Oil Based Drilling Fluid Waste: An Overview on Highly Reported But Less Explored Sink For Environmentally Persistent Pollutants

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Abstract. Operational discharges of spent drilling fluid, produced water, and accumulated drill cuttings from oil and gas industry are a continuous point source of environmental pollution. To meet the strict environmental standard for waste disposal, oil and gas industry is facing a numerous challenges in technological development to ensure a clean and safe environment. Oil and gas industry generates a large amount of spent drilling fluid, produced water, and drill cuttings, which are very different in every drilling operation in terms of composition and characterisation. This review article highlights the knowledge gap in identifying the different sources of waste streams in combined drilling waste. This paper also emphasises how different chemicals turn into environmentally significant pollutants after serving great performance in oil and gas drilling operations. For instance, oil based drilling fluid performs excellent in deeper drilling and drilling in harsh geological conditions, but ended with (produces) a significant amount of persistent toxic pollutants in the environment. This review paper provides an overview on the basic concepts of drilling fluids and their functions, sources and characterisation of drilling wastes, and highlights some environmentally significant elements including different minerals present in drilling waste stream.

1. Introduction

Oil and gas industrial exploration operational discharge, accidental spillage, or improperly disposed drilling wastes have serious detrimental effects on human and environment. When oil & gas drilling fluids and cuttings are disposed on the ground surface, the liquid fraction of chemicals start seeping through the ground and eventually these chemicals destroy the living organisms in the ground and pollute the groundwater [1]. Consequently, oil based drilling fluids (OBFs) and associated drill cuttings have become a major challenge in the industry for compliance with the requirements of zero discharge. Due to the European Union (EU) Waste Framework Directive (WFD), new legislations have been implemented in the EU member countries including United Kingdom for the recycling of wastes with a mission to prevent and reduce landfilling of waste [2,3].

In oil and gas industry, OBFs play an important role in drilling operation by providing relatively better shale inhibition, lubricity, and thermal stability characteristics [4,5]. It performs various functions including removing and cleaning drill cuttings from the drilling operation, cooling and lubricating the drill bit, controlling the hydraulic pressure, and ensuring a hydrostatic head to help integrating the wellbore wall and protecting from well blowouts [6,7]. Where reliable shale inhibition, better borehole stability, low filtration rates, low formation damage, low corrosion, and excellent lubricity are needed especially in sensitive well or geological conditions, invert-emulsion systems (OBFs and synthetic oil based fluid) are preferable [8,9]. The OBFs systems were developed and introduced in the 1960s to reduce and rectify different drilling issues such as, formation clays, swell and slough issues involved in WBFs, downhole temperature control, contaminants and stuck pipe and torque and drag [10,11,12]. In OBFs system, oil is the continuous phase and is formulated with diesel, mineral oil, or low-toxicity linear olefins and paraffins, (linear olefins and paraffins are sometimes considered as synthetic oils based

on the synthesis from smaller molecules) [13]. Barium sulphate (barite) and organophillic bentonite are commonly used in the OBFs for increasing the system density and for improving the viscosity property respectively and therefore better functional properties [14].
Back in 1970, different environmental organisations and government agencies designed a guideline which has today been implemented in different processing industries including oil and gas industry [1]. It follows that drilling is one of the major chemical intensive operation in the oilfield and has a significant source of chemical exposure and subsequent health effects [15,16]. In oil based drilling operation, OBFs containing drill-cutting discharge in offshore-drilling is not permitted to most areas. During the drilling operation, a large amount of pollutants are introduced in drilling fluids, which is a big challenge with respect to solid waste handling in process operations. All such drill cuttings and spent drilling fluids are processed, and shipped to shore for disposal [17]. In case of onshore operations, pit burial is the most common technique used for drill cuttings management. In this process, drill cuttings have been temporarily stored in earthen pits for both onsite and offsite operation before disposal to the land or subsurface [18]. Hence, this review highlights the sources and characterisation of drilling wastes, and environmentally significant constituents present in drilling wastes to provide support for designing effective waste treatment plan.

2. Sources of drilling wastes

In oil and gas industry, the well drilling process produces two main types of wastes; drill cuttings, and spent mud [19]. In drilling operation, the pressure applied to penetrate the drill pipe into the oil and gas reservoirs produces a large amount of pieces of rock being drilled to fall to the bottom of the well bore [20,21]. These pieces, referred to as drill cuttings, clog the well if not carried out. Drilling fluid, also known as mud due to its consistency and appearance, is circulated in the well to transport the drill cuttings to surface [22,23]. In most deep drilling operation, oil based fluids (OBFs) are used instead of water based fluids (WBFs) depending on the drilling conditions for efficient and cost-effective operations. It is quite common practice to use both WBFs and OBFs in drilling the same well, with WBFs for shallow portion of the well and OBFs for deep drilling [19]. The sources of drilling wastes largely depend on the cuttings based on the geological condition of the borehole, the depth of the well, and the fluid used in the drilling operation [24]. The accumulation of drill cuttings is estimated in the range of 130 to 560 m^3 per well and the possible sources and components of wastes are presented below [25].

- Waste lubricants: lube oil, grease
- Spacers: mineral oil, surfactants
- Spent contaminated water based muds: mud, mineral oil
- WBM cuttings: formation solids, WBM, mineral oil
- Spent OBMs : mud, mineral oil
- OBM cuttings: formation solids, OBMs
- Spent bulk chemical: cement, bentonite, barites, viscosifiers, thinners, fluid loss protective additives
- Spent special products: scavengers, defoamers, tracers

The variations in drilling fluids composition and the variations in geological formation generate a complex mixture of drilling fluid wastes, which cannot be classified into any classical drilling fluid waste profile. For an example, in OBFs base oil may be of various natures and also the additives used in OBFs may be of very complex form such as surfactants, organophilic clays, viscosifyers [16,25]

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3. Characteristics of drilling wastes

In 2004, World Oil's categorised drilling fluids into nine distinct types including dispersed freshwater, non-dispersed fresh water, saltwater, oil-based, synthetic-based, air, mist, foam, and gasified drilling fluid systems [10,12]. These drilling fluids can be broadly classified as either liquid or pneumatic [26]. Drilling fluid selection in a drilling operation depends mainly on the geological formation information of the wellbore area. However, drilling fluids should possess various physical properties, such as thixotropy and rheology to make the drilling operation economical and sustainable [27]. After the drilling operation, accumulated drill cuttings are suspended, assimilated, or dissolved in the drilling fluids without affecting its physical properties [28]. These fluids may contain a wide variety of dissolved minerals, dissolved and dispersed oil compounds, salts, metal ions, naturally occurring radioactive materials (NORM) and dissolved gases. To meet the environmental regulations, these fluids may need to be treated to a satisfactory level before disposing them in landfill. To identify the concerning constituents present in waste stream and to design the effective treatment process, the accurate and detailed physical and chemical characterisations of wastes are necessary [24].

The physical composition of drilling wastes is mainly based on the type of drill cuttings produced. These cuttings are generally a reflection of the geological constituents of the sub-surface being drilled as well as the individual solid or chemical components originally contained in the drilling fluid [19]. In 1996, drilling operation was estimated to accumulate 7 million m^3 drill cuttings in North Sea between the years 1964 and 1993 and was projected to 12 million m^3 by 2000. Although the sources and compositions of wastes vary from site to site, their behaviour towards biological activities, cohesion with oil rich silts remain the same in nature. In a typical drill cutting pile, the pile is assumed to compose of 20-60% water, a bulk density of 1.6-2.3 g/cm^3, and a particle size ranging from 10μm to 2 cm [29,30]. Hudgins [31] reported the most comprehensive study to date available in open literature covering ten operating companies and six chemical suppliers in North Sea that obtained data (see Fig 1) on the specific types and quantities of chemicals used in their operation and identified the properties of these chemicals. The survey [31] also presented the discharge quantities and concentrations of chemicals during exploration and production activities performed by these companies in the North Sea. However, based on the Hudgins [31] survey results it can be summarised that the WBM accumulated more than three times the volume of discharge compare to OBM. It also noticed that the weighting agents, salinity, and bentonitic chemicals accumulated about 90% of the total WBM discharge.

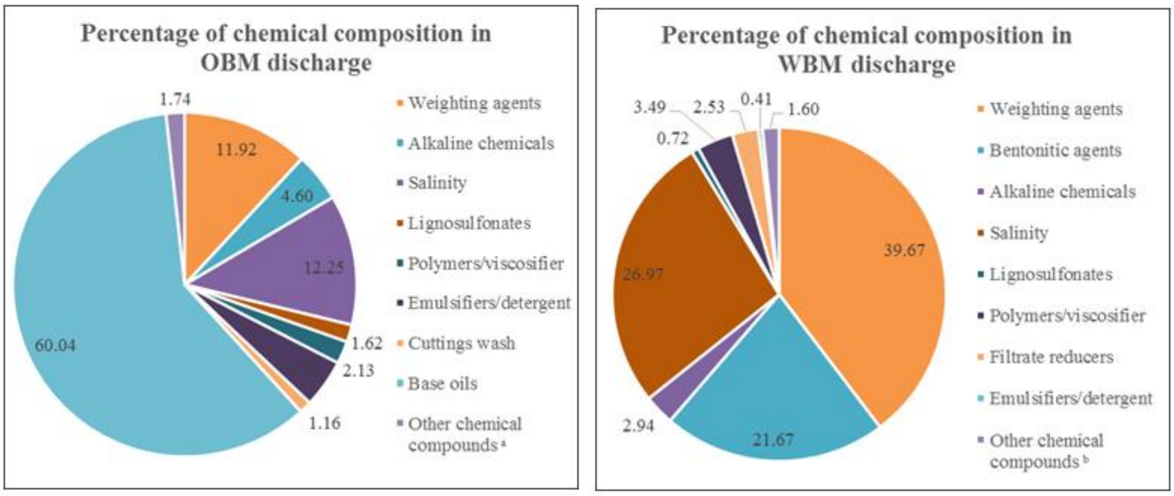

Fig. *1* Percentage of individual chemical constituents present in OBM and WBM discharge adapted from Hudgins [31].

Note: a) Bentonic agents, lost circulation, lignites, filtrate reducers, gilsonite, wetting agents, and thinning agents. b) Lost circulation, lignites, gilsonite, defoamers, biocides, corrosion inhibitors, scale inhibitors, drilling lubricants, pipe-release agents, oxygen scavengers, shale inhibitors, and thinning agents.

It can be concluded by highlighting that about 53% of chemicals that are used in drilling operation are discharged as wastes and thus cause the pollutants burden in the environment [31,32].

The chemical composition of drill cuttings at the time of disposal is an indication of the drilled sub-surface strata and concentration of the chemical components of the drilling fluid that remain attached to the cuttings. The temporal trends towards drilling activities provide important information on the long term effects of drill cutting discharges on geochemical and hydrogeological conditions [33]. Findings from different groups confirm the presence of certain metals in drill cuttings and their potential effect on the environment. Among these metals Cd, Cr, Ni, As, Co, Cu, Pb, V, Zn, Al, Ba, Fe, Mn are predominant in drill cuttings [34,35]. During the period of 1981-1986, the average annual discharge of oil on cuttings to the Norwegian Continental Shelf (NCS) was 1940 tons and that was eliminated gradually by implementing different directives such as OSPAR Commission in OSPAR regions. In addition to oil on cuttings discharge, the amount of produced water (PW) discharge has increased significantly due to the well ageing and also the rising number of oil and gas exploration and production fields. Large volume of OBM cuttings and SBM cuttings piled up in the seafloor before the regulations implemented in 1993/1996. It was estimated that about 45,000 m^3, a height of around 25m, and a footprint of more than 20,000 m^2 cutting piles are still present in the northern and central part of the North Sea. About 79 large (>5000 m^3) and 66 small (<5000 m^3) cutting piles have been identified in United Kingdom Continental Shelf (UKCS) and NCS. Further, a significant concentration of total hydrocarbons (10,000 to 600,000 mg/kg) exist in the North Sea piles [36].
However even WBM cuttings with less hydrocarbon content may seriously affect benthic fauna by elevating oxygen consumption in sediments. The risk of drilling waste associated with WBM cuttings discharge to the ecosystem is presently considered low, but this statement cannot be verified from the published literature. However, the variation in the amount of drilling fluid that remains adhered to the drill cuttings at the time of disposal is influenced by the size of the cuttings. The smaller the size of cuttings, the harder it is to separate it from the drilling fluid. In addition to these metals derived from the drilling fluid and geologic formation being drilled, cuttings may also contain some petroleum hydrocarbons closely linked to that of the reservoir rock [33].

4. Environmentally concerned constituents in drilling waste

Soil contamination is hazardous to health and environment through its action on surface waters, ground waters and vegetation (phytotoxicity, bioaccumulation). Oil and gas industries, like other process industries, have a detrimental effect on environment [37]. The hazardous effect of the environmentally significant constituents in the produced drilling wastes is predominantly dependent on each constituent, its concentration at exposure, biotic environment at point of discharge and the duration of exposure.

The typical type of drilling wastes and their potential constituents are [25]:

- WBM cuttings: Heavy metals, inorganic salts, biocides, hydrocarbons
- OBM cuttings: Heavy metals, inorganic salts, hydrocarbons, solid/cuttings
- Spent OBM: Heavy metals, inorganic salts, hydrocarbons, solid/cuttings, BOD, surfactants
- Spent WBM: Metals including heavy metals, inorganic salts, hydrocarbons, biocides, hydrocarbons, solid/cuttings, BOD,
- Waste lubricants: Heavy metals, organic compounds.

Some of the metals are suspected to be present in concentrations significantly higher than the naturally occurring concentrations of the sediments, which makes the disposal of these wastes a critical environmental concern [25,34]. Arsenic, nickel, copper, chromium, zinc, anthracene, diuron, fluoranthene, naphthalene, phenanthrene, and pyrene are considered as environmentally significant chemicals according to the literature [35,37,38].

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Although the amount of drilling fluid constituents is very low, most of them especially heavy metals have a chronic effect on environment. The pollutants may nowadays be categorised in two different groups of pollutants: List I and List II as shown on Table 1 according to European Council Directive 76/464/EEC [39]. List I group are substances, which are toxic, persistent, and possess the bioaccumulation properties while List II is a group of chemicals, which have deleterious effect on the aquatic environment. However, list II pollutants can be confined to a given area and also the pollutants concentration varies based on the characteristics and location of the water into which the pollutants are discharged.

Table 1: List I and II pollutants in environment.

Type of pollutants	Members of pollutant groups
	Organohalogen compounds and substances
	Organophosphorus compounds
	Organotin compounds
List I	Carcinogenic substances
	Mercury and its compounds*
	Cadmium and its compounds*
	Persistent mineral oils and hydrocarbons of petroleum origin
	Persistent synthetic substances
	Certain metals, metalloids, and their compounds: 1) Zinc 2) Copper* 3) Nickel* 4) Chromium (Cr(VI)*)
	5) Lead* 6) Selenium* 7) Arsenic* 8) Antimony* 9) Molybdenum 10) Titanium 11) Tin* 12) Barium
	13) Beryllium 14) Boron 15) Uranium 16) Vanadium 17) Cobalt 18) Thalium* 19) Tellurium* 20) Silver
	Biocides and their derivatives
List II	Toxic or persistent organic compounds of silicon and its substances
	Inorganic compounds of phosphorus and elemental phosphorus
	Non persistent mineral oils and hydrocarbons of petroleum origin
	Cyanides and fluorides
	Substances causing oxygen imbalance such as ammonia, nitrites

*: Hazardous waste classified in according to Directive 2008/98/EC

In 2008, the Waste Framework Directive 2008/98/EC brought legal changes to the list of waste and hazardous waste criteria based on the source and composition of wastes [40]. In this amendment the source of waste is identified into 20 chapters (from 01 to 20) and the different types of waste in the list are fully defined by the six-digit code (first two digits is chapter heading and the rest four digits for identifying sub-groups). Based on this Commission Decision, environmentally significant and hazardous elements or compounds which are present in drilling fluid wastes are denoted by * mark in Table 1 [41].

In addition, country specific requirements for discharge of drilling fluids and cuttings also do play a role in environmental protection. For instance, in the United Kingdom the OSPAR2000/3 discharge regulation comes into play and compliance requires limit of less than 1% oil on cuttings and do advise on when to inject cuttings or return to shore and oil recovery. The OSPAR2000/3 regulation does not permit discharge of synthetic based mud (SBM) cuttings offshore [39,42].

5. Future trends on drilling waste

To meet the strict environmental regulations, sustainable and effective waste management remains a big challenge in oil and gas industry. Fortunately, new waste treatment or clean-up operation may eliminate this problem and in addition, we should explore a new window to turn these hazardous wastes into value added products [44]. To utilise these pollutant materials which exist in wastes, it is very important to understand the sources of drilling fluid wastes, chemical composition, and characterisation of these

wastes. Since oil based drilling fluids (OBFs) consist of diesel or mineral oil containing different types of polycyclic aromatic hydrocarbons (PAHs) and are also considered as a flammable hazard source, care consideration should be taken to design the cleaning or treatment processes [45].
Different mechanisms have been developed and continue to improve aimed at treating drill cutting waste including non-biological treatment processes and disposal options and bioremediation technologies for treating drill cuttings [20,2]. However, the potential environmental impacts of spent drilling fluids and drill cuttings after treatment are still considered as serious health and safety concerning issues [46,47,48].
Today, significant amount of drilling wastes accumulated during drilling operations are disposed off in the landfill or seabed without recovering the useful elements/compounds present in these wastes [18,49]. Treating these wastes to reuse and recycle them in different beneficial uses remains a significant challenge and any step to improve these processes are considered as sustainable and effective measures to reduce the environmental pollution in future [48,49,50,51]. For instance, the Waste to Want research being run at Centre for Advanced Engineering Materials at Robert Gordon University on the novel application of nanoclays extracted from spent oil based drilling mud (drilling fluid) clean-up as nanofiller in the manufacture of nanocomposite materials offers new solutions [44,52]. To use the beneficiary elements or compounds present in drilling fluid waste, it is important to first comprehensively analyse the composition and characterisation of this waste.

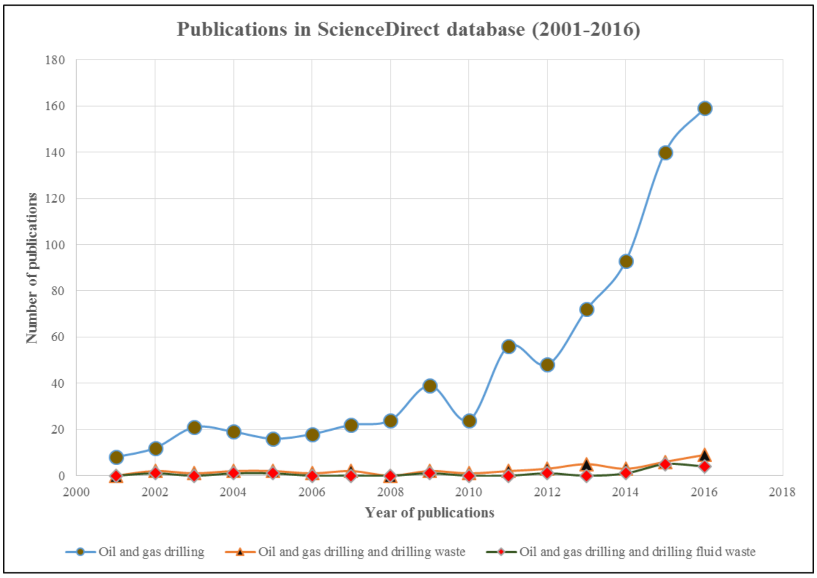

Fig. 2: Articles published in ScienceDirect database from 2001-2016

Analysis of recent publication records since 2001 (Fig 2) shows a continuous positive trend on research in oil and gas drilling operation though disappointing little to show on oil and gas drilling waste and drilling fluid waste. The survey covers the key words search in title, abstract, and keywords in publications from 2001 to 2016. 771 articles have been published during this time based on oil and gas drilling whereas only 41 papers have been published on oil and gas drilling waste. The number is even fewer in drilling fluid waste related publications which is 15 publications in last 16 years. There is a need of extensive research on drilling waste, especially drilling fluid related waste which meets cost savings needs and increased environmental awareness.
This paper highlights that composition of drilling fluid waste and the importance of making this waste into resources is not widely explored. Drilling fluid waste accumulation by its individual components might be a potential area where more research work needs to focus to optimise the use of individual drilling waste constituents in reuse or recycling operation. Fig 2 depicts the increasing interest in drilling

operation related publications, but ironically the interest in investigation to the effect of individual ingredients of drilling wastes on environment is not well documented which is needed for a sustainable waste management in oil and gas exploration and production industry.

6. Conclusion

The accumulated drilling fluid wastes in oil and gas industry is different in every operation site. The variations in drilling operations including using drilling fluid with different compositions and the variations in geological conditions make these waste streams so diverse that there is not any standard drilling fluid waste profile tool to identify the composition and character of the wastes. The scenario is even more complex in offshore drilling operation as the unique sediment characteristics, benthic community, and hydrodynamic regime also influence the drilling waste characteristics.

To design a sustainable and viable drilling waste management plan/model, the first step is to identify the composition and nature of the pollutants in the wastes. Based on this information different waste treatment plan can be placed in operation such as, thermal treatment, thermo-mechanical treatment, biological treatment, encapsulation of pollutants. To meet the current strict environmental regulations with respect to disposal of this waste or to recycle or recover valuable components such as certain metals, identification of drilling waste composition and characterisation analysis is the obvious first step to move forward to the next stages. However, the environment is still facing the biggest challenge - are these treatment measures capable of producing pollutants free or environmentally safe discharge or producing pollutants free or eco-friendly solid waste? The solution might be very difficult as these treatment processes involve space requirements, duration of treatment operation, operational cost, investment cost, monitoring requirement, expertise etc. These obligations open up a new era of research to use this waste as a raw material to make valuable products rather than incurring burden to the environment.

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