Toxicity of drilling fluids in aquatic organisms: a review

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Abstract

Offshore oil-well drilling has been a subject of great interest to environmental regulatory agencies worldwide. The drilling fluids used in this process involve a complex mixture of chemicals and are largely discharged into the ocean. Acute and chronic toxicity tests have been done to better understand the effects of different types of drilling fluids on aquatic organisms. The aim of this article was to analyze all the studies related to the toxicity of drilling fluids published during the period of 2000 to 2017 by conducting a thorough review through the Scopus and Science Direct databases. Out of 154 articles, only 25 showed relevant information about the toxicity of drilling fluids. Acute toxicity tests were the predominant tests employed, appearing in 56% of the articles. Invertebrates were the most evaluated taxa, used in 64% of cases and represented mainly by Crustacea (32%), Mollusca (16%), and other invertebrates. Vertebrates were represented only by fish, constituting 32% of the cases. Water-based drilling fluids (WBFs) (32%) were the most frequently tested, followed by synthetic-based fluids or muds (SBFs) (24%) and oil-based fluids (OBFs) (16%). Individual components were tested in 12% of the cases, while 16% of studies included more than one type of drilling fluid. After analyzing the toxicity of drilling fluids and the sensitivity of aquatic organisms presented in 25 articles published in scientific journals, we concluded that WBFs—showing, in general, lower values of median lethal concentrations than do natural oil- and SBFs—are the most toxic drilling fluids to invertebrates in the short term. The gaps of information found in this review indicate that future studies need to address the acute and chronic effects of WBFs in both juvenile and adult fish and in other vertebrates; they also need to address the chronic effects of non-aqueous-based fluids on adult invertebrates. As crustaceans are more sensitive to drilling fluids than are mollusks, it is also recommended that they be used in future studies.

Keywords: Ecotoxicology, drilling muds, drilling fluids, petroleum activities, acute and chronic toxicity.

INTRODUCTION

World oil production has increased over the last ten years from 3,954.2 million tonnes in 2007 to 4,387.1 million tonnes in 2017 (British Petroleum, 2018). The high level of oil and gas exploration activities at sea and the scarce data about the impact of their waste on aquatic ecosystems have challenged the established rules and guidelines for petroleum industrial managers.

Drilling is one of the main activities used for mineral exploration, including oil, which requires circulating fluids (i.e., drilling fluids or muds) in the borehole for formation-cutting stabilization, lifting, and suspension, and for hole cleaning, bit cooling, surface pressure control, and drill string lubrication (Gandhi & Sarkar, 2016). Different kinds of drilling fluids may be used, including water, bentonite mud, cutting oil, and polymers, which are categorized (according to their main component) as water-based fluids (WBFs), oil-
based fluids (OBFs) (Gandhi & Sarkar, 2016), or synthetic-based fluids (SBFs) (Vincent-Akpuetal., 2010; Contreras-León et al., 2013).

Particles and other chemical components present in the formation cuttings may incorporate into the drilling fluid, and these become the main type of waste related to drilling fluid due to the large volumes that are generated and discharged. For this reason, the toxicity of drilling fluids is of concern to regulatory agencies, which require biological testing of the effect of the whole mix and of the individual components of drilling fluids (Sanzoneet al., 2018).

Laboratory toxicity tests provide useful empirical data to predict the biological effects of drilling fluids on aquatic environments. Tests are requested by environmental regulators for the granting of drilling license concessions at new fields. Scientific articles relating to this subject often present laboratory tests in which a range of pelagic and benthic species have been tested with some of the main drilling fluids currently in use by the petroleum industry.

Considering the large amounts and potential hazards of drilling-fluid waste within aquatic organisms, it is necessary to concentrate efforts on missing data and the data required for the development for management programs. Therefore, a review of the related literature is the first step in identifying and synthesizing the available relevant information about drilling fluids; thereafter, information gaps can be identified (Galvão & Pereira, 2014; Gomes & Caminha, 2014).

Therefore, the purpose of this review is to explore the main scientific studies on the toxicity of drilling fluids published during the period of 2000 to 2017 to obtain a global view of the existing knowledge, to identify the problems that remain unresolved, and to discern the prospects for progressing this area of study.

MATERIALS AND METHODS

The literature published in scientific periodicals within the period of January 2000 and October 2017 was obtained through a search of scientific articles in two important databases: Scopus and Science Direct. Three keywords were used in each search: “drilling fluids,” “drilling muds,” and “toxicity.” The following data were compiled and analyzed using graphical representations within the Microsoft Excel program: number and type of articles per database; type of drilling fluids or components tested; species used to evaluate toxicity and their taxonomic levels; type of test, in accordance with the time of exposure and level of damage analyzed; the journal, and its impact factor, in which the article was published; the country where the study took place; and the levels of contaminants that promoted a response in the tested organisms. In order to understand and draw conclusions about gaps of information and the levels of toxicity of the different types of drilling fluids, we summarize their effects by taxonomical level (vertebrates and invertebrates), by ontogenetic stage (gametes, post-larvae, juveniles, and adults), by short- and long-term effect (acute and chronic tests), and by type of drilling fluids or muds (water-based fluids [WBFs] or non-aqueous-based fluids [NABF], which includes natural oil-based fluids [OBFs] and synthetic-based fluids [SBFs]).

RESULTS AND DISCUSSION

Articles’ contributions by database, journal, and country

A total of 154 articles were obtained by searching both databases. Of those, 151 articles were found in Scopus and 24 articles were found in Science Direct. Twenty-one articles were found in both databases (Figure 1). Most articles evaluated the operational performance of drilling fluids and their products, with little or no relevant toxicological information. Only 25 articles included related to the toxicity of drilling fluids to aquatic organisms, and therefore, these articles were chosen for further analysis (Table 1).

Studies related to drilling fluids’ toxicity, a relevant and current topic, have been published in scientific journals with high impact factors, such as the Marine Pollution Bulletin, Environmental Pollution, and Marine Environmental Research. Forty-four percent of the identified articles were published in journals with an impact factor higher than 2.0 (see Table 1). The countries that have emerged as new exploratory frontiers for petroleum, such as Nigeria and Australia, contributed the greatest number of studies on the toxicity of drilling fluids during the period of January 2000 to October 2017 (Fig. 2).

Most represented tests, in accordance with time of exposure

The time of exposure and the criteria used for evaluating toxicity determine which kind of test is applied: acute or chronic. Acute tests respond with short-exposure tests (usually lasting 1 to 4 days) and use the mortality or loss of activity of the test organisms as evaluation criteria. Chronic tests, in contrast, evaluate sublethal levels of

![Figure 1. Articles published during the period of January 2000 to October 2017, found in the Scopus and Science Direct databases, which showed relevant information about the toxicity of drilling fluids.](image-url)
Table 1. Articles with relevant toxicological information about drilling fluids published during the period of January 2000 to October 2017, obtained from the Scopus and Science Direct databases, indicating the impact factor of their respective journals, in accordance with Journal Citation Reports of 2016 (https://www.ufrb.edu.br/pscienciasagrarias/images/Edital_primeiro_semestre_2018/2017JournalImpactFactor.pdf).

| Drilling fluid | Species | Taxonomic level | Test type | Journal | Impact factor | Authors, year |
|----------------|---------|-----------------|-----------|---------|---------------|---------------|
| WBFs           | *Calanus finmarchicus* | Crustacea, Copepoda | Acute     | *J. Toxicol. Environ. Health, A* | 2.731 (2016) | Farkas et al., 2017 |
| ACs            | *Vibrio fischeri* | Proteobacteria | Acute     | *Drilling Fluid Completion Fluid* | 0.350 (2015) | Zhu and Liu, 2015 |
| WBFs           | *Lytechinus variegatus* (sea urchin) | Equinodermata | Acute     | *Bol. Invest. Mar. Cost.* | 0.100 (2016) | Benavides et al., 2014 |
| SBFs (EBF, IOBF, LAOBF) | *Pagrus auratus* (Fish) | Actinopterygii, Perciformes | Acute and Chronic | *PLoS ONE* | 2.806 (2016) | Gagnon and Bakhtyar, 2013 |
| WBFs and SBFs  | *Litopenaeus vannamei* (Shrimp) | Crustacea, Decapoda | Acute     | *Ciencia, Tecnol. Futuro* | 0.310 (2016) | Contreras-León et al., 2013 |
| SBF (Parateq)  | *Oreochromis niloticus* (Nile Tilapia) | Actinopterygii, Cichliformes | Acute     | *Jour. Fish. Aquat. Science* | 0.630 (2016) | Vincent-Akpu and Sikoki, 2013 |
| Water-based individual components | *Modiolus modiolus* | | | | |
| | *Venerupis senegalensis* | Mollusca, Bivalvia | Chronic | *Mar. Pollut. Bull.* | 3.146 (2016) | Strachan and Kingston, 2012 |
| | *Dosinia exoleta* | | | | |
| | *Chlamys varia* | | | | |
| OBFs (Rheosyn 1416) | *Pagrus auratus* (Fish) | Actinopterygii, Perciformes | Chronic | *Environ. Monit. Assess.* | 1.687 (2016) | Bakhtyar and Gagnon, 2012 |
| OBFs            | *Tilapia mossambica* | Actinopterygii, Perciformes | Acute     | *J. Hazard. Toxic Radioact. Waste* | 0.740 (2015) | Sil et al., 2012 |
| | *Boleophthalmus boaddarti* | | | | |
| | *Mugil persia* | Mugiliformes | | | |
| | *Rhabditis (Pellioditis) marina* | Nematode | Acute and Chronic | *Mar. Environ. Res.* | 3.101 (2016) | Lira et al., 2011 |
| OBFs            | *Palaemonetes africanus* (Shrimp) | Crustacea, Decapoda | Acute     | *Afr. J. Aquat. Sci.* | 0.670 (2016) | Ogeleka and Tudararo-Aherobo, 2011 |

Continue
Table 1. Articles with relevant toxicological information about drilling fluids published during the period of January 2000 to October 2017, obtained from the Scopus and Science Direct databases, indicating the impact factor of their respective journals, in accordance with Journal Citation Reports of 2016 (https://www.ufrb.edu.br/pgcienciasagrarias/images/Edital_primeiro_semestre_2018/2017JournalImpactFactor.pdf).

| Drilling fluid | Species | Taxonomic level | Test type | Journal | Impact factor | Authors, year |
|----------------|---------|-----------------|-----------|---------|---------------|---------------|
| SBF (XP-07)    | *Tilapia guineensis* | Actinopterygiid, Perciformes | Acute | *Ciência Rural* | 0.417 (2016) | Vincent-Akpu et al., 2010 |
| ACs (lubricants) | *Palaemonetes africanus* (Shrimp) | Crustacea, Decapoda | Acute | *Toxicol. Environ. Chem.* | 0.795 (2016) | Otaigbe et al., 2006 |
| ACs            | *Neomysis watschensis* | Crustacea, Mysida | Acute | *J. Environ. Sci.* | 2.937 (2016) | Yan et al., 2003 |
| Review of all types of drilling fluids | Assorted | Assorted | Acute and Chronic | *Mar. Pollut. Bull.* | 3.146 (2016) | Holdway, 2002 |
| SBFs (EBF, IOBF, and paraffin) | *Grandidierella sp.* | Crustacea, Amphipoda | Acute | *Environ. Toxicol.* | 2.937 (2016) | Tsvetnenko et al., 2000 |
| SBFs (EBF, IOBF, and paraffin) | *Paphies elongata* | Mollusca, Bivalvia | Acute | *Environ. Toxicol.* | 2.937 (2016) | Tsvetnenko et al., 2000 |
| OBF (diesel oil) and SBF (IOBF) | *Leptocheirus plumulosus* | Crustacea, Amphipoda | Acute | *Environ. Toxicol.* | 2.937 (2016) | Still et al., 2000 |
| OB (diesel oil) and SBF (IOBF) | *Tilapia guineensis* | Actinopterygiid, Perciformes | Acute | *Jordan J. Biol. Sci.* | Not found | Imarhiagbe and Atuanya, 2017 |
| OBFS and WBFs | *Desmoscaris trispinosa,* *Palaemonetes africanus* (Shrimp) | Crustacea, Decapoda | Acute | *Arab. J. Geosci.* | 0.955 (2016) | Okogbue et al., 2016 |
| OBFS and WBFs | *Geodia barreti* (sponges) | Poriifera | Acute and Chronic | *Environ. Pollut.* | 5.099 (2016) | Edge et al., 2016 |
| OBFS and WBFs | *Argopecten nucleus* | Mollusca, Bivalvia | Acute and Chronic | *Bol. Invest. Mar. Cost.* | 0.100 (2016) | Rodríguez-Satizábal et al., 2015 |
| OBFS and WBFs | *Ammonia tepida* | Foraminifera | Chronic | *Ecol. Indicators* | 3.898 (2016) | Denoyelle et al., 2012 |
Toxicity of drilling fluids in aquatic organisms:

Table 1. Articles with relevant toxicological information about drilling fluids published during the period of January 2000 to October 2017, obtained from the Scopus and Science Direct databases, indicating the impact factor of their respective journals, in accordance with Journal Citation Reports of 2016 (https://www.ufrb.edu.br/pesquisaisagrarais/images/Edital_primeiro_semestre_2018/2017JournalImpactFactor.pdf).

| Drilling fluid | Species | Taxonomic level | Test type | Journal | Impact factor | Authors, year |
|----------------|---------|-----------------|-----------|---------|--------------|---------------|
| SBFs           | *Oreochromis mossambicus* (Tilapia) | Actinopterygii, Perciformes | Acute and Chronic | *Polycyclic Aromatic Compounds* | 1.568 (2016) | Jagwani et al., 2011 |
| WBFs (barite and bentonite) | *Cerastoderma edule*, *Macoma balthica* | Mollusca, Bivalvia | Acute and Chronic | *Mar. Pollut. Bull.* | 3.146 (2016) | Barlow and Kingston, 2001 |
| SBF (Parateq)  | *Tilapia guineensis* | Actinopterygii, Perciformes | Acute and Chronic | *Rev. Cientifica UDO Agrícola* | 0.18 (2014) | Vincent-Akpu and Chindah, 2009 |

AC: additive component; EBF: ester-based fluid; IOBF: isomerized olefin–based fluid; LAOBF: linear alpha olefin–based fluid; OBF: oil-based fluid; SBF: synthetic-based fluid; WBF: water-based fluid.

most articles that evaluated the toxicity of drilling fluids applied acute tests (56%), while only three performed long-lasting exposure assays (i.e., chronic tests; Fig. 3). The low cost and simple execution of acute tests make them the preferred and most used tests (Zagatto and Bertoletti, 2008). However, as a result, the lack of long-term exposure studies to evaluate sublethal levels of toxicity in aquatic organisms has been recognized (Denoyelle et al., 2012); this means there is currently little background information available about the chronic effects of toxic components in drilling fluids, and it is these that have a larger probability of having effects at the population level.

Test organisms

A number of parameters must be considered when selecting a species in which to evaluate toxicity, and it is not always possible select a species that is ideal in relation to each of these parameters. Ideally, a group of species representing a wide range of sensitivities should be used (Rand, 1995), but this is rarely possible due to the high cost of a multi-species approach. Rand (1995) recommended the following criteria be used when choosing an animal for testing: it should be of high abundance and availability; be a component of the ecosystem that is suffering the impact of toxins; be commercially or ecologically important; and be easy to manage through routine laboratory maintenance.

It was found in this review that the most used taxa for studying drilling fluids were invertebrates (64%), while vertebrates, represented exclusively by fish, were used in only 32% of the studies (Fig. 4). Fish are located at the top of the food chain and are highly visible resources. Fish, as aquatic organisms, are heavily affected by pollutants due to their direct contact with water through their body surface and gills. Because fish are food resources for humans, this becomes a food safety issue; fish and fishery products are generally considered to be at a high risk for pathogens, natural toxins, and other possible contaminants.
Invertebrates were mostly represented by crustaceans, which were used at the same rate as were fish (Fig. 4). Among crustaceans, shrimp were the most tested organisms, followed by amphipods and copepods. *Palaemonetes africanus*, a shrimp species of brackish water and prey of large vertebrates, was used by Ogeleka and Tudararo-Aherobo (2011) to study the acute toxicity of a non-aqueous-based drilling fluid. This organism, which is easily transported and maintained in laboratory conditions, produced consistent and reproducible responses to toxic substances. The bivalve *Argopecten nucleus* was used by Rodríguez-Satizábal et al. (2015) as test organisms for evaluating the acute and chronic effects of drilling fluids in Colombia. This species is widely distributed in the Caribbean; it is a commercially important species in Colombia, and the technology for culturing and reproduction in laboratories has already been established. The shrimp species *Litopenaeus vannamei* was also used in Colombia for short-term toxicity tests of drilling fluids (WBFs and SBFs) (Contreras-León et al., 2013). The species is distributed from southern Mexico to northern Peru and represents an important portion of the industrial and artisanal fishery industry of the Colombian Pacific coast. This species has also been successfully introduced in commercial farming facilities. Denoyelle et al. (2012) used the benthic foraminifera *Ammonia tepida* for the chronic evaluation of drilling fluid toxicity due to their long-term exposure sensitivity to pollutants, detected by physiological responses such as pseudopodal activity and chamber addition. Since the 1960s, foraminifera have increasingly been used as bioindicators of anthropogenic impacts on marine environments. They are unicellular organisms protected externally by a calcareous shell, and they are found in all marine latitudes. They show different forms at different trophic levels (e.g., planktonic or benthonic) and therefore have different levels of sensitivity to chemical compounds (Denoyelle et al., 2012). Other groups of crustaceans that have been used for evaluating the toxicity of drilling fluids are amphipods and copepods. Amphipods are sensitive organisms that are easy to maintain, have low maintenance costs, and have good reproducibility, allowing for the selection of low-toxicity drilling fluids. Examples of amphipods are *Grandidierella sp.* and *Leptocheirus plumulosus*, which have been used to compare the toxicity of SBFs (Tsvetnenko et al., 2000; Still et al., 2000).

**Types of drilling fluids**

The exact chemical composition of the all varieties of drilling fluids are not known, but studies on their general composition have revealed that they contain complex mixtures of highly volatile materials and toxic substances, such as aromatic compounds and heavy metals (Vincent-Akpu et al., 2010). Drilling fluids are classified as either WBFs (or muds WBM) or as non-aqueous-based fluids ([NABFs] or muds [NABMs]), in accordance with the chemical composition of the base of the fluid (Ogeleka & Tudararo-Aherobo, 2011). WBFs include barite, bentonite, lignite, and lignosulphonate, with a limited list of additive products (Holdway, 2002). NABFs are divided further into OBMs, enhanced mineral oil-based fluids (EMOBFs), and SBFs (Ogeleka & Tudararo-Aherobo, 2011). Within SBFs are ester-based fluids (EBFs), isomerized olefin–based fluids (IOBFs), and linear alfa olefin–based fluids (LAOBFs) (Ogeleka & Tudararo-Aherobo, 2011; Gagnon & Bakhtyar, 2013). WBFs were the most frequently tested muds in the present review, appearing in 25 of the studied articles (Fig. 5). OBMs were the least tested during the period of January 2007 to October 2017.

**Effect of different types of drilling fluids on aquatic organisms**

Holdway (2002) reviewed articles that examined the chronic and acute effects of drilling fluids and chemical additives in temperate and tropical marine environments, and, at that time, drew attention to the need for long-lasting studies and to perform experiments with fluid dispersion as it occurs in real environments, in order to understand exposure concentrations and the effects of dilution at sea. The author also concluded that drilling fluids with larger amounts of anti-foams and wetting agents (both mixtures of surfactants) would have significantly greater toxicities. The effects of

![Image](image_url)

**Figure 4.** Number and percentage of species by taxonomic classification used as animal models for evaluating the toxicity of drilling fluids, the results of which were published during the period of January 2000 to October 2017. FS Fish; CR: Crustacea; ML: Mollusca; EQ: Equinodermata; PO: Porifera; NM: Nematoda; FM: Foraminifera; BC: Bacteria.
different drilling fluids and their components observed within this review, in relation to be short- and long-term exposure, are listed in Table 2.

Effects on vertebrates

Acute effects

There was no available information about the acute effects of SBFs on juvenile fish or of WBFs on adult fish (Table 3). The median lethal component (LC₅₀) for juvenile fish ranged from 125 mg L⁻¹ for WBFs to 6,000 mg L⁻¹ for natural OBWs (Imarhiagbe and Atuanya, 2017), indicating the higher toxicity of WBF than of OBW for juvenile fish (Table 3).

In adult fish, toxicity varied depending on which drilling mud phase was tested and to which kind of habitat the fish was adapted. The LC₅₀ (96 h) for OBW in adult fish varied from 16,713 mg L⁻¹ for OBWs in marine fish to 770,000 mg L⁻¹ of the suspended particulate phase (SPP) in freshwater fish (Table 3). For SBF, the LC₅₀ (96 h) varied from 2,210 mg L⁻¹ (Parateq) to 40,390 mg L⁻¹ of the SPP of an Indian well. In accordance with the data presented by Sil et al,(2012), marine fish are more sensitive to drilling fluids than are freshwater or benthonic fish (see Table 3), and Parateq appears to be the most toxic of the tested fluids to vertebrates, as measured in adult fish. Comparing juveniles and adults, WBF was most toxic to juveniles (125 mg L⁻¹), followed by OBW to juveniles (6,000 mg L⁻¹) and OBW to adult marine fish (16,713 mg L⁻¹).

Chronic effects

Short-term bioassays assessing mortality as the main response substantially underestimate the effects of toxicants at the population level (Lira et al., 2011). Physiological and behavioral changes observed in chronic toxicity tests enable the evaluation of subtle adverse effects on the exposed organisms. Chronic effects will, in turn, result in changes in population parameters, such as a decreased survival because of disfunction or carcinogenicity, due to the cumulative effect of the toxicant; decreased survival in the early life stages of the following generations due to abnormalities in early life stages; and decreased fertility and fecundity due to abnormal gametes. Although chronic assays have a higher cost and are more time-consuming, they provide more accurate information about the toxicity of substances (Zagatto and Bertoletti, 2008). Despite their importance, the chronic effects of drilling fluids on vertebrates (fish, in this case) have been neglected in both juveniles and adults, as this has been evaluated only for SBFs. Therefore, no data is available to indicate the toxic effects of WBF and OBWs on fish.

Gagnon and Bakhtyar (2013) investigated the chronic effects of SBF and its components in juvenile pink snappers (Pagrus auratus) after long-term exposure. The authors evaluated ethoxyresorufin-O-deethylase (EROD) activity, biliary metabolites, DNA damage, stress proteins, and other physiological conditions, which allowed them to conclude that although SBF may be non-toxic in the short term, it does have an effect on the health of juvenile fish in the long term. They found that after 20 days of exposure to SBF, the EROD activity, sorbitol dehydrogenase (SDH), and heat shock protein (HSP)-70 activities increased, as did the pyrene metabolite and DNA damage. In adult fish, after three months’ exposure to SBF, a decrease in oocyte maturation and delayed spermatogenesis, preventing fertilization, were observed (Table 3). Bakhtyar and Gagnon (2012) found that some additive components (ACs) were less toxic than others, suggesting that replacing some ACs with less toxic components, as evaluated by chronic tests, may reduce the impact of drilling fluids on the aquatic biota.

Effects on invertebrates

Invertebrates have largely been used to evaluate the toxicity of WBF on aquatic organisms in both the short and long term. However, the long-term effects have not been studied as closely, with the long-term effect of SBF and OBW having only been evaluated in foraminifera.

Acute effects

Although there is a long list of studies on the short-term effects of toxins on invertebrates, there is no information available about the toxicity of OBW to juvenile invertebrates. WBF prevents the fertilization of Echinodermata gametes after 1 h of exposure to 3,649 ± 400 mg L⁻¹ (Benavides et al., 2014). The LC₅₀ (96 h) in post-larvae crustaceans varied from 4,224 ppm of WBF to 308,248 ppm of SBF (Contreras-León et al., 2013), indicating the higher toxicity of WBF (Table 4). Juveniles mollusks were less sensitive than were crustaceans, with an LC₅₀ (96 h) that varied from 9,113 ppm of WBF to > 1,000,000 ppm of SBF (Rodríguez-Satizábal et al., 2015), while juveniles crustaceans may be sensitive to 12,000 ppm of SBF (Yan et al., 2003) (Table 4).

The LC₅₀ (96 h) in adult crustaceans may vary from 320 mg L⁻¹ of WBF (Farkas et al., 2017) to 17,200 mg L⁻¹ of OBW (Okogbue et al., 2016), showing, again, the higher toxicity of WBF than of OBW. The toxic effect of synthetic fluids may
### Table 2. Data from the reviewed articles showing the effects after short- and long-term exposure to different drilling muds.

| Drilling fluid | Species | Test type | Time of exposure | Animal stage | Response | Authors, year |
|----------------|---------|-----------|------------------|--------------|----------|---------------|
| WBFs           | *Calanus finmarchicus* (Crustacea) | Acute | 96 h | Adults (stage V) | LC50 = 320 mg L⁻¹ | Farkas et al., 2017 |
|                | *Lytechinus variegatus* (Echinodermata) | Acute | 1 h | Gametes | Fecundity inhibition, EC50 = 3,649 ± 400 mg L⁻¹ | Benavides et al., 2014 |
| SBFs (EBF, IOBF, and LAOBF) | *Pagrus auratus* (Fish) | Chronic | 28 d | Juveniles | IOBF and LAOBF: increased EROD activity; LAOBF: increased HSP-70; no DNA damage | Gagnon and Bakhtyar, 2013 |
| WBFs and SBFs  | *Litopenaeus vannamei* (Crustacea) | Acute | 96 h | Post-larvae | WBF: LC50 = 4,224 – 26,635 ppm SBF: LC50 = 40,781 – 308,248 ppm | Contreras-León et al., 2013 |
| SBF (Parateq)  | *Oreochromis niloticus* (Fish) | Acute | 96 h | Adults | LC50 = 2,210 mg L⁻¹ | Vincent-Akpu and Sikoki, 2013 |
| Water-based individual components (standard barite, fine barite, ilmenite, and bentonite) | *Modiolus modiolus* (*Mm*) | Chronic | 28 d | Adults | Bentonite: increased filtration rate; bentonite and fine barite: no lethal response; ilmenite and standard barite: gill damage and lethal response at days 4–5 (*Cv*), day 11 (*De*), days 9–12 (*Fs*), and day 19 (*Mm*) | Strachan and Kingston, 2012 |
| Synthetic OBFs (Rheosyn 1416) and individual components | *Pagrus auratus* (Fish) | Chronic | 21 d | Juveniles | Increased EROD activity with Emul S50, LSL 10, Bentone 38; increased pyrene metabolite with mud Syndrill 80:20, Emul S50, Wetout, and LSL 10; increased SDH activity with Syndrill 80:20, Emul S50; DNA damage with Syndrill 80:20, Emul S50, and LSL 10 SP: LC50 = 200,000 mg L⁻¹ in freshwater fish (*Tm*) and 31,107 mg L⁻¹ in marine fish (*Mp*); SPP: 770,000 mg L⁻¹ (*Tm*) and 42,614 mg L⁻¹ (*Mp*); 243,652 mg kg⁻¹ in benthic organisms (*Bb*); OBF: 22,414 mg L⁻¹ (*Tm*), 16,713 mg L⁻¹ (*Mp*), and 167,340 mg kg⁻¹ (*Bb*) | Bakhtyar and Gagnon, 2012 |
| OBFs           | *Tilapia mossambica* (*Tm*) | Acute | 96 h | Adults | LC50 = 101 mg kg⁻¹ (95% CI: 49–153 mg kg⁻¹) | Sil et al., 2012 |
| Boleophthalmus boddarti (*Bb*) | *Mugil persia* (*Mp*) (Fish) | Acute | 96 h | Adults | Increased EROD activity with Emul S50, LSL 10, Bentone 38; increased pyrene metabolite with mud Syndrill 80:20, Emul S50, Wetout, and LSL 10; increased SDH activity with Syndrill 80:20, Emul S50, and LSL 10 SP: LC50 = 200,000 mg L⁻¹ in freshwater fish (*Tm*) and 31,107 mg L⁻¹ in marine fish (*Mp*); SPP: 770,000 mg L⁻¹ (*Tm*) and 42,614 mg L⁻¹ (*Mp*); 243,652 mg kg⁻¹ in benthic organisms (*Bb*); OBF: 22,414 mg L⁻¹ (*Tm*), 16,713 mg L⁻¹ (*Mp*), and 167,340 mg kg⁻¹ (*Bb*) | Bakhtyar and Gagnon, 2012 |
| Metals at levels observed in drilling muds (barium and cadmium) | *Rhabditis (Pellioditis) marina* (Nematoda) | Chronic | 10 days (2 generations) | Adult males and gravid females | Increased EROD activity with Emul S50, LSL 10, Bentone 38; increased pyrene metabolite with mud Syndrill 80:20, Emul S50, Wetout, and LSL 10; increased SDH activity with Syndrill 80:20, Emul S50, and LSL 10 SP: LC50 = 200,000 mg L⁻¹ in freshwater fish (*Tm*) and 31,107 mg L⁻¹ in marine fish (*Mp*); SPP: 770,000 mg L⁻¹ (*Tm*) and 42,614 mg L⁻¹ (*Mp*); 243,652 mg kg⁻¹ in benthic organisms (*Bb*); OBF: 22,414 mg L⁻¹ (*Tm*), 16,713 mg L⁻¹ (*Mp*), and 167,340 mg kg⁻¹ (*Bb*) | Lira et al., 2011 |
| OBF (GlycolTM) | *Palaemonetes africanus* (Crustacea) | Acute | 10 days | Adults | LC50 = 101 mg kg⁻¹ (95% CI: 49–153 mg kg⁻¹) | Ogeleka and Tudararo-Aherobo, 2011 |
### Table 2: Data from the reviewed articles showing the effects after short- and long-term exposure to different drilling muds.

| Drilling fluid | Species (Order) | Test type | Time of exposure | Animal stage | Response | Authors, year |
|----------------|----------------|-----------|------------------|--------------|----------|--------------|
| SBF (XP-07)    | *Tilapia guineensis* (Fish) | Acute | 96 h | Fry, fingerling, and post-fingerling | LC50 = 5.63 % (fry), 7.77 % (fingerling), 6.93% (post fingerling) | Vincent-Akpu *et al.*., 2010 |
| ACs (lubricants) | *Palaeomonetes africanus* (Crustacea) | Acute | 96 h | Adult | Lubricant 1: LC50 = 350 mg L⁻¹; lubricant 2 of high molecular weight: 210 mg L⁻¹, less diffusion; lubricant 3 of high acidity: 620 mg L⁻¹. | Otaigbe *et al.*, 2006 |
| ACs            | *Neomysis watschensis* | Acute | 96 h | Juveniles | SPP: LC50 = 12,000–1,000,000 ppm, depending on the type of drilling fluid | Yan *et al.*, 2003 |
| SBFs (EBFs, IOBFs, and paraffin) | *Grandidierella sp.* (Gsp) (Crustacea) | Acute | 96 h | Adults | 10 d, LC50 = 200–1,500 mg kg⁻¹ (Gsp); 20,000 mg kg⁻¹ (Pe) | |
|                | *Paphies elongata* (Pe) (Mollusca) | Acute | 10 days | Adults | Natural sediments: LC50 = 2,825 mg kg⁻¹ (95% CL 568–14,042); formulated sediments: 3,795 mg kg⁻¹ (95% CL 3,284–4,385); diesel: 539–703 mg kg⁻¹; drilling fluids: 1,609–3,720 mg kg⁻¹, depending on the type | Still *et al.*, 2000 |
| OB (diesel oil) and SBF (IO) | *Leptocheirus plumulosus* (Crustacea) | Acute | 96 h | Randomly selected | Washed cuttings: LC50 = 16,900–17,200 mg L⁻¹ (Pa), 9,800–10,900 mg L⁻¹ (Dt); unwashed cuttings: LC50 = 10,300–11,350 mg L⁻¹ (Pa), 6,200–6,700 mg L⁻¹ (Dt); Reduced lysosomal membrane stability using 50 and 100 mg L⁻¹ TSS barite after 12 h; after 14 days, it was reduced using 30 mg L⁻¹ | Okogbue *et al.*, 2016 |
| OBFs and WBFs | *Tilapia guineensis* (Fish) | Acute | 96 h | Juveniles | WBF: LC50 = 125 mg L⁻¹; NABF: 6,000 mg L⁻¹ | Imarhiagbe and Atuanya, 2017 |
| OBFs (washed and non-washed muds) | *Desmocaris trispinosa* (Dt) | Acute | 96 h | Adults | Washed cuttings: LC50 = 16,900–17,200 mg L⁻¹ (Pa), 9,800–10,900 mg L⁻¹ (Dt); unwashed cuttings: LC50 = 10,300–11,350 mg L⁻¹ (Pa), 6,200–6,700 mg L⁻¹ (Dt); Reduced lysosomal membrane stability using 50 and 100 mg L⁻¹ TSS barite after 12 h; after 14 days, it was reduced using 30 mg L⁻¹ | Okogbue *et al.*, 2016 |
| OBFs (washed and non-washed muds) | *Palaeomonetes africanus* (Pa) (Crustacea) | Acute | 96 h | Adults | Washed cuttings: LC50 = 16,900–17,200 mg L⁻¹ (Pa), 9,800–10,900 mg L⁻¹ (Dt); unwashed cuttings: LC50 = 10,300–11,350 mg L⁻¹ (Pa), 6,200–6,700 mg L⁻¹ (Dt); Reduced lysosomal membrane stability using 50 and 100 mg L⁻¹ TSS barite after 12 h; after 14 days, it was reduced using 30 mg L⁻¹ | Okogbue *et al.*, 2016 |
| WBFs (barite and bentonite) | *Geodiabarretti* (Spongia) | Acute and Chronic | 12 h, 14 d | Size range: 0.1–1 kg | Reduced lysosomal membrane stability using 50 and 100 mg L⁻¹ TSS barite after 12 h; after 14 days, it was reduced using 30 mg L⁻¹ | Edge *et al.*, 2016 |
| WBFs and SBFs | *Argopecten nucleus* (Mollusca) | Acute and Chronic | 96 h, 30 d | Juveniles | 96 h, WBF: LC50 = 9.113–50,446 ppm; SBF: 40,520 – > 1,000,000 ppm; 30 d, larger toxic effect on survival and growth with WBF than with SBF | Rodriguez-Satizabalet *et al.*, 2015 |
| WBFs and OBFs | *Ammonia tepida* (Foraminifera) | Chronic | 30 d | Adults | Reduction of pseudopodal activity with ≥ 500 mg L⁻¹ NABF and ≥ 100 mg L⁻¹ WBF | Denoyelle *et al.*, 2012 |
| SBFs | *Oreochromis mossambicus* (Fish) | Acute and Chronic | 96 h | Adults | SP: LC50 = 37,550 mg L⁻¹; SPP: 40,390 mg L⁻¹ | Jagwani *et al.*, 2011 |
vary greatly, showing LC$_{50}$ (96 h) values as low as 101 mg kg$^{-1}$ of Glycol$^\text{TM}$ (Ogeleka and Tudararo-Aherobo, 2011) to 3,720 mg kg$^{-1}$ of IOBF in Crustacea (Still et al., 2000) and 20,000 mg kg$^{-1}$ of EBF, IOBF, and paraffin in Mollusca (Tsvetnenko et al., 2000); this also demonstrates a higher sensitivity in crustaceans than in mollusks (Table 4).

**Chronic effects**

The long-term effects of WBF in invertebrates have been described as a reduction in lysosomal membrane stability in sponges, which may begin after as little as 1 h of exposure at concentrations of 50–100 mg L$^{-1}$ or after 14 days at a concentration of 30 mg L$^{-1}$ (Edge et al., 2016; Table 4). Also,

**Table 2.** Data from the reviewed articles showing the effects after short- and long-term exposure to different drilling muds.

| Drilling fluid | Species | Test type | Time of exposure | Animal stage | Response | Authors, year |
|----------------|---------|-----------|------------------|--------------|----------|---------------|
| WBF (barite)   | *Cerastoderma edule*<br>*Macoma balthica*<br>(Mollusca) | Acute and Chronic | 12 d | Adults | 100% dead at the end of the experiment; gill damage: ctenidia severely affected | Barlow and Kingston, 2001 |
| SBF (Parateq)  | *Tilapia guineensis*<br>(Fish) | Acute and Chronic | 96 h, 12 weeks | Adults and post-fingerlings | Long-term inhibition of oocyte maturation and delay in spermatogenesis; 96 h, LC50 = 5.47% | Vincent-Akpu and Chindah, 2009 |

AC: additive component; EROD: ethoxyresorufin-O-deethylase; HSP: heat shock protein; EC50: effective concentration; LC$_{50}$: median lethal concentration; LOEC: lowest effect concentration; NABFs: non-aqueous-based fluid; OBF: oil-based fluid; SBF: synthetic-based fluid; SDH: sorbitol dehydrogenase; SP: solid phase; SPP: suspended particulate phase; TSS: total suspended solid concentration; WBF: water-based fluid.

**Table 3.** Short- and long-term effects on vertebrates of different kind of drilling fluids, obtained from the literature review and organized by ontogenetic stage and type of drilling fluid or component.

| Taxonomic level | WBFs | Natural OBFs | NABFs | SBFs |
|-----------------|------|--------------|-------|------|
| Juveniles (Fish)| LC50 (96 h) = 125 mg L$^{-1}$ (fsw) | LC50 (96 h) = 6,000 mg L$^{-1}$ (fsw) | No information available | No information available |
| Adults (Fish)   | LC50 (96 h) = 31,107 mg L$^{-1}$ (mar) | SP: 31,107 mg L$^{-1}$ (Parateq) (4) | 2,210 mg L$^{-1}$ (Parateq) (4), 37,550 mg L$^{-1}$ (SP), and 40,390 mg L$^{-1}$ (SPP) | Increase of EROD, HSP-70, and SDH activity; increase of pyrene metabolite and DNA damage (2) |
|                 | 200,000 mg L$^{-1}$ (fsw) (3) | SPP: from the Indian well (5); 42,614 mg L$^{-1}$ (mar), 243,652 mg L$^{-1}$ (ben), 770,000 mg L$^{-1}$ (fsw) (3) | 2,210 mg L$^{-1}$ (Parateq) (4), 37,550 mg L$^{-1}$ (SP), and 40,390 mg L$^{-1}$ (SPP) | Increase of EROD, HSP-70, and SDH activity; increase of pyrene metabolite and DNA damage (2) |
|                 | 167,340 mg L$^{-1}$ (ben) (3) | OBF: 16,713 mg L$^{-1}$ (mar), 22,414 mg L$^{-1}$ (fsw), 167,340 mg L$^{-1}$ (ben) (3) | 2,210 mg L$^{-1}$ (Parateq) (4), 37,550 mg L$^{-1}$ (SP), and 40,390 mg L$^{-1}$ (SPP) | Increase of EROD, HSP-70, and SDH activity; increase of pyrene metabolite and DNA damage (2) |

LC$_{50}$: median lethal concentration; EROD: ethoxyresorufin-O-deethylase; SDH: sorbitol dehydrogenase; HSP: heat shock protein; SP: solid phase; SPP: suspended particulate phase; mar: marine; fsw: freshwater; ben: benthonic; (1) Imarhiagbe and Atuanya, 2017; (2) Bakhtyar and Gagnon, 2012; Gagnon and Bakhtyar, 2013; (3) Sil et al., 2012; (4) Vincent-Akpu and Sikoki, 2013; (5) Jagwani et al., 2011; (6) Vincent-Akpu and Chindah, 2009; (7) Vincent-Akpu et al., 2010.
Table 4. Short- and long-term effects on invertebrates of different kind of drilling fluids obtained from the literature review and organized by ontogenetic stage and type of drilling fluid.

| Taxonomic level     | WBFs                        | Natural OBFs                  | NABFs                        | SBFs                          |
|---------------------|-----------------------------|-------------------------------|------------------------------|-------------------------------|
| Gametes (Echinodermata) |                            |                               |                              |                               |
|                     | 1 h:                        |                               |                              |                               |
|                     | Fecundity inhibition        | No information available      |                              | No information available      |
|                     | 3,649 ± 400 mg L⁻¹ (1)      |                               |                              |                               |
| Post-larvae (Crustacea) | LC₅₀ (96 h) =               |                               |                              |                               |
|                     | 4,224–26,635 ppm (2)        | No information available      |                              |                               |
| Juveniles (Crustacea) |                               | LC₅₀ (96 h) =                 |                              |                               |
|                     | No information available    | No information available      |                              | SPP: 12,000–1,000,000 ppm (3) |
| (Mollusca) | LC₅₀ (96 h) =               | LC₅₀ (96 h) =                 |                              |                               |
|                     | 9,113–50,446 ppm (4)        | No information available      |                              | 40,500 – > 1,000,000 ppm (4)  |
| (Mollusca) | Long-term, 30 days:         | Long-term:                    |                              | Long-term, 30 days:           |
|                     | Toxic effect on survival and growth | No information available |                              | Toxic effect on survival and growth |
| Adults (Crustacea) | LC₅₀ (96 h) =               | LC₅₀ (96 h) =                 |                              |                               |
|                     | 320 mg L⁻¹(5)               | 2,825 mg kg⁻¹(6)             |                              |                               |
|                     |                             | 6,200 – 17,200 mg L⁻¹(7)      |                              |                               |
|                     |                             | 101 mg kg⁻¹ (Glycol™) (8)    |                              |                               |
|                     |                             | 210 – 620 mg kg⁻¹ (lubricants) (9) |                              |                               |
|                     |                             | 200 – 1,500 mg kg⁻¹ (E, IO, paraffin) (10) |                              |                               |
|                     |                             | 1,600 – 3,720 mg kg⁻¹ (IOBF) (6) |                              |                               |
| (Mollusca) | LC₅₀ (96 h) =               | 2,825 mg kg⁻¹ (E, IO, paraffin) (10) | 101 mg kg⁻¹ (Glycol™) (8) |                               |
|                     | 210 – 620 mg kg⁻¹ (lubricants) (9) |                              |                               |                               |
| (Mollusca) | No information available    | No information available      |                              | 20,000 mg kg⁻¹ (EBF, IOBF, and paraffin) (10) |
| (Spongia) | 12 h:                      | No information available      |                              |                               |
|                     | Decrease in lysosomal membrane stability | No information available |                              | No information available      |
|                     | 50–100 mg L⁻¹(11)           |                              |                              |                               |
| (Nematoda) | 10 days:                   | No information available      |                              | No information available      |
|                     | LC₅₀ (10 d) = 8.82 ppm Ba; decrease of population size: | No information available |                              | No information available      |
|                     | 400–2,000 ppm Ba and 2.40–2.68 ppm Cd (12) |                              |                              |                               |
| (Mollusca) | 4 – 19 days                | Std. particulate barite and ilmenite: | 100% dead, gill ctenidia severely damaged (13) | No information available      |
| (Spongia) | 14 days:                   | No information available      |                              | No information available      |
|                     | Decrease of lysosomal membrane stability at 30 mg L⁻¹(11) | No information available |                              | No information available      |
| (Foraminifera) | 30 days:                   | No information available      |                              | No information available      |
|                     | Decreased pseudopodal activity at ≥ 100 mg L⁻¹(14) | No information available |                              | 30 days:                      |
|                     | Decreased pseudopodal activity at ≥ 100 mg L⁻¹(14) | No information available |                              | No information available      |

LC₅₀: median lethal concentration; SPP: suspended particulate phase; mar: marine; fsw: freshwater; ben: bentonic; EBF: ester-based fluid; (IOBF) isomerized olefin-based fluid. (1) Benavides et al., 2014; (2) Contreras-León et al., 2013; (3) Yan et al., 2003; (4) Rodriguez-Santizábal et al., 2015; (5) Farkas et al., 2017; (6) Still et al., 2000; (7) Okogbue et al., 2016; (8) Ogeleka and Tudararo-Aherobo et al., 2011; (9) Otaigbe et al., 2006; (10) Tsvetnenko et al., 2000; (11) Edge et al., 2016; (12) Lira et al., 2011; (13) Strachan and Kingston, 2012; (14) Denoyelle et al., 2012.
a decrease in Nematoda population size was observed with concentrations as low as 2.4 ppm Cd and 400 ppm Ba (Lira et al., 2011). In mollusks, standard-sized barite (20.1 µm) and ilmenite (12.8 µm) WBFs caused the death of all mollusks tested between the 4th and 19th days of exposure, due to physical interference with gill function (Strachan and Kingston, 2012). Finally, WBF caused a decrease in foraminifera pseudopodal activity after 30 days at concentrations ≥ 100 mg L⁻¹, with effects only seen for OBF when the concentration was ≥ 500 mg L⁻¹ (Denoyelle et al., 2012); this again demonstrates the higher toxicity of WBF over NABFs.

Final remarks

Environmental studies evaluating the impact of petroleum exploration on coastal organisms have shown to be relevant and continuous over the years. Such studies have been most abundant in developing countries and those in which the offshore oil industry has recently been growing; this is because such countries need to provide subsidies to industrial managers for getting environmental licenses. In general, acute tests were the most common, which can be explained by their low cost, the small-scale infrastructure needed, and their rapid results. Invertebrates were the most commonly used aquatic organisms in testing the toxicity of drilling fluids. Through our review, we can highlight some gaps in the knowledge about the toxicity of drilling fluids, such as the absence of studies of the acute and chronic effects of WBF in both juvenile and adult fish; studies of the chronic effects of NABFs in adult invertebrates; studies including micro- or mesocosm experiments; and studies with benthic organisms that produce information about the marine floor.

WBF were shown to be more toxic than NABFs, although they can suffer biodegradation mediated by fungi and bacteria (Imarhiagbe & Atuahya, 2017). SBFs were recommended initially as containing low-toxicity components for the marine biota, based on results of acute tests (Holdway, 2002). Nonetheless, more recently, chronic assays have demonstrated that SBFs may have chronic effects on aquatic organisms at long-term exposure (Gagnon and Bakhtyar, 2013), which may be related to their low biodegradability. New synthetic component shave been developed to improve the performance of OBFs, giving them a biodegradability similar to that of WBFs (Sil et al., 2012) to minimize their impact on the environment. Nonetheless, there are large variations in the toxicity of these components, making toxicological tests necessary in order to choose components with low toxicity for petroleum exploration (Bakhtyar and Gagnon, 2012; Otaigbe et al., 2016).

Despite the limitations of toxicity tests, including their failure to faithfully reproduce exposure to the levels experienced in the natural environment, such tests can provide valuable information about the potential effects of drilling fluids on aquatic organisms. In addition, the open possibilities for studying the toxicity of other offshore waste, such as that generated from cementing operations. Toxicity evaluations may promote the use of environmentally friendly products and ACs, replacing those that have proven to be harmful to marine biota.

CONCLUSIONS

Toxicity of drilling fluids and sensitivity of organisms

WBFs were, in general, more toxic to juvenile and adult invertebrates than were SBFs after short-term exposure. WBFs showed higher toxicity to juvenile fish (LC₅₀ [96 h] = 125 mg L⁻¹) than did OBFs. OBFs showed less toxicity to juvenile fish (LC₅₀ [96 h] = 6,000 mg L⁻¹), and even less to adult marine fish (LC₅₀ [96 h] = 16,713 mg L⁻¹); however, marine fish were the most sensitive to drilling fluids when compared to freshwater and benthan fish.

Glycol™ (101 mg kg⁻¹) and Parateq (2,210 mg L⁻¹) in adult invertebrates and vertebrates, respectively, were the most toxic SBF. In mollusks, standard-sized barite (20.1 µm) and ilmenite (12.8 µm) WBFs were the most toxic because of their long-term physical interference with gill function. Juvenile mollusks (min. LC₅₀ [96 h] = 40,500 ppm) and adult mollusks (20,000 mg kg⁻¹) were less sensitive to SBFs than were juvenile crustaceans (min. LC₅₀ [96 h] = 12,000 ppm) and adult crustaceans (3,720 mg kg⁻¹).

Information gaps

There was no information available during the period analyzed about the toxic effects of SBFs on juvenile fish, nor of the toxic effects of WBFs on adult fish. The chronic effects on vertebrates (fish, in this case) have only been evaluated in relation to SBFs, with an absence of studies on the toxic effects of WBFs and OBFs on juvenile and adult fish. The long-term effects of OBFs and SBFs on invertebrates have also been neglected, as these effects were only studied in relation to foraminifera.

We can conclude that future studies need to address the acute and chronic effects of WBFs on both juvenile and adult fish and on other vertebrates; in addition, the chronic effects of NABFs on adult invertebrates must be investigated. As crustaceans were more sensitive to drilling fluids than were mollusks, it is recommended that they be used in future studies.

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