Local Plant Seed Oils (Esters): The Frontier of Geothermal Drilling Applications – A Review*

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Abstract

A typical oil well may generate between 1 000 and 1 500 tonnes of drilled cuttings with average oil retention of 15% which are generally discharged into the sea. This activity affects vast areas around the drilling sites especially if the drilling fluids are formulated from conventional oil based fluids. Most mineral oils, diesel, petrochemical synthetic fluids have become a threat to the environment because of their high level of toxicity and cost of containment, hauling, and disposal. Many base oil fluids have been developed over the years to address these challenges but with very little successes. Plant esters have the potential to be used as drilling fluids as they meet the economic, technical and environmental requirements of the American Petroleum Institute (API). The use of plant esters can help alleviate challenges such as ill-health problems faced by workers, boost nutrients in soils if discharged onshore and help drill through troublesome formations safely. This paper reviews the potential use of plant esters as an economically viable, technically acceptable, environmentally friendly and sustainable oil based fluid substitute for the drilling of high geothermal wells.

Keywords: Antioxidant, Drilling Fluid, Environment, Plant Esters, Temperature

1 Introduction

Most drilled geological formations remain a constant challenge due to their instability and water sensitiveness (Dosunmu and Ogunrinde, 2010). Water Based Mud (WBM), being environmentally friendly, would have been the most appropriate fluid for drilling but unfortunately, most of these WBMs have numerous drilling challenges at deeper depth and such High Pressure High Temperature (HPHT), environments. HPHT wells are those with bottom hole temperature above 150 °C and a pore pressure gradient exceeding 0.18 kg/m^3 (0.80 psi/ft) (Oriji and Dosunmu, 2012). Most of the WBMs face challenges such as high temperature rheological instability, fluid loss issues, shale instability and lubrication problems (Marinescu, 2007). Oil based (diesel and or mineral oil) drilling fluids on the other hand have been used to address these challenges since the late 1960s (Salleh and Tapavicza, 2004). The superior performance of invert emulsion fluids or Oil Based Mud (OBM) in challenging drilling operations such as HPHT has been the system of choice over WBM. OBMs ensure borehole stabilisation and provide better lubricity thereby given faster rates of penetration (Ismail, 2001). If the total cost of drilling is considered, then OBMs are cheaper than WBMs though they may have higher initial cost (Dosunmu and Ogunrinde, 2010). However, they are a cause for major environmental concern. This is due to the potential long-term liability for damage caused by mud spills and problems in disposal of oil contaminated drill cuttings. This is because of their non-biodegradability, toxicity, persistency and bio-accumulation in aerobic conditions, tainting of marine life affecting its eating qualities and severely impacting on the seafloor sediments and food chain (Dosunmu and Ogunrinde, 2010). Thus most mineral oils, diesel, petrochemical synthetic fluids have become a threat to the environment.

A typical oil well may generate between 1 000 and 1 500 tonnes of drilled cuttings with an average oil retention of 15% (around 150 - 225 tonnes) which are generally discharged into the sea (Dosunmu and Ogunrinde, 2010). This activity affects vast areas around the drilling sites especially if the drilling fluids are produced from conventional OBMs (Dosunmu and Ogunrinde, 2010). Though OBMs have numerous advantages over WBMs, at temperatures higher than 150 ^{o}C (300 °F), most OBM systems suffer reduced rheology and filtration control (Ibeh, 2007). In areas where they are allowed, the costs of containment, hauling, and disposal make their use undesirable (Marinescu, 2007; Tehrani, 2007).

Diesel oil muds are recalcitrant fluids or have very slow biodegradability, with the presence of Benzene, Ethylbenzene, Toluene and Xylenes (BETX). Polynuclear Aromatics oils are quite flammable and also gel in cold climates (Anon., 2012). These oils affect major wellbore stability issues such as elastomer compatibility, Equivalent Circulation Density (ECD), temperature effects on fluid's rheology (fluid degradation), barite sagging, and compressibility due to high pressure and fluid's stability (Proehl, 2006; Aluyor and Ori-Jesu, 2008).

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Mineral oil drilling fluids which were introduced as drilling fluid systems in 1980s to offer low toxicity, non-polluting alternative to diesel drilling fluid systems still produce toxic effect to the micro-organisms although the oil is less hazardous than diesel (Ismail, 2001).

From the 1970s, the Environmental Protection Agency (EPA) in USA and other regulatory bodies from other major oil and gas producing nations have been advocating and imposing increasingly stringent environmental laws and regulations affecting all aspects of petroleum related operations; from exploration, production and refining to distribution (Fadairo *et al.,* 2012). This is to ensure the use of environmentally friendly drilling fluids but unfortunately, only a few drilling fluids are able to comply with the stringent EPA standards (Anon., 2004). Environmental problems associated with complex drilling fluids, especially OBM in particular, are among the major concerns of world communities (Fadairo *et al.,* 2012).

The oil and gas industry was therefore challenged to find a solution to this problem by formulating a drilling fluid that satisfies both the environmental and technical criteria by having excellent technical performance at high geothermal gradients, meeting the American Petroleum Institute (API) standards and as well be cost effective. The fluid must be able to clean the borehole of drilled cuttings, hold cuttings and weight materials in suspension when circulation is stopped, maintain formation pressure, must be cost effective in handling, and have minimal impact on the environment. Synthetic oil Based Muds (SBM) are now finding more applications in the industry to mitigate the environmental challenges because they are known to be readily biodegradable in oceans, especially those made from vegetable oil fluids (Dosunmu and Ogunrinde, 2010). Synthetic Based drilling Fluids (SBF) are particularly useful for drilling deepwater and deviated wells (Neff *et al.,* 2000).

SBMs (pseudo-oils) are formed with synthetic fluids which are essentially free of undesirable Polycyclic Aromatic Hydrocarbons (PAHs) and very biodegradable (Lee, 1998; Neff *et al.,* 2000). Synthetic fluids are of the synthetic hydrocarbon (olefins), ether, acetal, esters (which plant seed oils belong) (Lee, 1998; Neff *et al*., 2000). Most of these SBFs are produced chemically and are quite expensive to use (Neff *et al*., 2000). Synthetic hydrocarbons are derived from polymerised olefins and include Linear Alpha Olefins (LAOs), Poly Alpha Olefins (PAOs), and Internal Olefins (IOs) while ethers are saturated hydrocarbons with an oxygen atom in the centre and are formed when alcohols with different chain lengths are condensed and partially oxidised to produce mono- and di-ethers. Acetals are dialkylethers formed by the acid-catalysed reaction of an aldehyde with an alcohol or carbonyl compound. They are closely related to ethers but esters are generally prepared under acid catalysis conditions from the condensation reaction of alcohols and organic acids. Vegetable and fat oils falls under esters. A typical ester has a chemical formula of $C_{26}H_{52}O_2$ (Neff *et al.,* 2000).

Plant seed oils like those of Rapeseed, Jatropha, Mahua, Cottonseed, Sesame, Soya bean, Palm, Palm-kernel, rubber, groundnut, refined waste cooking oil, are potential raw material substitutes for oil based (diesel) (Fadairo *et al.,* 2012). These vegetable oil based fluids or plant esters have ecotoxicological properties; with aerobical and anaerobical esters that are readily degradable (Salleh and Tapavicza, 2004; Dosunmu and Ogunrinde, 2010). They can carry out the same functions as (diesel) oil based drilling fluid and equally meet up with the Health, Safety and Environment (HSE) standards (Fadairo *et al.,* 2012). The growing demand for biodegradable materials has opened an avenue for the use of plant seed oils as an alternative to petroleum based materials (Alves and Gomes de Oliveira, 2008). Malaysia's palm oil and palm kernel oils have proved to be environmentally friendly source of base drilling fluids (Salleh and Tapavicza, 2004). Ghana and the rest of Africa cultivate a huge amount of these plant seed oils. These oils could be used locally in formulating environmentally friendly drilling fluids for the Gulf of Guinea and other parts of the world. This paper reviews the potential use of plant esters as an economic, technical, health, safety and environmentally friendly oil based fluid substitute for the drilling of high geothermal wells.

2 Resources and Methods Used

2.1 Materials

The materials used in this paper were information gathered from journals, conference proceedings, unpublished materials and websites. The major conference proceedings materials used include proceedings at the Society of Petroleum Engineers (SPE) Drilling Conference, the Nigeria Annual International Conference and Exhibition, and the North Africa Technical and Exhibition. Others include unpublished thesis, dissertations, reports and Renewable and Sustainable Energy Reviews.

2.2 Methods

The method employed involved reviewing of the materials, comparing and considering published results on the use of drilling fluids with much focus on esters, noting the technical, Health, Safety and Environment (HSE) issues, economic and the sustainability of the local esters.

3 Results and Discussion

The findings from the reviewed materials are presented and discussed under the technical, HSE, economic, and the sustainability of the local esters.

3.1 Technical Considerations

It is the recommendation of API that for any base oil to become suitable for the formulation of any drilling fluid, it must be able to maintain its stability under any given condition to ensure wellbore stability at all times. Such oils must also ensure geothermal fluid compatibility with elastomer of Blow-Out Preventers (BOPs) especially for HPHT environments. They must also have very low pour and cloud points and lower viscosity to ensure easy flows at low temperature regimes, have high flash and fire points to avoid easy catching of fire of the base oil used. Unfortunately, plant esters in their natural state do not meet all these technical requirements. Though they have high flash and fire points, negligible aromatic contents, high aniline points. They however lack sufficient oxidative stability but have higher viscosity, poor pour and cloud points. The higher viscosity, poor pour and cloud points make the oils unsuitable for low temperature applications while their oxidative instability makes them undesirable at high geothermal regions.

3.1.1 Strengths

According to Lee (1998) and Neff *et al.* (2000), esters are generally prepared under acid catalysis conditions from the condensation reaction of alcohols and organic acids. There are numerous categories or structures of esters because of the alkyl group associated with the alcohol or acid. The chain length and branching of the fatty acids and alcohol can be modified to optimise viscosity, pour point, and hydrolytic stability. Esters are somewhat polar and more water soluble and are relatively stable under neutral pH conditions.

One major challenge facing the formulation of drilling fluid for HPHT wells is formulating a mud type that will be compatible with the elastomer of BOPs (Proehl, 2006) while a key eye on technical performance. Di-ethers, PAO and Detergent Alkylates are less compatible with elastomers while esters have a wider range of compatibility (Aluyor and Ori-Jesu, 2008). Esters generally have higher carbon number and the higher the carbon number, the better the skin compatibility (Lee, 1998) therefore making them very compatible with the elastomer of BPOs to ensure effective well control.

A good oil base mud is one that is easily compatible with oilfield additives especially with emulsifiers to ensure a strong emulsion at all times. The relative stability of a water-in-oil emulsion mud is indicated by the breakdown voltage at which the emulsion becomes conductive (The higher the value at API test temperature of 48.9 ^{o}C (120 ^{o}F), the more stable the mud system and vice-versa (Apaleke *et al*., 2012). Esters have very high electrical stabilities (Ekeinde, 2014), and are therefore able to ensure continuous wellbore stability. The API fluid characterisation for some plant seed oils are shown in Table 1.

Table 1 API Fluid Characterisation for Some Plant Seed Oils

(Amorin, 2016) Note: CO is Coconut Oil, GO is Groundnut Oil, JO is Jatropha Oil, PKO is Palm-Kernel Oil, SO is Soyabean Oil, XB1000 is Refined Waste Cooking Oil.

API Tests	CO	GO	JO	PKO	SO	XB1000	API
Flash Point (^{o}C)	300	292	265	268	318	180	≥ 66
Fire Point (^{o}C)	324	310	290	286	354	238	≥ 93
Pour Point (^{o}C)	17	23	0	22	-8	1	-
Cloud Point (^{o}C)	20	27	4	25	-4	4	-
Specific Gravity (15.56 ^{o}C)	0.919	0.917	0.913	0.918	0.916	0.872	-
Aniline Value (^{o}C)	> 60	> 60	> 60	> 60	> 60	> 60	> 60

3.1.2 Plant Ester Challenges

According to Lee (1998) and Neff *et al.* (2000), though esters are relatively stable under neutral conditions, under basic or acidic conditions they may undergo hydrolysis and revert back to the acid and alcohol which cause the oils to lose their stability. This process must therefore be prevented from occurring during drilling operations.

Most crops from the temperate and tropical regions are drying oils. They have low melting points and solidify when exposed to oxygen through chemical processes (Okoli, 2013). The rate of drying is directly proportional to the iodine value of the oil (Okoli, 2013). Most of the vegetable oils such as rapeseed, soyabean, groundnut, cotton, sunflower, coconut and palm oils would require further refinery processes to obtain an API biodiesel standard (Okullo *et al*., 2012) because of their dying nature.

The presence of hydroxide (OH) group in most of these vegetable oils tend to increase their viscosity significantly due to hydrogen bonding (Okullo *et al*., 2012). It is the high viscosity that makes most of these vegetable oils unsuitable to be used as biodiesel. They alsobecome uneconomical because of the need for transesterification processes such as dilution, microemulsion, pyrolysis and catalytic cracking in an effort to reduce their viscosity. These processes however do affect other chemical properties of the oil (Okullo *et al*., 2012. These oils have high viscosity indices about twice those of mineral oils, and about 11-12 times higher than diesel fuel and at ambient temperatures, have base viscosity that are relatively 2 to 4 times higher than other oil based fluids. As temperature increases, the fluids thin significantly more than other oils (Aluyor and Ori-Jesu, 2008; Eze *et al.,* 2013; Baidu, 2014) and would therefore require more viscosifiers to manage drilling fluid viscosities.

The lack of sufficient oxidative stability, lower viscosity, poor pour and cloud points of the local oils would therefore require some improvements to meet the API base oil standards.

3.1.3 Vegetable Oils Stability Improvements

The stabilities of vegetable oils could be improved in many ways. Depressants could be used to improve the poor pour and cloud points of the oils while the poor thermal stability could be improved by genetic modification processes, chemical alterations and or through the use of antioxidants.

3.1.4 Pour and Cloud Points Improvement

Cloud point is the temperature at which a cloud of wax crystals appear at a bottom of the jar of oil or when solid crystals are observed in an oil when cooled (Nowatzki *et al.*, 2012). It gives a rough idea of the temperature above which the oil can be safely handled without wax coagulation which causes filter clogging. The pour point of oil or product is the lowest temperature at which oil is observed to flow under the conditions of the test (Soliman, 2009). Pour Point Depressants (PPD) are additives that react through surface adsorption on wax crystals to inhibit growth of wax crystals and their capacity to adsorb oil and form gels (Ajithkumar, 2011). Some common pour point depressants are polymethacrylates, polyacrylates and alkalated naphthalene. The typical levels of application are 0.1 to 1.0% (Ajithkumar, 2011). A 0.3% addition of polymethacrylate based PPD to coconut oil (predominantly saturated fatty acid composition) brought the pour point value from 24 °C to 18 °C. For the application of styrenated phenol (SP) (from 1 to 20% addition) the pour point was enhanced from 24 °C to 12 °C when 15% SP was added (Ajithkumar, 2011).

In a study by Ooi *et al*. (2005) to improve the poor cold stability of Palm Oil Methyl Esters (POME) with palm-based oligomers , one sample code-named EP produced the most promising results. The work showed a reduction in pour point of about 15.0 ºC by the addition of 2% EP to the POME while the biggest depression in cloud point was about 6.4 ºC by the addition of 4% EP to the POME. The 2% EP addition depressed the pour point and cloud point to -3.0 ºC and 3.9 ºC respectively and also reduced the fat content significantly.

3.1.5 Oxidation Stability Improvement

Untreated oils oxidise easily during their use and polymerise to a plastic like consistency (Aluyor and Ori-Jesu, 2008). There are basically three ways of improving the stability of oils. These are through genetic modification using biotechnology to produce oils that have high saturated acid. Others are chemical modifications through hydrogenation of the vegetable oil to alter the fatty acids and, finally the use of antioxidants (additives) (Aluyor and Ori-Jesu, 2008). The use of an antioxidant is one of the most efficient and cost effective ways to improve oxidative stability. Vegetable oils have some amount of natural antioxidants such as ascorbic acids, α-tocopherole, β-carotene, chlorogenic acids and flavonoids (Aluyor and Ori-Jesu, 2008).

The antioxidants react with the fat radical to form a stable radical impending oxygen reaction (Aluyor and Ori-Jesu, 2008). They function as hydrogen donors by either inhibiting the formation of free alkyl radicals in the initiation step or by interrupting the propagation of the free radical chain reacting with lipid free radicals to form stable and complex compounds (Aluyor and Ori-Jesu, 2008).

Some popular antioxidants are of the hydroxylphenol compounds. Common phenolic antioxidants include butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), propyl gallate (PG) and tertiary butyl hydroquinone (TBHQ) (Aluyor and Ori-Jesu, 2008). The presence of metallic ions such as copper and iron act as pro-oxidants and must be removed by synergists like citric acid, phosphoric acid and some of their derivatives to enhance the effectiveness of primary antioxidants (Aluyor and Ori-Jesu, 2008; Akaranta and Akaho, 2012). They act as metal chelators. They bind metal ions that contribute to rancidity as they catalyse free-radical oxidation of lipids (Akaranta and Akaho, 2012).

Natural antioxidants are also finding root in the oxidation stability of vegetable oils because they are environmental friendly. Red onion skin (Allium Cepa) has tannins in its protective layers of the plant tissues, a polyhydroxyphenol of the flavonoid type (Akaranta and Akaho, 2012) which are also good natural antioxidants. Flavonoids of red onion and peanut skin extracts have strong potential to be used as antioxidants for vegetable oils and as inhibitors for unwanted polymerisation of some vinyl monomers (Akaranta, 2007). The addition of red pepper oil to soybean and sunflower oils inhibited the effect on oxidation in these oils (Aluyor and Ori-Jesu, 2008).

Warner and Gehring (2009), determined the frying stability of both untreated and treated soyabean oil (SBO) treated with a natural citric acid-based antioxidant (EPT-OILShield). Tortilla chips were fried with 0.05% and 0.50% of EPT-OILShield at 180 ^oC for up to 65 hours and the free fatty acids (FFA) and total polar compounds (TPC) were measured. Addition of 0.05% EPT-OILShield reduced the FFA and TPC than the untreated oil. This helped to apparently retain the aging of the chips because of the reduction of hexanal levels in the chips fried. Rancid level in the treated oil was also observed to be very low while the α-tocopherol levels were significantly higher helping to inhibit oxidation in the chips during storage.

Reda (2011), also investigated the thermal stabilities of some antioxidants, using canola vegetable oil to evaluate their resistance to thermal oxidation for constant heating at 180 °C (356 ^oF) per 8 hours for 10 days. The antioxidants used were ascorbic acid, sorbic acid, citric acid and sodium erythorbate. Others were 3, 5-di-tertbutyl-4-hydroxytoluene (BHT), 2, 3-tert-butyl-4-methoxyphenol (BHA), tertiary butyl hydroquinone (TBHQ), propylgallate (PG) the phytic acid antioxidant and the sucrose acetate isobutyrate (SAIB; mixture of esters of sucrose) additive, often used in the food industry. He observed that at temperature below 180 ºC, citric acid, sodium erythorbate, BHA, BHT, TBHQ and sorbic acid decompose while at temperatures between 180 and 200 ºC. Phytic acid, ascorbic acid and PG, exhibited the most resistance properties before decomposing above 200 and 220 ºC respectively.

Akaranta and Akaho (2012), examined the antioxidant potentials of citric acid and onion skin extract on the oxidative stability of vegetable oil considering the peroxide values to a temperature of 180 ^oC. They concluded that a blend of 0.1 g of citric acid and 0.1 g onion skin extract in [100 g] of oil oil resulted in a better antioxidative potential than the use of the extracts alone. Akaranta and Akaho (2012), reported that the blend of two or more antioxidants most often prove to be more effective than the effect of one; one antioxidant reinforcing the effect of the other for maximum efficiency.

3.2 Health, Safety and Environment

Health, Safety and Environment (HSE) deals with occupational health and safety at work places and the protection of the environment (Anon., 2014a). It is an API requirement that any oil to be used as a potential drilling fluid meets certain basic HSE requirements such as flash, fire and aniline points, aromatic contents and biodegradability stability tests. This is to protect the workers who work on these base fluids from related fluid diseases, hazards and prevent contamination of working environments.

The recommended API flash and fire points of any base oil to be used as a drilling fluid must be equal to or greater than 65.6 ^oC (150 ^oF) and 93.3 ^oC (200 ^oF) respectively (Mohammed, 2013). This is because they determine the flammability hazards of the oils. Higher flash points are good indications for safe handling and storage purposes (Hossain and Davis, 2010). Synthetic fluids (esters) are known to have much higher flash points (>144 ^oC) than diesel and mineral oils (<100 ^oC), therefore reducing their possibility of starting a fire or explosion on a drilling rig (Candler *et al*, 1993; Park *et al*., 1993; Anon., 2014b). Ekeinde (2014) investigated the stability of some plant esters such as palm oil, palm kernel oil and groundnut oil and reported that the plant oils have very high flash point that would ensure product handling safety and other technical prospects such as good compatibility with other oilfield additives, viscosity that.

It is also reported that esters are essentially free of undesirable polycyclic aromatic hydrocarbons and do have aniline values generally higher than the recommended API minimum value of 60 ^oC (140 ^oF) indicating their lower or nontoxicity levels making them safer for humans to handle (Lee, 1998; Neff *et al*., 2000).

The use of plant or vegetable oils as base drilling fluid applications may also help alleviate ill-health drilling problems faced by workers, such as skin cancer and inhalation of toxic mist in the mud working environments. This is because they are nonaromatic, nontoxic add nutrients to soils when discharged, biodegradable, and require less cost to formulate compared to mineral and diesel oils (Ismail, 2001; Alves and Gomes de Oliveira, 2008). Biodegradability is the most important aspect with regard to the environmental fate of a substance, that is, a substance is susceptible to biochemical breakdown by the action of microorganisms (Alves and Gomes de Oliveira, 2008). Due to their biodegradability they are permitted to be discharged on-site with minimal impact to the environment (Veil, and Daly, 1999).

Dosunmu and Ogunrinde (2010) in finding out the viability and environmental friendliness of some of these plant oils formulated palm and groundnut based fluids with standard oilfield additives and compared their results with one formulated with a diesel based fluid. The authors reported that the palm and groundnut oils were environmentally friendly because they helped improved crop growth when discharged into farm lands.

3.3 Economics

A good mud program should always aim at maximising returns on investment. Such a mud will always be economical despite its initial cost per barrel (Ogbonna, 2010). The initial cost of formulating synthetic fluids compared to OBM may be doubled but the cost of containment, hauling, and disposal of OBMs after use are quite high compared to SBMs (Tehrani, 2007; Vajargah *et al.,* 2009; Growcock and Patel, 2011). The use of cheaper local SBFs with its allowed discharges at drilling sites therefore offsets its initial cost of formulation. Thus transportation and disposal costs are saved (Vajargah *et al.,* 2009). SBM can also be used repeatedly to such an extent that major cost reductions can be achieved with minimal Non Productive Time (NPT). The use of SBMs can reduce drilling times and well costs by 50 to 60% (Vajargah *et al.,* 2009). Generally, the net cost of using SBM is significantly less than WBMs and OBMs though their initial costs may still be higher (Growcock and Patel, 2011). According to a study conducted by Veil *et al*. (1995), the total costs for WBM wells arranged between $ 9.6 - 14.7 million while that of SBM wells cost in the range 4.4- 6.5 million .

3.3.1 Drilled Cuttings Disposal Cost Options

The primary options available for disposal of oil based drilling cuttings are either offshore or onshore discharge (Derrick, 2001; Bernier *et al.,* 2003). For offshore discharges, the cuttings (nontoxic) are either discharged overboard from drilling vessels or platforms after undergoing treatment passing through solids control equipment. They can also be re-injected into permeable subterranean formations where drill cuttings are ground to fine particle sizes and disposed off, along with entrained nontoxic drilling base oils. For onshore disposal, the cuttings and the associated nontoxic oils are collected and transported for treatment (e.g. thermal desorption, land farming) if necessary and final disposal by techniques such as land filling, land spreading, injection, or re-use (Bernier *et al.,* 2003).

The non-discharge disposal options (offshore) require equipment such as auger or vacuum systems to move cuttings from solids control equipment to offloading point or on-site injection plant (Derrick, 2001). A typical casing programme, drilled with oil based or synthetic oil based muds, may generate conservatively 159 m^3 (1 000 bbls) of cuttings offshore (Derrick, 2001). The transportation of these cuttings onshore may incur additional charges of about $ 2 500/day for rental and operation of cuttings handling equipment and $ 277/tonne of waste for transport to shore or to an alternate offshore disposal site (Derrick, 2001). Further treatment onshore may also incur additional cost. For example, in the case of thermal treatment, an additional $ 251/tonne may be incurred while for incineration treatment $ 111/tonne may be incurred. For treated land-farm disposal, an additional $ 37/tonne would be spent while for untreated landfill, $ 74/tonne is charged. Also, for treated landfill disposal, a charge of $ 208/tonne is incurred while for onshore injection, an amount of $ 130/tonne may be spent (Derrick, 2001). The discharge of cuttings offshore is the least expensive, operationally uncomplicated and safest (Satterlee *et al*., 2011).

For the purpose of discharging, these NonAqueous Fluids (NAFs) used in drilling mud formulation are grouped according to their aromatic hydrocarbon content and include the following (Bernier et al., 2003; Satterlee *et al.,* 2011):

(i) Group I NAF has polycyclic aromatic hydrocarbon (PAH) content of diesel-oil typically 2 to 4% (high aromatic content). Due to concerns about toxicity, diesel oil cuttings are not discharged. Group I NABFs are defined by having PAH levels greater than 0.35%;
(ii) Group II NAF (medium aromatic content) are known as Low Toxicity Mineral Oil-Based Fluids (LTMBF). They were developed to address the concerns of the potential toxicity of diesel based fluids. The PAH content of the diesel-oil fluids is less than 0.35% but greater than 0.0001%; and
(iii) Group III NAF (low to negligible aromatic content) are the newest generation of drilling fluids include highly processed mineral oils and synthetic based fluids. They are produced by chemical reactions of relatively pure compounds that include synthetic hydrocarbons (olefins, paraffins and esters). These fluids are discharged in many offshore areas such as the Gulf of Mexico, Azerbaijan, Angola, Nigeria, Equatorial Guinea, Congo, Thailand, Malaysia, Newfoundland, Australia and Indonesia.

Among the SBFs, ester based fluids or fatty acid esters (vegetable or plant seed oils) are known to be relatively inexpensive and environmentally friendly (Shah, *et al.,* 2010). The incremental drilled cuttings cost per well ranges from \$ 450 000 with a Group III and basic solids control equipment to \$ 1 400 000 for onshore landfill disposal after thermal treatment of cuttings drilled with a Group II NADF (Fig. 1).

According to Anawe, *et al*. (2012), most vegetable oils require lesser amount of weighing material to weight muds compared to commercial base fluids to achieve the same mud densities. This makes the vegetable base fluids more economical over commercial ones too.

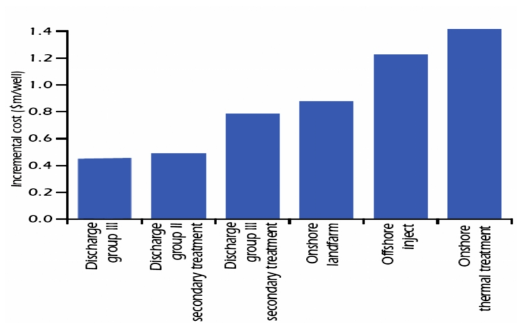

Fig. 1 Relative Costs of Disposal Options

3.4 Sustainability - SBF Prospects

Sustainability is defined as the "development which meets the needs of the present without compromising the ability of future generations to meet their own needs" (Drexhage and Murphy, 2010). The three pillars of sustainability are economic development, social equity and environmental protection. The cultivation, production and usage of these oils can be able to satisfy these three pillars of sustainability both domestically and industrially if more attention is given it. The world is endowed with much agriculture land for the production of these oils. As at 2011, 38.4% of the world's land area was covered by agricultural land (Anon., 2017a). The production of vegetable oils has grown to more than 45.36 million tonnes (100 billion pounds) annually during the 20th century (Anon., 1998). In 2001, the production rose to 319 million metric tonnes. Less percentage of the total production of each oilseed was used directly as food. For example, in 2000, the global vegetable oil consumption was about 76 million tonnes (Anon, 2017b). Higher percentage of the oilseed produced are rather crushed to extract oil. On average, crushed seeds oils give about 26% yield (cottonseed gives minimum yield of 15% where else coprah gives a maximum of 62%) (Anon., 2017b). The worldwide production of some selected oil crops in 2014 is shown in Table 2. The co-product of these processed oils are pressed cakes which are good organic soil improvers; organic fertilizers rich in Nitrogen, Phosphorus and Potassium (NPK) and also a very good animal feed sources (Amoah, 2006 and Anon., 2010). Many refined waste cooking oils (biodiesel) or Fatty Acid Methyl Ester (FAME) produced through biofuel distillation (Anon., 2014c) are also potential local esters to be considered for the formulations of ester based fluids. The production of this is also on the increase creating safer environment and job prospects.

Table 2 2014 Worldwide Production of Selected Oil Crops (Anon., 2017c)

Oil Crops	Production (Tonnes Per Year)
Oil palm	52,821,076
Soybean	308,436,057
Rapeseed	70,954,407
Palm kernels	15,913,911
Cottonseed	46,657,005
Groundnut with shell	42,316,355
Olive	15,516,980
Coconut	61,440,691
Maize	1,021,616,584
Sesame seed	5,469,023
Linseed	2,564,535
Safflower seed	867,659

3.4 Project Implementation Benefits

According to Amorin, (2016), the use of these less toxic and very biodegradable plant seed oils (local SBFs) would benefit both the host nation and the oil and gas industry as a whole.

3.4.1 Oil and Gas Industry

The oil and gas industries would benefit in many areas including the following (Amorin, 2016):

a) Less legal issues associated with cuttings discharge and spillages of local SBMs. The accidental spillages of cuttings offshore may not attract much stringent sanctions since the base fluid is non or less toxic and very biodegradable.
b) Reduce drilling cost:
    (i) Cutting down importation taxes associated with OBFs products imports;
    (ii) Cutting down disposal cost; since the local SBFs are less harmful and very biodegradable, they are easily permitted to be discharged offshore. Operators will therefore cut down cost of transporting cuttings onshore for disposal purposes; and

c) As oil based fluid, muds could be re-conditioned and re-used to reduce cost of formulating a new mud system entirely.
d) Minimise Non Productive Time (NPT):
    (i) Reduce drilling challenges such as elastomer fluid compatibility issues, fluid rheology instability, minimise high ECD issues and enhance log rounds; and
    (ii) Ensure consistent manpower availability; minimise injuries and ill-health of workers associated with working with toxic base fluids.

3.4.1 Host Nation

The host nation as a whole would also benefit in the following ways (Amorin, 2016):

(i) Creation of jobs in the form of cultivation and processing of these oils;
(ii) Earning of more foreign exchange through the exportation of these fluids to other countries; and
(iii) Helping to ensure a sustainable and conducive working and living environment for all.

4 Conclusions

As the industry looks for an economically and environmentally friendly drilling fluid, it is imperative to concentrate on these cheaper plant esters. The sources of these plant esters are in abundance in most parts of the country and can be produced on large scales to meet the needs of the industry. With the right formulations these oils could help address major geothermal drilling issues such as fluid compatible with BOP elastomer, temperature effects on fluid's rheology (fluid degradation) and issue of barite sagging, compressibility due to high pressure and fluid stability.

The applications of the right stability processes to these plant oils would make them very geothermally stable. This would enable them satisfy both the environmental and technical criteria of API standards.

There must therefore be more research on the use of these plant oils such as jatropha oil, palm oil, palm-kernel oil, coconut oil, soyabean oil, and refined waste home-cooking oil, *etc* to promote their usage in drilling wells for geothermal formations. This would as well benefit the local economy in job creation and contribute to a sustainable drilling management.

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