes over extensive areas, either to reach the surface or be occasionally trapped in what are to become oil reservoirs [1].

Heavy oil is a naturally occurring, unrefined petroleum that is basically composed of hydrocarbon deposits and other organic materials. The heavy oil can be processed into more useful products like gasoline, kerosene, jet fuel, diesel, heating oil, and other allied products called petrochemicals by refining process.

Basically, crude oil undergoes various stages of exploration before getting to the end consumers or retailers. The overall well-to-consumer supply chain for petroleum products is often described as being segmented into three main segments:

- Upstream activities: This comprises the preliminary stages. It involves exploration activities of crude oil deposits leading to the production of crude oil. Companies in this category include ExxonMobil and Shell Petroleum; they own rights to drill. Also included in this category are companies providing support services such as Halliburton.

- Midstream activities: These involve the transportation of crude oil to refinery; the refining of crude oil into marketable products; and the onward distribution of these products to wholesalers and retailers. Included in this category are companies that transport oil by pipeline, truck, or barge (e.g., Magellan Pipeline, Tulsa, Oklahoma) and companies that refine crude oil (e.g., Tesoro, San Antonio, Texas).

- Downstream activities: Similarly, these categories of activities involve the retail end of petroleum industry. Gasoline stations are the main downstream companies; companies that supply heating oil or propane also fall into this category [2].

The American Petroleum Institute (API) classifies crude oils according to their contents, origins, and specific gravity. Light crude oils or sweet crude are liquid petroleum with low density and can flow freely at room temperature. They are characterized by low viscosity (a property that defines ease of flow), low specific gravity, and high API gravity due to the presence of a high proportion of light hydrocarbon fractions basically from C_6–C_{12}. However, heavy crude oils are highly viscous that cannot easily flow to production wells under normal reservoir conditions. They yield more heat upon burning but have lower API gravity [3].

2. Heavy oils

In the past decades, heavy oils were formed when certain algae species degrades hydrocarbon deposits which lead to the loss of its lighter hydrocarbon fractions, leaving behind the heavier hydrocarbon fractions. By definition, heavy crude oil is oil with high viscosity (approximately 10,000 centipoise). Heavy crude oil ranges from free flowing oil to bitumen and/or tar sands "ultraheavy oil" that is actually embedded in sand and located at depths less than 75 m [4].

Heavy oils are among the class of unconventional crude oil. They are one of the world's largest resources as well as a potential major contributor to the future of energy globally. They are found all over the world with Canada and Venezuela accounting for more than half of world deposits. Basically, the processing of heavy crude oil is faced with challenges such as cost of extraction/processing, haulage to refineries, and processing them into valuable products meeting market demands while adhering to environmental requirements. In addition, the market for selling these heavy crude oil directly is limited because only a few existing refineries are capable of receiving and/or processing such low-quality crude oils [5].

Heavy crude oil is usually characterized by a low content of lighter cuts and contains significantly higher contents of asphaltenes (altered fragments of organic chemical compounds) (**Tables 1** and **2**), which have been reported to greatly

Fraction	Weight percentage (%)	Elementary composition based on C_{20}+ (%)				
		C	H	N	O	S
Asphaltene	14.1	83.8	7.5	1.3	1.7	4.8
Resin	37.3	82.8	8.9	1.5	2	4.3
Aromatic	37.2	84.3	10	<0.3	1.1	4
Saturate	11.4	86.6	13	<0.3	<0.2	<0.1

Table 1.
Typical elemental composition for heavy oil [5].

Origin	Composition (%)					H/C ratio
	Carbon	Hydrogen	Nitrogen	Oxygen	Sulfur	
United States[a]	88.6	7.4	0.8	2.7	0.5	1
Kuwait[a]	82.4	7.9	0.9	1.4	7.4	1.44
Venezuela[a]	85.5	8.1	3.3	1.8	1.3	1.14
Mexico[a]	81.4	8	0.6	1.7	8.3	1.18
Brazil[b]	83	9	2	—	—	1.3
Italy[a]	78	8.8	Trace	3	10.2	1.35
Canada[a]	85.1	11.1	0.7	2.5	0.6	1.56

[a]*Data from Marcel Dekker, Inc. [8].*
[b]*Total content of oxygen and sulfur is 6%.*

Table 2.
Elemental composition of asphaltenes from several oil samples [7].

complicate the refining process. Subsequently, certain asphaltene requires that the heavy oil also undergo a special refining process called deasphalting [6]. The impurities present in heavy crude oil are in the form of compounds of sulfur, oxygen, hydrogen, nitrogen, carbon, and the heavy metals (nickel and vanadium) [4].

The first Canadian producers of heavy bitumen known as Athabasca oil sands used surface mining with massive equipment to mine the oil sands, separate the bitumen from the sand, and return the sand to the excavation site. More recent bitumen production uses the steam-assisted gravity drainage (SAGD) method developed by the Alberta Oil Sands Technology and Research Authority in the 1980s. SAGD uses steam to heat the bitumen, allowing it to flow by gravity to a reservoir where it is recovered [9].

Orinoco tar sand is the most common unconventional crude oil produced in Venezuela. Typical qualities for Venezuelan unconventional crude oils are 5–15° API gravity, 4–6 wt% sulfur, and 1–2 wt% nitrogen. There are also conventionally produced heavy crude oils such as Ku-Maloob-Zaap oil that is very similar in quality to unconventional heavy crudes [9].

More recently, there have been wide ranges of crude oil upgrading options that can allow a large selection of upgraded crude oil qualities. They range from the simple process of diluting with light sweet crude oil (naphtha or natural gas condensates) to produce Maya crude equivalent to complex flow schemes that include delayed coking and residue hydrocracking, as well as other various high-pressure hydrocracking technologies. Specifications for producing this crude type include a gravity target range of around 20–25° API and a target sulfur content of around 3–4 wt%. More so, there is currently high demand for this quality crude oil because the production of Maya and other similar heavy crude oils has been declining in recent years. Exports of Maya crude oil have decreased by about 1 million barrel per day over the last 7 years. Heavy oil processing capacity has increased significantly over the same period (notably at Reliance, Jamnagar, India; Motiva, Port Arthur, USA; and Marathon, Garyville, USA).

Creating a higher-quality, sweet synthetic crude oil with API gravity between 30 and 40° API opens up the potential market for upgraded crude oil by an order of magnitude, because most refineries are capable of processing crude oils within this gravity range. It may be difficult for the producer to justify the cost of the additional upgrading required. However, this level of upgrading could be phased in, if necessary, to accommodate potential market changes in the future. In the same vein, creating high-quality finished products directly from unconventional crude oils is possible but unlikely to be economically viable unless the refinery's location is near a large, high-value market for finished products, has economic logistical options available for product movement, or has a unique specification it can meet. For example, ultralow pour point diesel is a high-value product in Western Canada, near the upgrader site, because of the cold winter season at that location [9].

3. Crude oil exploration and exploitation

Oil exploration and exploitation is a major revenue earner in petroleum-producing countries [10] and serves as the driver of the economies of some of these countries. However, like most human activities, it results in environmental hazards that could be referred to as "slow poisons," in that they often take a long time before causing disease and, in extreme cases, death [11]. The usually unrecognized and slow action of the hazards created by oil exploration and exploitation makes it difficult to fully appreciate their contribution to the disease burden in a country like Nigeria, especially in the oil-bearing communities [12].

4. Crude oil processing

4.1 Separation

The first step of crude oil processing involves the separation of the complex mixtures in the heavy crude according to their molecular weight via atmospheric distillation at atmospheric pressure. During the process, which is also referred to as topping (refining), the oil is subjected to intense heated at the base of a 60 m distillation column at a temperature of 350–400°C, causing it to turn to vapor. The vapors rises inside the column, while the heaviest molecules, or residuals, remain at the bottom. As the vapors rise, the molecules condense into liquids at different temperatures along the length of the fractionating column. Only gases reach the top of the column, where the temperature has dropped to about 150°C. The liquids, which have become increasingly light, are collected on trays located at different heights of the column. Each tray collects a different petroleum fraction, with highly viscous hydrocarbons like asphalt (bitumen) at the bottom and gases at the top.

4.2 Conversion

The heavy fraction leftover after atmospheric distillation still retains many compounds of medium density. This fraction is transferred to another column where it undergoes a second round of distillation to recover middle distillates like heavy fuel oil and diesel.

In the conversion process, the residual heavy hydrocarbon molecules from the separation process are broken down into two or more lighter molecules. The conversion process also known as catalytic cracking is carried out at 500°C. This converts 75% of the heavy products into gas, gasoline, and diesel. The yield can be increased further by adding hydrogen, a process called hydrocracking, or by using deep conversion to remove carbon. The more complex the operation, the more it costs and the more energy it uses.

4.3 Treating

Treating entails deliberate removal of molecules that are corrosive or results in air pollution, especially sulfur. Commencing from January 1, 2009, gasoline and diesel sold in Europe cannot contain sulfur in excess of 10 parts per million (ppm) or 10 mg per kg. The purpose of these measures is to improve air quality and optimize the effectiveness of catalytic converters used to treat exhaust gas. For diesel fraction, desulfurization is done at 370°C and at a pressure of 60 bar. The hydrogen employed in the process reacts with the sulfur to form hydrogen sulfide (H_2S), which is then further treated to remove the sulfur, an important industrial material. Similarly, lighter fractions of kerosene, butane, and propane are washed in a caustic soda (sodium hydroxide) solution to remove thiols, also known as mercaptans. This process is referred to as sweetening [13].

5. Challenges associated with heavy crude oil processing

5.1 Gas flaring

Gas flaring has been one of the most challenging energy and environmental problems facing the world today [14]. As a matter of fact, this act has been condemned in different countries of the world, but the practice has not been totally abolished in some countries especially in the emerging economies [15]. The act of flaring has been allowed by petroleum-producing countries with insufficient fund and investment on structural infrastructure for the efficient utilization of the associated gases obtained from crude oil refining processes [16]. This is in-line with the definition of gas flaring, according to the Canadian Association of Petroleum Producers, as the controlled burning of natural gas that cannot be processed for sale or use because of technical or economic reasons (**Figure 1**) [17]. The World Bank estimates that the annual amount of associated natural gas being flared and vented is about 110 billion cubic meters (bcm), which is practically enough to provide the combined annual natural gas consumption of Germany and France, with Nigeria topping the list of highest gas flaring countries (**Table 3**). Also, estimates calculated from satellite images of flares (National Oceanic and Atmospheric Administration, (NOAA) data, reported by Global Gas Flaring Reduction Partnership (GGFR) indicate that global gas flaring in 2012 alone was 144 bcm. This represents massive resource wastage and a remarkable environmental problem, representing some 400 million tons in CO_2 release into the environment and being at the level of one third of EU's gas consumption [18]. In addition, the amount is twice the annual gas consumption of Africa and three quarters of the Russian gas export [19, 20].

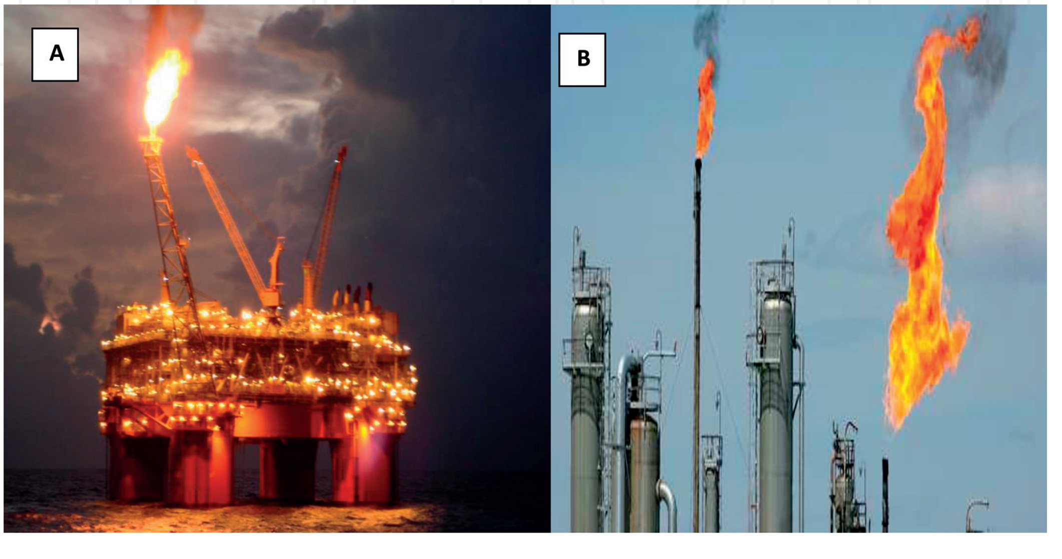

Figure 1.
Flaring (A) from start-up operations on the Deepwater Atlantis platform [15] (B) in Nigeria [16].

2004 rank	Country	Reported flaring, 2004	2004 rank	Country	Reported flaring, 2004
1.	Nigeria	24.1	11.	U.S.A.	2.8
2.	Russia	14.7	12.	Kazakhstan	2.7
3.	Iran	13.3	13.	Libya	2.5
4.	Iraq	8.6	14.	Azerbaijan	2.5
5.	Angola	6.8	15.	Mexico	1.6
6.	Qatar	4.5	16.	UK	1.6
7.	Algeria	4.3	17.	Brazil	1.5**
8.	Venezuela	3.7**	18.	Gabon	1.4
9.	Equatorial Guinea	3.6	19.	Cameroon	1.1
10.	Indonesia	3.5**	20.	Canada	1.0
	Total top 20	**107.5**			

**Source: GGFR (The Global Gas Flaring Reduction Public-Private Partnership).*
***These figures, expressed in billion cubic meters (bcm) may include some venting as well, due to unavailability of segregated data [19].*

Table 3.
Top 20 gas flaring countries in the world [19].*

A flare is normally visible and generates both noise and heat. During flaring, the burned gas generates mainly water vapor and CO_2. Generally, the gases being flared consist of a mixture of different gases; their composition depends on the source of the gas going to the flare system. Natural gas predominantly contains about 90% methane (CH_4) with ethane and small amounts of other hydrocarbons as well as variable amount of inert gases like N_2 and CO_2 [14, 21]. Efficient combustion process involves achieving good mixing ratios between the fuel gas and air (or steam) [22] and on the absence of liquids. Notably, low pressure pipe flares are not intended to handle liquids and do not perform efficiently when hydrocarbon liquids are released into the flare system [23].

Typical gas flaring systems are set up on onshore and offshore platforms of production fields, on transport ships, port facilities, storage tank farms, and along distribution pipelines to vent off trapped gas. The system consists of the flare stack or boom and pipes which collect the gases to be flared (**Figure 2**) [24]. Most flaring processes take place at the top of stack through combustion of gases with the visible flame. However, the height of the flame depends upon the volume of released gas, while brightness and color of the flame largely depend upon composition. The tip of the flare at the end of the stack or boom is designed to assist entrainment of air into the flare to improve burning efficiency. Seals located in the stack prevent flashback of the flame, and a vessel at the base of the stack removes and conserves any liquids from the gas passing to the flare [20].

5.1.1 Classification of flaring processes

5.1.1.1 Emergency flaring

Emergency flaring occurs in cases of fire outbreak, breakage of valves, or compressor failures. This leads to the burning of a large volume of gas within a very short time [20].

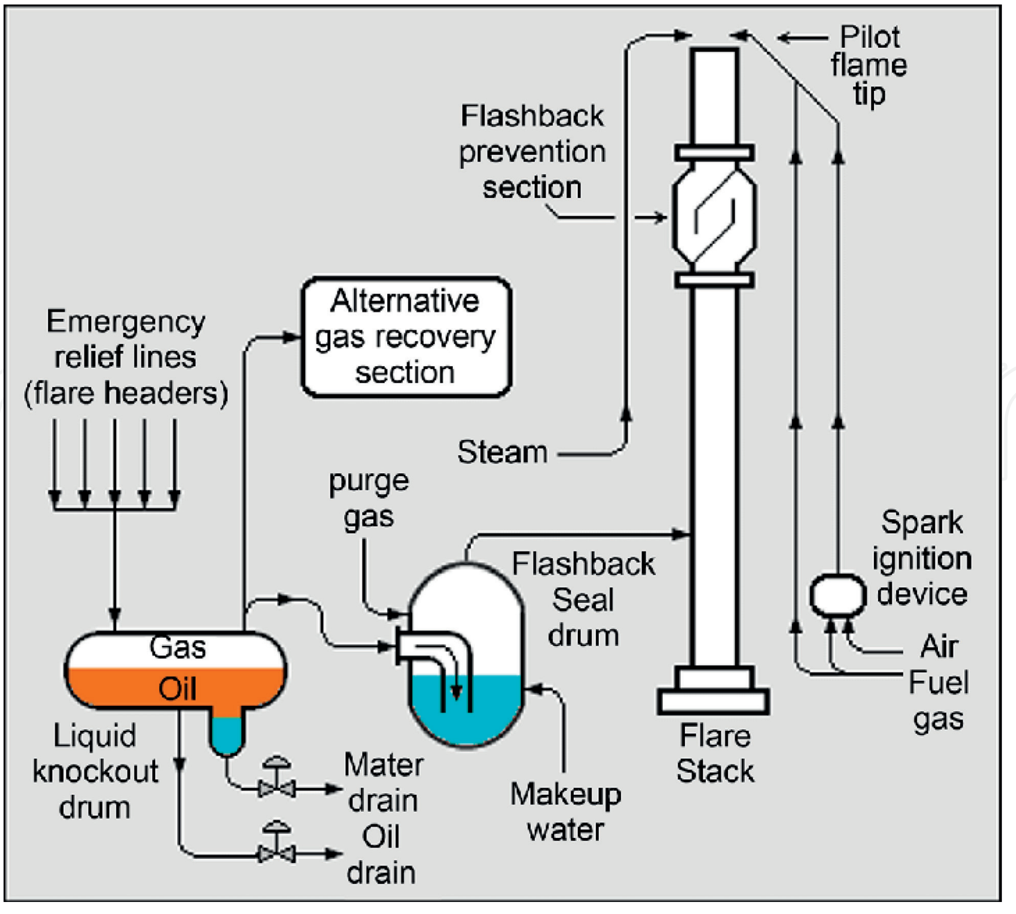

Figure 2.
Schematic flow diagrams of an overall vertical elevated flare stack system [25].

5.1.1.2 Process flaring

Process flaring usually comes with a lower rate, such as during petrochemical process; this involves the removal and subsequent flaring of waste gases in the production stream. The volumes of flared gas at such processes can vary during normal functionality and plant failures from a few m^3/h to thousands m^3/h, respectively [26].

5.1.1.3 Production flaring

Production flaring occurs in the exploration of crude oil. Large volumes of gas are usually combusted during the evaluation of a gas-oil potential test as an indication of the capacity of the well for production.

It has been reported that the flares contain recognized toxins, such as benzene, which pollute the environment drastically [27].

5.2 Environmental challenges associated with gas flaring

5.2.1 Climate change

Gas flaring contributes to climate change, which has serious environmental implications globally. The burning of fossil fuel gives off carbon dioxide, methane, and other gases which has led to global warming with more serious environmental challenges for developing countries, especially Africa which is highly vulnerable with limited ability to adapt [28]. The Intergovernmental Panel on Climate Change (IPCC), a scientific body set up in 1988 by the UN and the World Meteorological

Organization to consider climate change, has projected that in the twenty-first century, the problem of climate change will get worse due to the frequent release of greenhouse gases warming up the world.

Flaring releases carbon dioxide and methane which are the two major greenhouse gases, with methane more toxic and harmful than carbon dioxide. According to the global warming potential estimates, a kg of methane is about 21 times that of a kg of carbon dioxide when the effects are considered over 100 years [29]. Research shows that flaring at lower efficiency emits a higher amount of methane than carbon dioxide. This is because those less-efficient flares tend to have more moisture and particles in them reflecting a high amount of heat. Consequently, they produce similar effect on the ozone layer like aerosols [30–32].

5.2.2 Acid rain

Flaring also contributes to local and by extension regional environmental problems, such as acid rain with attendant impact on agriculture, forests, and other physical infrastructures [33]. The main causes of acid rain are emissions of sulfur oxides (SO_x), nitrogen oxides (NO_x), and carbon dioxide which combine with atmospheric vapor to form sulfuric acid, nitric acid, and weak carbonate acids. Acid rain has been largely implicated in the corrosion of corrugated roofs/buildings in the Niger Delta region of Nigeria due to excessive flaring [34]. The corrosion rate in this region of Nigeria is faster when compared to other regions of the country.

Acid rain acidifies lakes and streams and damages vegetation. In addition, acid rain accelerates the decay of building materials and paints. In addition, these contaminants acidify the soil, hence depleting soil nutrient, decreasing soil fertility, and reducing the nutritional value of crops cultivated within such flaring vicinity [35]. The effects of the changes in temperature on crops included stunted growth, scotched plants, and such other effects as withered young crops [36]. In some cases, there is no vegetation (**Figure 3**) in the areas surrounding the flare due partly to the tremendous heat that is produced and acidic nature of the soil pH [37].

5.2.3 Agriculture

Gas flaring has also been studied widely and reported to show negative effects on plant growth and wildlife [20]. Studies on the effects of waste gas flares on the surrounding vegetation in southeastern Nigeria show that the effect of flare extends

Figure 3.
Effect of acid rain on the environment [38].

well beyond a distance of 110 m from the stacks, with the exception of the suppression of the flowering of short-day plants [39]. It was therefore recommended that further studies were necessary to determine the effects of the flares on the productivity of crops grown in the region (**Table 4**) [41]. Soils of the study area are quickly losing their fertility and capacity for sustainable agriculture due to the acidification of the soils by the various pollutants associated with gas flaring in the area. This is in agreement with previous studies [35].

In one of our unpublished data, it was discovered that the carbon (^{13}C) isotopic composition for various categories of plants have been altered due to gas flaring in the region. Studies show that gas flaring significantly affects not only the microclimate but also the soil's physiochemical properties of the flare sites [42]. This was reflected in the study on the effect of gas flaring on maize yield size. The study reveals increased soil physiochemical properties (such as sand content of the soil, pH, bulk density, air and soil temperatures) toward the flare site. It was recommended that for an optimum yield of maize within the Niger Delta where gas flaring is taking place, the maize must not be cultivated within 2 km of the bund wall of the flare sites.

Furthermore, the destructive effect of gas flaring on wildlife has also been reported [43]. The study opined that gas flaring has been associated with the disruption of wildlife in the immediate surrounding area. As a result, the continuous bright light of gas flares scares wildlife causing them to migrate to more friendly territories or locations.

5.2.4 Health effects

Gas flaring causes the adjoining communities to suffer from increased health risks caused by exposure to those hazardous air pollutants emitted during incomplete combustion of gas flare. These pollutants are associated with a variety of adverse health impacts, including deformities in children, skin problems, cancer, lung damage, neurological and respiratory tract diseases, reproductive and developmental effects, etc. [44–46].

Information from the World Bank on the adverse health impact of particulate matter suggests that gas flaring from Bayelsa State, in Nigeria, would likely result to 49 premature deaths, 4960 respiratory illness among children, and 120 asthma attacks annually [47]. Also, the US Environmental Protection Agency (EPA) warns that exposure to benzene causes acute leukemia and a variety of other blood-related disorders in humans. Exposure to H_2S at concentrations below the permissible limit can cause spontaneous abortion [48].

5.3 Current trend in global gas flaring

Over the years, policies and regulations to tackle the menace of gas flaring have been stepped up considerably by various oil-producing countries with oil and gas companies taking active steps to plan and implement flare-reduction measures.

Distance of farmland from flare site	Percentage loss in yield of crops (%)
100 m	100
600 m	45
1 km	10

Table 4.
Loss in crop yield due to gas flaring [40].

Globally, a decline in the volume of associated gases flared from 2005 to 2010 of about 20% has been reported [18].

Azerbaijan's national oil company, State Oil Company of Azerbaijan Republic (SOCAR), had reduced her associated petroleum gas flaring and venting almost by half to less than 300 million cubic meters within 2 years after joining the GGFR in 2010. The key to this success was measurement (by relying on available data on how much, where, and how gas was being flared) and planning, with the GGFR contributing to both. The GGFR helped by providing measuring equipment and trained the company's staff in using it. Based on information gathered, SOCAR in collaboration with the British Petroleum Company drafted a gas recovery plan that put 1.6 bcm of natural gas to productive use in 5 years. This was used to power Azerbaijan's economy and development while ensuring a cleaner environment.

In the Al-Shaheen project, GGFR partnered with Qatar Petroleum and Maersk and worked together to capture and use 180 million cubic feet of gas per day for power generation. The gas, produced as a byproduct of pumping oil from 300 offshore wells, had been flared since oil production started at the Al-Shaheen field in 1994. This hitherto wasted gas is now being used to provide about a third of Qatar's electricity, and the gas emissions have been drastically reduced at the completion of the project.

Mexico likewise reduced gas flaring by 66% in 2 years owing to collaboration among the country's Secretary of Energy, its national oil company, Pemex, regulators, and GGFR. Pemex is committed to reducing gas flaring while strengthening flaring and venting regulations, as well as investing in gas recovery strategies.

The government in partnership with operating companies in the Republic of Congo developed a 350 megawatt gas-to-power project feeding two power plants with gas from the M'Boundi oil field. The laudable initiative has reduced emissions of greenhouse gases and increased access to electricity for some 300,000 people.

Kuwait Oil Company and GGFR worked together on a plan to reduce flaring below 1% of the intake associated gas and reach a "technical limit" for gas flaring reduction.

In Nigeria, huge investments from GGFR partners have also helped in reducing gas flaring by 4 bcm in the past 5 years: from 18.6 bcm in 2006 to 14.6 bcm in 2011. GGFR is working with the government and the oil companies to continue building on this positive trend. The World Bank also provides partial risk guarantees to investors in gas-to-power projects [49].

5.4 Crude oil spillage

Oil spillage have been a global issue that has been occurring since the discovery of crude oil [50]; spillage have the potentials of adversely affecting the different spheres of the environment such as coastal and marine habitats, wildlife, fisheries, and human activities (**Figure 2**) [51–53]. Crude oil spillage is simply regarded as the unlawful release of liquid petroleum hydrocarbons within the environments, due to accident and/or intentional human factors. This phenomenon occurs in different forms, and it is attributed to several factors as discussed below.

5.4.1 Equipment failures

Thousands of barrels of oil have been spilt into the environment through failures of oil pipelines and tanks in the country. This spillage is a result of lack of regular maintenance of the pipelines, drilling rigs, and storage tanks and leakages/spills during processing and at refining plants. Some of these facilities have been in use for decades without replacement.

5.4.2 Human error/theft

Sabotage is another major cause of oil spillage in some countries like Nigeria. Some of the citizens of the country with connivance with people from other countries engage in oil bunkering. They damage and destroy oil pipelines in their effort to steal oil from them. Shell Petroleum Development Company (SPDC) in 1996 claimed that sabotage was responsible for more than 60% of all oil spilled at its facilities in Nigeria, stressing that the percentage has increased over the years because the number of sabotage incidents has increased adding that spills due to corrosion of pipelines have decreased with programs to replace oil pipelines (**Figure 4**, **Table 5**). Pirates are stealing Nigeria's crude oil at a phenomenal rate, carting away nearly 300,000 barrels per day, and selling it illegally to the international trade market [41, 54]. **Table 6** gives an example of the number of spills and the reported volumes of oil spilled into the marine environment from 1997 to 2014. Nigeria's largest spill till date was an offshore well blowout in January 1980, when an estimated 200,000 barrels of oil (8.4 million US gallons) spilled into the Atlantic Ocean from an oil industry facility, and that incidence damaged 340 hectares of mangrove [56]. In Russia, aging and leaking pipelines are responsible for the wastage of millions of tons of oil a year, causing widespread environmental damage that largely goes unreported, according to Greenpeace Russia. However, reports have it that the Russia's 4.5 million tons of leaked oil is seven times greater than the BP Deepwater Horizon spill in the Gulf of Mexico in 2010 [57].

Notably, in the highest oil-producing region in Russia (Khanty-Mansi region in Northwestern Siberia), the annual oil spills from pipelines amounted to 5781.4 tons on an area of 229.6 hectares in 2009. In 2010, the Russian Company, Rosneft, alone spilled 3738 tons, and in 2011 a total of 5289 tons of oil was spilled in the region [58, 59].

Oil spills have and are still posing major threat to the environment of the oil-producing areas, which if not effectively checked can lead to the total destruction of the ecosystems. During an oil spill incidence in water, the gaseous and liquid components evaporate with time. Some other components immediately get dissolved in the water and become oxidized, while some undergo bacterial changes and eventually sink to the bottom. Oil spills often result in contamination of surface water with hydrocarbons and trace metals (**Figure 5**) [10]. Also, the soil is contaminated with a wanton negative impact on the terrestrial inhabitants. As the continued evaporation of the volatile and semivolatile lower-molecular-weight compounds affects aerial life, the dissolution of the less-volatile components with the resulting emulsified water affects aquatic life [60].

In addition, oil spill destroys plants and animals in the estuarine habitat. Oil settles on beaches and kills organisms that live there; it also settles on ocean floor

Figure 4.
Oil pipelines in Okrika community, Niger Delta [55].

Causes	Number (N = 135)	Percentage
Mechanical failure	23	17.04
Corrosion	21	15.56
Operational error	17	12.59
Third party activity	28	20.74
Natural hazard	3	2.22
Unknown	43	31.85

Table 5.
The causes of oil pipeline failures between 1999 and 2005 [51].

Year	Total number of reported spills	Quantity in barrels	Source
1997	339	59,272.00	[49]
1998	390	—	
1999	319	—	
2000	637	84,072.00	
2001	412	120,967.00	
2010	537	17,658.10	[50]
2011	673	66,906.84	
2012	844	17,526.37	
2013	522	4066.20	
2014	1087	10,302.16	

Table 6.
Reported oil spillage in the Niger Delta region.

Figure 5.
Impact of oil spillage on (A) loss of vegetation in Ogoni land, Niger Delta [62]. (B) Russia wasting millions of tons of oil from leaking pipes [56].

and kills benthic (bottom-dwelling) organisms such as crabs. Oil poisons algae, disrupts major food chains, and decreases the yield of edible crustaceans. It also coats birds, impairing their flight or reducing the insulative property of their feathers, thus making the birds more vulnerable to cold. Oil spill also endangers fish hatcheries in coastal waters and as well contaminates the flesh of marketable fish. Studies show that the pollution caused by oil spillage does not end with the mopping up of the spilled oil [61].

It is now known that health risk is not averted by abstinence or nonconsumption of fish killed by spilled oil. Some of the fishes and animals that escape death from oil spill pollution are known to have taken in some of the toxic substances, which in turn get into human beings that eat them as a result of bioaccumulation of these substances. This will in turn cause infections on man coupled with other "side effects" such as genetic mutations [61]. In another study [63], the density of sandstone interlaced with shale, beach ridge sand, and medium-coarse sand samples was reduced by 17.7, 13.3, and 15.0% on the average, respectively, due to oil spillage. Furthermore, crude oil-rich beach ridge sand, sandstone interlaced with shale, and medium-coarse sand decreased averagely by 4.4, 9.9, and 15.2%, respectively, of the original value of the specific heat capacity of the unmixed samples, while thermal conductivity of the crude oil beach ridge sand, medium-coarse sand, and sandstone interlaced with shale derivative increased by 9.8, 2.6, and 12.3%, respectively, on the average.

For example, a Nigerian coastal environment housing an extensive mangrove ecosystem has been destroyed. The mangrove was once a source of both woods being used as fuel for the indigenous people and a habitat for the area's biodiversity, but it is now unable to survive the oil toxicity of its habitat. Oil spills in the Niger Delta have been a regular occurrence, and the resultant degradation of the surrounding environment has caused significant tension between the people living in the region and the multinational oil companies operating there [64].

5.5 Noise

Noise pollution is one of the environmental impacts associated with heavy crude processing. The main sources of noise during the production of heavy crude oil would include compressor and pumping stations, producing wells, and vehicular traffic [65]. It has been reported that compressor stations produce noise levels between 64 and 86 dBA close to the station to between 58 and 75 dBA at about 1 mile (1.6 km) away from the station [66]. The direct impacts from the noise pollution would be localized disturbance to wildlife and residents.

5.6 Ecological resources

The major impacts to ecological resources during production of heavy crude oil could occur from disturbance of wildlife from noise and human activity; exposure of biota to contaminants; and death of biota from accidental collision with ground facilities or vehicles [67]. The presence of production wells, ancillary facilities, and access road can also reduce the habitat quality, disturb the biota, and thus affect ecological resources [68]. The presence of an oil field could also interfere with the migratory and other behaviors of some wildlife. The inappropriate discharge of produced water onto the soil or surface water bodies can result in high salinity which will not be able to sustain plant growth. In locations where naturally occurring radioactive material (NORM)-bearing produced water and solid wastes are generated, mismanagement of these wastes can result in radiological contamination of soils or surface water bodies leading to more harmful effects on humans [69].

5.7 Hazardous materials and waste management

Improper handling of industrial/hazardous waste obtained from the processing of heavy crude oil could cause an adverse effect on the ecosystem when released into the environment. These wastes are usually produced during routine operations in process plants [65]. Chemicals contained in open pits used to store wastes may pose a threat to wildlife and livestock because of potential seepage of such chemicals into the underground water. Sand separated from produced water should be properly disposed as it is often contaminated with oil, trace amounts of metals, or other naturally occurring constituents. Production processes could also cause accumulation of large volumes of scale and sludge wastes inside pipelines and storage vessels [70]. These wastes may be transported to offsite disposal facilities. Produced water can become a significant waste stream during the production of crude oil.

5.8 Air quality

The primary emission sources during the production of heavy crude oil include compressor and pumping station operations, vehicular traffic, production well operations, separation of oil phases, and on-site storage of the crude oil. Toxic pollutants emitted during operations would include volatile organic compounds (VOCs), nitrogen oxides, sulfur dioxide, carbon monoxide, benzene, toluene, ethylbenzene, xylenes, polycyclic aromatic hydrocarbons (PAHs), hydrogen sulfide, particulates, ozone, and methane which normally pose as impurities in operation columns [71].

5.9 Health and safety

Potential impacts to general public health and safety during production include accidental injury or death to workers and, to a lesser extent, the public. Health impacts could also result from water contamination, air pollutions, noise, soil contamination, and stress (e.g., associated with living near an industrial zone) [65]. Potential fires and explosions could constitute hazards. Cavitation could ignite grass fires. Increased or reckless driving by oil or gas workers would also create hazards. In addition, health and safety hazards include working in extreme weather conditions and possible contact with natural hazards, such as uneven terrain and dangerous plants, animals, or insects [72].

6. Conclusion

The processing of heavy crude oil generates different types of toxic organic and inorganic pollutants which pose direct or indirect impacts on the environment. Gas flaring, oil spillage, and pipeline vandalization have been some of the major processes leading to the release of toxic pollutants into the environment. Equipment failure and sabotage/theft have been major causes of oil spillage. These incidences have destroyed the coastal vegetation, polluted ground/surface water, and led to ethnic and regional crises. Other environmental impacts associated with heavy crude oil processing include noise pollution from producing wells, interference with ecological resources, release of hazardous materials, reduction in air quality, and health and safety implication. It is therefore pertinent for the petroleum sector to adopt procedures that would provide a reasonable degree of protection to the environment. Such procedural techniques, if implemented, should be able to reduce or eradicate those toxic pollutants.

Conflict of interest

The authors declare no conflict of interest.

Author details

Samuel O. Sojinu* and Onome Ejeromedoghene
Department of Chemistry, Federal University of Agriculture, Abeokuta, Nigeria

*Address all correspondence to: sojinuok2000@yahoo.com

References

[1] Kingston PF. Long-term environmental impact of oil spills: Review paper. Spill Science and Technology Bulletin. 2002;**7**(1-2):53-61

[2] Wikipedia. API gravity. 2018 [Retrieved December 14, 2018]. Available from: https://en.wikipedia.org/wiki/API_gravity

[3] JBlumsac S. The process of crude oil refining. [Retrieved December 14, 2018]. Available from: https://www.e-education.psu.edu/eme801/node/470

[4] Halliburton.Heavy oil. 2018 [Retrieved December 14, 2018]. Available from: https://www.halliburton.com/en-US/ps/solutions/heavy-oil/default.html

[5] Gateau P, Hénaut I, Barré L, Argillier JF. Heavy oil dilution. Oil & Gas Science and Technology. 2000;**59**:503-509

[6] Santos RG, Loh W, Bannwart AC, Trevisan OV. An overview of heavy oil properties and its recovery and transportation methods. Brazilian Journal of Chemical Engineering. 2014;**31**(3):571-590

[7] Loh W, Mohamed RS, Santos RG. Crude oil asphaltenes: Colloidal aspects. In: Somasundaram P, editor. Encyclopedia of Colloid and Surface Science. New York: Taylor and Francis; 2007

[8] Speight JG. The Chemistry and Technology of Petroleum. New York: Marcel Dekker, Inc; 1991

[9] Alain-Yves HUC. Heavy Crude Oils From Geology to Upgrading: An Overview. 2010. Available from: http://www.editionstechnip.com/en/catalogue-detail/1044/heavy-crude-oils.html [Accessed: October 4, 2018]

[10] Digital Refining, Processing, Operations and Maintenance. 2012. Available from: http://www.digitalrefining.com/article/1000563,Challenges_of_heavy_crude_processing.html#.W7kGW9dKgdU [Accessed: October 4, 2018]

[11] Ordinioha B, Brisibe S. The human health implications of crude oil spills in the Niger Delta, Nigeria: An interpretation of published studies. Nigerian Medical Journal. 2013;**54**(1):10-16

[12] World Health Organization. The World Health Report 2002: Reducing Risks, Promoting Healthy Life. Geneva: World Health Organization; 2003. pp. 1-71

[13] WHO. Facing the Facts: The Impact of Chronic Disease in Nigeria. Geneva: WHO; 2005. Available from: http://www.who.int/chp/chronic_disease_report/en/

[14] Planete Energies. The Three Stages of Refining. 2015 [Retrieved December 4, 2018]. Available from: https://www.planete-energies.com/en/medias/close/three-stages-refining

[15] Eman AE. Gas flaring in industry: An overview. Petroleum and Coal. 2015;**57**(5):532-555

[16] Anslem OA. Negative effects of gas flaring: The Nigerian experience. Journal of Environment Pollution and Human Health. 2013;**1**(1):6-8. DOI: 10.12691/jephh-1-1-2

[17] JINN. Gas Flaring in Nigeria: An Overview, Justice in Nigeria Now. 2010. Available from: www.justiceinnigerianow.org

[18] Canadian Association of Petroleum Producers. Flaring and Venting. 2012. Available from: http://www.capp.ca/environmentCommunity/

airClimateChange/Pages/FlaringVenting.aspx [Accessed: October 10, 2012]

[19] Haugland T, Saunier S, Pederstad A, Holm T, Darani H, Kertesheva A. Associated petroleum gas flaring study for Russia, Kazakhstan, Turkmenistan, and Azerbaijan—Final Report. Carbon Limit. 2013;**13**(28):1-80

[20] Gervet B. Gas Flaring Emission Contributes to Global Warming. Luleå, Sweden: Renewable Energy Research Group Division of Architecture and Infrastructure, Luleå University of Technology; 2007

[21] Ismail OS, Umukoro GE. Global impact of gas flaring. Energy and Power Engineering. 2012;**4**:290-302. DOI: 10.4236/epe.2012.44039

[22] Peterson J, Tuttle N, Cooper H, Baukal C. Minimise facility flaring. Hydrocarbon Processing. 2007;**86**(6):111-115

[23] Gzar HA, Kseer KM. Pollutants emission and dispersion from flares: A gaussian case-study in Iraq. Journal of Al Nahrain University. 2009;**12**(4):38-57

[24] Duck B. Reducing emissions in plant flaring operations. Hydrocarbon World. 2011;**6**(1):42-45

[25] Wikipedia, The Free Encyclopedia. Gas flare. 2012. Available from: http://en.wikipedia.org/wiki/Gas_flare

[26] Aregbe AG. Natural gas flaring—Alternative solutions. World Journal of Engineering and Technology. 2017;**5**:139-153

[27] United States Environmental Protection Agency. Industrial Flares. 1991. United States Environmental Protection Agency. Available from: http://www.epa.gov/ttn/chief/ap42/ch13/final/c13s05.pdf [Accessed: October 13, 2012]

[28] Gas Flaring in Nigeria, Friends of the Earth Media Briefing. 2004. p. 1-2. Available from: www.foe.co.uk/resource/media_briefing/gasflaringinnigeria.pdf [Accessed: October 14, 2004]

[29] Uwem U, Akpan EB. Gas flaring in Nigeria: Problems and prospects. Global Journal of Politics and Law Research. 2017;**5**(1):16-28. Online ISSN: ISSN 2053-6593

[30] The International Association of Oil & Gas Producers (OGP). Flaring & Venting in the Oil & Gas Exploration & Production Industry: An Overview of Purpose, Quantities, Issues, Practices and Trends. Flaring and Venting Task Force Report, Report No. 2.79/288. 2000

[31] Bassey N. Gas flaring: Assaulting communities, jeopardizing the world. In: Proceedings at the National Environmental Consultation, the Environmental Rights Action in Conjunction with the Federal Ministry of Environment; December 10-11, 2008. Abuja; 2008

[32] Orubu CO, Odusola A, Ehwarieme W. The Nigerian oil industry: Environmental diseconomies, management strategies and the need for community involvement. Journal of Human Ecology. 2004;**16**(3):203-214

[33] Gobo AE, Richard G, Ubong IUJ. Health impact of gas flares on Igwuruta/Umuechem communities in Rivers state. Journal of Applied Sciences and Environmental Management. 2009;**13**(3):27-33

[34] Hassan A, Konhy R. Gas flaring in Nigeria: Analysis of changes in its consequent carbon emission and reporting. Accounting Forum. 2013;**37**(2):124-134

[35] Imevbore AAA, Adeyemi SA. Environmental monitoring in relation to pollution and control of oil

pollution. Proceeding at the Seminar on the Petroleum Industry and the Nigerian environment. 1981;**6**:135-142 (In: Ref. [16])

[36] Orimoogunje OI, Ayanlade A, Akinkuolie TA, Odiong AU. Perception on the effect of gas flaring on the environment. Research Journal of Environmental and Earth Sciences. 2010;**2**(4):188-193

[37] Ubani EC, Onyejekwe IM. Environmental impact analysis of gas flaring in the Niger delta region of Nigeria. The American Journal of Scientific and Industrial Research. 2013;**4**(2):246-252

[38] Packwood R. Dead spruce trees killed by 'acid rain'. [Retrieved December 14, 2018]. Available from: https://www.gettyimages.com/detail/photo/dead-spruce-trees-killed-by-acid-rainhigh-res-stockphotography/126541656

[39] Augustine OI, Sanford WW. The effects of waste gas flares on the surrounding vegetation in south-eastern Nigeria. Journal of Applied Ecology. 1976;**13**(1):177-187. DOI: 10.2307/2401936

[40] Adeyemo AM. The oil industry extraministerial institutions and sustainable agricultural development: A case study of Okrika L.G.A of Rivers state, in Nigeria. Journal of Oil and Politics. 2002;**2**(1):60-78

[41] Ejiba IV, Onya SC, Adams OK. Impact of oil pollution on livelihood: Evidence from the Niger Delta region of Nigeria. Journal of Scientific Research and Reports. 2016;**12**(5):1-12

[42] Odjugo PAO, Osemwenkhae EJ. Natural gas flaring affects microclimate and reduces maize (Zea mays) yield. International Journal of Agriculture and Biology. 2009;**11**(4):408-412

[43] Hutchful E. Disarmament and development: An African view. IDS Bulletin. 1985;**16**(4):61-67

[44] Ovuakporaye SI, Aloamaka CP, Ojieh AE, Ejebe DE, Mordi JC. Effects of gas flaring on lung function among residents of a gas flaring community in Delta state, Nigeria. Research Journal of Environmental and Earth Sciences. 2012;**4**(5):525-528

[45] Canadian Public Health Association. Background to 2000 Resolution No. 3: Gas Flaring. Canadian Public Health Association 2000 Position Paper; 2000

[46] Kostiuk LW, Thomas GP. Characterization of Gases and Liquids Flared at Battery Sites in the Western Canadian Sedimentary Basin. Technical Report. Edmonton: University of Alberta; 2004. 95 p

[47] Collins C, Oshodi O. Improper abandonment of oil. Nigerians in America. 2010. Available from: http://www.nigeriansinamerica.com/articles/4403/1/Improper-Abandonement-Of-Oil/Page1.html

[48] Argo J. Unhealthy Effects of Upstream Oil and Gas Flaring, Save Our Seas and Shores (SOSS). Nova Scotia; 2002

[49] World Bank Group. Global Gas Flaring Reduction Results. Fact Sheet. [Retrieved December 14 2018]. Available from: http://siteresources.worldbank.org/EXTSDNET/Resources/GGFR-Results-Fact-Sheet.pdf

[50] Kadafa AA. Oil exploration and spillage in the Niger Delta of Nigeria. Civil and Environmental Research. 2012;**2**(3):38-51

[51] Fattal P, Maanan M, Tillier I, Rollo N, Robin M, Pottier P. Coastal

vulnerability to oil spill pollution: The case of Noirmoutier Island (France). Journal of Coastal Research. 2010;**26**(5):879-887

[52] Beyer J, Trannum HC, Bakke T, Hodson PV, Collier TK. Environmental effects of the deepwater horizon oil spill: A review. Marine Pollution Bulletin. 2016;**110**(1):28-51. DOI: 10.1016/j. marpolbul.2016.06.027

[53] Ifelebuegu AO, Ukpebor JE, Ahukannah AU, Nnadi EO, Theophilus SC. Environmental effects of crude oil spill on the physicochemical and hydrobiological characteristics of the Nun River, Nigeria Delta. Environmental Monitoring and Assessment. 2017;**189**(173):1-12

[54] Saleh MA, Ashiru MA, Sanni JE, Ahmed TA, Muhammad S. Risk and environmental implications of oil spillage in Nigeria (Niger-Delta region). International Journal of Geography and Environmental Management. 2017;**3**(2):44-53

[55] Kashi EA. Girl walks over oil pipelines in Okrika, Rivers State, Nigeria with a Shell umbrella. 2016 [Retrieved December 14, 2018]. Available from: http://ukpuru.tumblr.com/post/138384416907/a-girl-walks-over-oil-pipelines-in-okrikarivers

[56] Achebe CH, Nneke UC, Anisiji OE. Analysis of oil pipeline failures in the oil and gas industries in the Niger delta area of Nigeria. In: Proceedings of The International Multi Conference of Engineers and Computer Scientists. 2012. pp. 1274-1279

[57] Sharkov D. Russia Wasting Millions of Tonnes of Oil From Leaking Pipes. 2015 [Retrieved December 14, 2018]. Available from: https://www.newsweek.com/2015/04/17/russia-need-not-drill-arctic-if-itrepairs-oil-pipelineleaks-321372.html

[58] Moskovchenko DV. Oil products in bottom sediments of water bodies in Khanty-Mansi autonomous Okrug. Water Resources. 2005;**32**(1):79-83

[59] Vaver OY. The analysis of social conflicts of environmental management in the Khanty-Mansi autonomous Okrug—Ugra. Geographical Sciences. 2012;**11**:533-537

[60] Akpofure EA, Efere ML, Ayawei P. The Adverse Effects of Crude Oil Spills in the Niger Delta. Urhobo Historical Society. 2000;**1**:21-23

[61] Atubi AO. Effects of oil spillage on human health in producing communities of Delta state, Nigeria. European Journal of Business and Social Sciences. 2015;**4**(8):14-30

[62] Greyl L. Multinational Oil Companies on the Niger Delta, Nigeria. 2018 March 15 [Retrieved December 14, 2018]. Available from: https://ejatlas.org/conflict/multinational-oil-companieson-the-niger-delta-nigeria

[63] George NJ, Akpabio GT, Udofia KM. The implication of oil spillage on the thermal properties of soil samples in the Niger Delta, southern Nigeria. Archives of Physics Research. 2010;**1**(4):64-72

[64] Nwilo CP, Badejo TO. Impacts and Management of Oil Spill Pollution along the Nigerian Coastal Areas. Lagos, Nigeria: Department of Survey and Geoinformatics, University of Lagos; 2005. pp. 567-570. Available from: www.fig.net/pub.figpub36/chapters/chapter_8.pdf

[65] Ngene S, Tota-Maharaj K, Eke P, Hills C. Environmental and economic impacts of crude oil and natural gas production in developing countries. International Journal of Economy Energy & Environment. 2016;**1**(3):64-73

[66] Davorin M. Risk Analysis for Prevention of Hazardous Situations in Petroleum and Natural Gas Engineering. IGI Global; 2013. 433 p ISBN: 10:9781466647770

[67] Ouren DS, Haas C, Melcher CP, Stewart SC, Ponds PD, Sexton NR, et al. Environmental Effects of Off-Highway Vehicles on Bureau of Land Management Lands: A Literature Synthesis, Annotated Bibliographies, Extensive Bibliographies, and Internet Resources. US Geological Survey Open File Report 1353. 2007. 225 p

[68] Macdonal C, Lockhart L, Gilman A. Effects of oil and gas activities on the environment and human health. In: AMAP Assessment. 2007

[69] Burton GA, Basu N, Ellis BR, Kapo KE, Entrekin S, Hydraulic NK. “Fracking”: Are surface water impacts an ecological concern? Environmental Toxicology and Chemistry Journal. 2014;**33**(8):1679-1689

[70] Attallah MF, Awwad NS, Aly HF. Environmental Radioactivity of TE-NORM Waste Produced from Petroleum Industry in Egypt: Review on Characterisation and Treatment. Rijeka, Croatia: Intech; 2012

[71] Oil and Gas Production Phase Impacts. Available from: www.teeic.indianaffairs.gov/er/oilgas/impact/prod/index.html [Accessed: August 31, 2016]

[72] McMichael AJ, Campbell-Lendrum DH, Corvalan CF, Ebi KL, Githeko AK, Scheraga JD, et al. Climate Change and Human Health: Risks and Responses. World Health Organisation; Geneva. 2003;1-338. ISBN: 924156248x