

## Toxicity of drilling fluids in aquatic organisms: a review

ASLAN, J.F.<sup>1</sup>; WEBER, L.I.<sup>2</sup>; IANNAcone, J.<sup>3</sup>; LUGON JUNIOR, J.<sup>4</sup>; SARAIVA, V.B.<sup>5</sup> & OLIVEIRA, M.M.<sup>5</sup>

<sup>1</sup> PETROBRAS /Programa de Pós-Graduação em Engenharia Ambiental/IFFluminense - Macaé

<sup>2</sup> Instituto de Biodiversidade e Sustentabilidade - Universidade Federal do Rio de Janeiro - Macaé

<sup>3</sup> Universidad Nacional Federico Villarreal - Universidad Ricardo Palma - Peru

<sup>4</sup> Programa de Pós-Graduação em Engenharia Ambiental – IFFluminense Campus Macaé

<sup>5</sup> Laboratório de Ecotoxicologia e Microbiologia Ambiental - LEMAM - IFFluminense - Campus Cabo Frio

Received January 28, 2019; Accept July 10, 2019

### 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-

\*Corresponding author: Manildo Marcião de Oliveira; e-mail: mmoliveira@iff.edu.br

based fluids (OBFs) (Gandhi & Sarkar, 2016), or synthetic-based fluids (SBFs) (Vincent-Akpueta, 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 (Sanzone *et 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

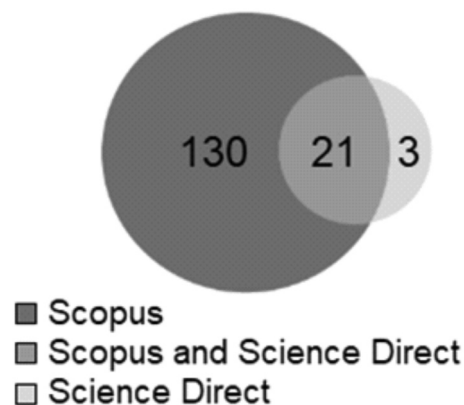
### *Articles' contributions by database, journal, and country*

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 correspond 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

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

**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](https://www.ufrb.edu.br/pgcienciasagrarias/images/Edital_primeiro_semestre_2018/2017JournalImpactFactor.pdf)).

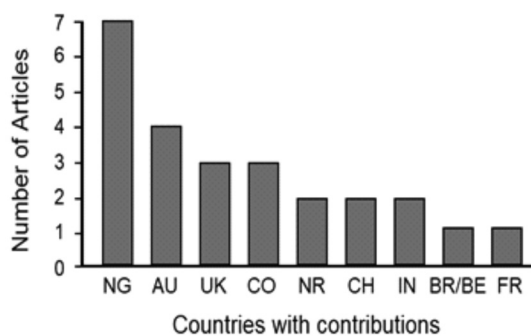
Drilling fluid	Species	Taxonomic level	Test type	Journal	Impact factor	Authors, year
SBF (XP-07)	<i>Tilapia guineensis</i>	Actinopterygii, Perciformes	Acute	<i>Ciência Rural</i>	0.417 (2016)	Vincent-Akpuet <i>et al.</i> , 2010
ACs (lubricants)	<i>Palaemonetes africanus</i> (Shrimp)	Crustacea, Decapoda	Acute	<i>Toxicol. Environ. Chem.</i>	0.795 (2016)	Otaigbeet <i>et al.</i> , 2006
ACs	<i>Neomysis watschensis</i>	Crustacea, Mysida	Acute	<i>J. Environ. Sci.</i>	2.937 (2016)	Yan <i>et al.</i> , 2003
Review of all types of drilling fluids	Assorted	Assorted	Acute and Chronic	<i>Mar. Pollut. Bull.</i>	3.146 (2016)	Holdway, 2002
SBFs (EBF, IOBF, and paraffin)	<i>Grandidierella sp.</i>	Crustacea, Amphipoda	Acute	<i>Environ. Toxicol.</i>	2.937 (2016)	Tsvetnenkoet <i>et al.</i> , 2000
	<i>Paphies elongata</i>	Mollusca, Bivalvia				
OBF (diesel oil) and SBF (IOBF)	<i>Leptocheirus plumulosus</i>	Crustacea, Amphipoda	Acute	<i>Environ. Toxicol.</i>	2.937 (2016)	Still <i>et al.</i> , 2000
OBFs and WBFs	<i>Tilapia guineensis</i>	Actinopterygii, Perciformes	Acute	<i>Jordan J. Biol. Sci.</i>	Not found	Imarhiagbe and Atuanya, 2017
OBFs (washed and non-washed fluids)	<i>Desmoscaris trispinosa,</i>	Crustacea, Decapoda	Acute	<i>Arab. J. Geosci.</i>	0.955 (2016)	Okogbueet <i>et al.</i> , 2016
	<i>Palaemonetes africanus</i> (Shrimp)					
WBFs (barite and bentonite)	<i>Geodia barretti</i>	Porifera (sponges)	Acute and Chronic	<i>Environ. Pollut.</i>	5.099 (2016)	Edge <i>et al.</i> , 2016
WBFs and SBFs	<i>Argopecten nucleus</i>	Mollusca, Bivalvia	Acute and Chronic	<i>Bol. Invest. Mar. Cost.</i>	0.100 (2016)	Rodríguez-Satizábalet <i>et al.</i> , 2015
WBFs and OBFs	<i>Ammonia tepida</i>	Foraminifera	Chronic	<i>Ecol. Indicators</i>	3.898 (2016)	Denoyelleet <i>et al.</i> , 2012

Continue

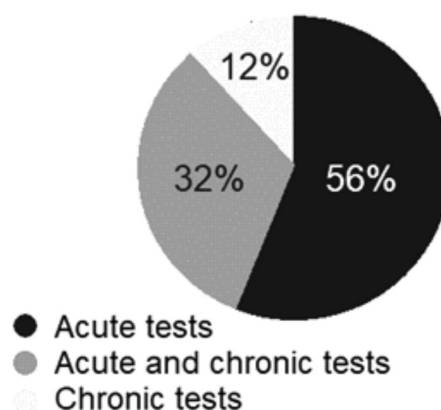
**Table 1.** Articles with relevant toxicological information about drilling fluids published during the period of January 2000 to October 2017, obtained from the Scopus and Science Direct databases, indicating the impact factor of their respective journals, in accordance with Journal Citation Reports of 2016 ([https://www.ufrb.edu.br/pgcienciasagrarias/images/Edital\\_primeiro\\_semestre\\_2018/2017JournalImpactFactor.pdf](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
SBFs	<i>Oreochromis mossambicus</i> (Tilapia)	Actinopterygii, Perciformes	Acute and Chronic	<i>Polycyclic Aromatic Compounds</i>	1.568 (2016)	Jagwaniet <i>al.</i> , 2011
WBFs (barite and bentonite)	<i>Cerastoderma edule</i> <i>Macoma balthica</i>	Mollusca, Bivalvia	Acute and Chronic	<i>Mar. Pollut. Bull.</i>	3.146 (2016)	Barlow and Kingston, 2001
SBF (Parateq)	<i>Tilapia guineensis</i>	Actinopterygii, Perciformes	Acute and Chronic	<i>Rev. Científica UDO Agrícola</i>	0.18 (2014)	Vincent-Akpu and Chindah, 2009

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



**Figure 2.** Number of articles published per country during the period of January 2000 to October 2017. NG: Nigeria; AU: Australia; UK: United Kingdom; CO: Colombia; NR: Norway; CH: China; IN: India; BR/BE: Brazil/Belgium; FR: France.



**Figure 3.** Percentage shares of the different types of tests, applied in accordance with the time of exposure, in studies published during the period of January 2000 to October 2017.

toxicity during long-term exposure (usually lasting more than 10 days)

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 Bertolotti, 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 (Denoyele *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

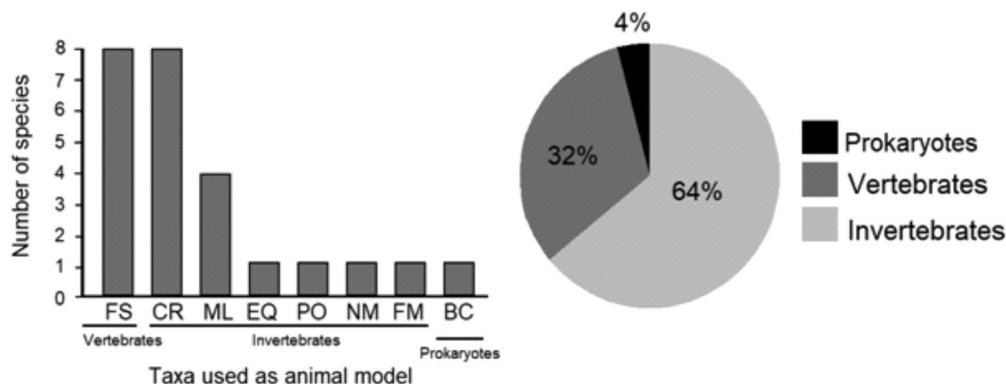
been used to compare the toxicity of SBFs (Tsvetnenko *et al.*, 2000; Still *et al.*, 2000).

### 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 OBFs, 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 alpha 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). OBFs 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



**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 ( $LC_{50}$ ) (96 h) for juvenile fish ranged from 125 mg L<sup>-1</sup> for WBFs to 6,000 mg L<sup>-1</sup> for natural OBFs (Imarhiagbe and Atuanya, 2017), indicating the higher toxicity of WBF than of OBF 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  $LC_{50}$  (96 h) for OBF in adult fish varied from 16,713 mg L<sup>-1</sup> for OBFs in marine fish to 770,000 mg L<sup>-1</sup> of the suspended particulate phase (SPP) in freshwater fish (Table 3). For SBF, the  $LC_{50}$  (96 h) varied from 2,210 mg L<sup>-1</sup> (Parateq) to 40,390 mg L<sup>-1</sup> 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<sup>-1</sup>), followed by OBF to juveniles (6,000 mg L<sup>-1</sup>) and OBF to adult marine fish (16,713 mg L<sup>-1</sup>).

#### 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 Bertolotti, 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 OBF 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, 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 OBF 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 OBF to juvenile invertebrates. WBF prevents the fertilization of Echinodermata gametes after 1 h of exposure to 3,649 ± 400 mg L<sup>-1</sup> (Benavides *et al.*, 2014). The  $LC_{50}$  (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  $LC_{50}$  (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 pp of SBF (Yan *et al.*, 2003) (Table 4).

The  $LC_{50}$  (96 h) in adult crustaceans may varied from 320 mg L<sup>-1</sup> of WBF (Farkas *et al.*, 2017) to 17,200 mg L<sup>-1</sup> of OBF (Okogbue *et al.*, 2016), showing, again, the higher toxicity of WBF than of OBF. The toxic effect of synthetic fluids may

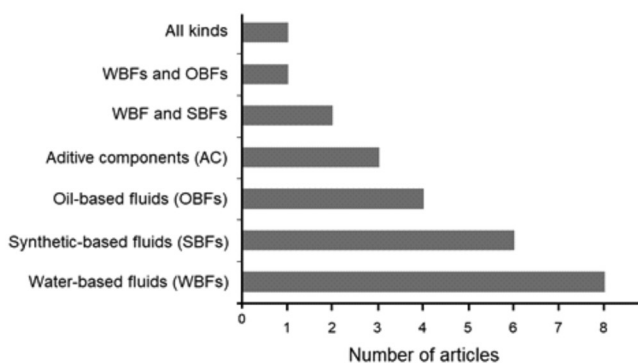


Figure 5. Types of drilling fluids tested in the 25 articles included in this review.

**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	<i>Calanus finmarchicus</i> (Crustacea)	Acute	96 h	Adults (stage V)	LC50 = 320 mg L <sup>-1</sup>	Farkas <i>et al.</i> , 2017
WBFs	<i>Lytechinus variegatus</i> (Echinodermata)	Acute	1 h	Gametes	Fecundity inhibition, EC50 = 3,649 ± 400 mg L <sup>-1</sup>	Benavides <i>et al.</i> , 2014
SBFs (EBF, IOBF, and LAOBF)	<i>Pagrus auratus</i> (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	<i>Litopenaeus vannamei</i> (Crustacea)	Acute	96 h	Post-larvae	WBF: LC50 = 4,224 – 26,635 ppm SBF: LC50 = 40,781 – 308,248 ppm	Contreras- León <i>et al.</i> , 2013
SBF (Parateq)	<i>Oreochromis niloticus</i> (Fish)	Acute	96 h	Adults	LC50 = 2,210 mg L <sup>-1</sup>	Vincent- Akpu and Sikoki, 2013
Water-based individual components (standard barite, fine barite, ilmenite, and bentonite)	<i>Modiolus modiolus</i> ( <i>Mm</i> ) <i>Venerupis senegalensis</i> ( <i>Vs</i> ) <i>Dosinia exoleta</i> ( <i>De</i> ) <i>Chlamys varia</i> ( <i>Cv</i> ) (Mollusca)	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 ( <i>Cv</i> ), day 11 ( <i>De</i> ), days 9–12 ( <i>Vs</i> ), and day 19 ( <i>Mm</i> )	Strachan and Kingston, 2012
Synthetic OBFs (Rheosyn 1416) and individual components	<i>Pagrus auratus</i> (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 <sup>-1</sup> in freshwater fish ( <i>Tm</i> ) and 31,107 mg L <sup>-1</sup> in marine fish ( <i>Mp</i> ); SPP: 770,000 mg L <sup>-1</sup> ( <i>Tm</i> ) and 42,614 mg L <sup>-1</sup> ( <i>Mp</i> ); 243,652 mg kg <sup>-1</sup> in benthic organisms ( <i>Bb</i> ); OBF: 22,414 mg L <sup>-1</sup> ( <i>Tm</i> ), 16,713 mg L <sup>-1</sup> ( <i>Mp</i> ), and 167,340 mg kg <sup>-1</sup> ( <i>Bb</i> )	Bakhtyar and Gagnon, 2012
OBFs	<i>Tilapia mossambica</i> ( <i>Tm</i> ) <i>Boleophthalmus boddarti</i> ( <i>Bb</i> ) <i>Mugil persia</i> ( <i>Mp</i> ) (Fish)	Acute	96 h	Adults	Barium: 400–2,000 ppm decreased population abundance and increased time of development; LOEC = 2.95 ppm, EC50 = 8.82 ppm; Cadmium: 2.40–2.68 ppm decreased population abundance	Sil <i>et al.</i> , 2012
Metals at levels observed in drilling muds (barium and cadmium)	<i>Rhabditis (Pellioiditis)</i> <i>marina</i> (Nematoda)	Chronic	10 days (2 generations)	Adult males and gravid females		Lira <i>et al.</i> , 2011
OBF (GlycolTM)	<i>Palaemonetes africanus</i> (Crustacea)	Acute	10 days	Adults	LC50 = 101 mg kg <sup>-1</sup> (95% CI: 49–153 mg kg <sup>-1</sup> )	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	Test type	Time of exposure	Animal stage	Response	Authors, year
SBF (XP-07)	<i>Tilapia guineensis</i> (Fish)	Acute	96 h	Fry, fingerling, and post- fingerling	LC50 = 5.63 % (fry), 7.77 % (fingerling), 6.93% (post fingerling)	Vincent- Akpuet <i>et al.</i> , 2010
ACs (lubricants)	<i>Palaemonetes africanus</i> (Crustacea)	Acute	96 h	Adult	Lubricant 1: LC50 = 350 mg L <sup>-1</sup> ; lubricant 2 of high molecular weight: 210 mg L <sup>-1</sup> , less diffusion; lubricant 3 of high acidity: 620 mg L <sup>-1</sup> .	Otaigbeet <i>et al.</i> , 2006
ACs	<i>Neomysis watschensis</i>	Acute	96 h	Juveniles	SPP: LC50 = 12,000–1,000,000 ppm, depending on the type of drilling fluid	Yan <i>et al.</i> , 2003
SBFs (EBFs, IOBFs, and paraffin)	<i>Grandidierella sp. (Gsp)</i> (Crustacea) <i>Paphies elongata (Pe)</i> (Mollusca)	Acute	96 h 10 days	Adults	10 d, LC50 = 200–1,500 mg kg <sup>-1</sup> ( <i>Gsp</i> ); 20,000 mg kg <sup>-1</sup> ( <i>Pe</i> )	
OBF (diesel oil) and SBF (IO)	<i>Leptocheirus plumulosus</i> (Crustacea)	Acute	96 h	Randomly selected	Natural sediments: LC50 = 2,825 mg kg <sup>-1</sup> (95% CL 568–14,042); formulated sediments: 3,795 mg kg <sup>-1</sup> (95% CL 3,284–4,385); diesel: 539–703 mg kg <sup>-1</sup> ; drilling fluids: 1,609–3,720 mg kg <sup>-1</sup> , depending on the type	Still <i>et al.</i> , 2000
OBFs and WBFs	<i>Tilapia guineensis</i> (Fish)	Acute	96 h	Juveniles	WBF: LC50 = 125 mg L <sup>-1</sup> ; NABF: 6,000 mg L <sup>-1</sup>	Imarhiagbe and Atuanya, 2017
OBFs (washed and non-washed muds)	<i>Desmocarlis trispinosa</i> ( <i>Dt</i> ) <i>Palaemonetes africanus</i> ( <i>Pa</i> ) (Crustacea)	Acute	96 h	Adults	Washed cuttings: LC50 = 16,900–17,200 mg L <sup>-1</sup> ( <i>Pa</i> ), 9,800–10,900 mg L <sup>-1</sup> ( <i>Dt</i> ); unwashed cuttings: LC50 = 10,300–11,350 mg L <sup>-1</sup> ( <i>Pa</i> ), 6,200 – 6,700 mg L <sup>-1</sup> ( <i>Dt</i> ) Reduced lysosomal membrane stability using 50 and 100 mg L <sup>-1</sup> TSS barite after 12 h; after 14 days, it was reduced using 30 mg L <sup>-1</sup>	Okogbueet <i>et al.</i> , 2016
WBFs (barite and bentonite)	<i>Geodiabarretti</i> (Spongia)	Acute and Chronic	12 h, 14 d	Size range: 0.1–1 kg	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	Edge <i>et al.</i> , 2016
WBFs and SBFs	<i>Argopecten nucleus</i> (Mollusca)	Acute and Chronic	96 h, 30 d	Juveniles	Reduction of pseudopodal activity with ≥ 500 mg L <sup>-1</sup> NABF and ≥ 100 mg L <sup>-1</sup> WBF	Rodríguez- Satizábalet <i>et al.</i> , 2015
WBFs and OBFs	<i>Ammonia tepida</i> (Foraminifera)	Chronic	30 d	Adults		Denoyelleet <i>et al.</i> , 2012
SBFs	<i>Oreochromis mossambicus</i> (Fish)	Acute and Chronic	96 h	Adults	SP: LC50 = 37,550 mg L <sup>-1</sup> ; SPP: 40,390 mg L <sup>-1</sup>	Jagwaniet <i>et al.</i> , 2011

**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)	<i>Cerastoderma edule</i> <i>Macoma balthica</i> (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)	<i>Tilapia guineensis</i> (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<sub>50</sub> : 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.

vary greatly, showing LC<sub>50</sub>(96 h) values as low as 101 mg kg<sup>-1</sup> of Glycol™ (Ogeleka and Tudararo-Aherobo, 2011) to 3,720 mg kg<sup>-1</sup> of IOBF in Crustacea (Still *et al.*, 2000) and 20,000 mg kg<sup>-1</sup> of EBF, IOBF, and paraffin in Mollusca (Tsvetnenkoet *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<sup>-1</sup> or after 14 days at a concentration of 30 mg L<sup>-1</sup> (Edge *et al.*, 2016; Table 4). Also,

**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	NABFs	
		Natural OBFs	SBFs
Juveniles (Fish)	LC50 (96 h) = 125 mg L <sup>-1</sup> (1) Long-term  No information available	LC50 (96 h) = 6,000 mg L <sup>-1</sup> (1) Long-term  No information available	LC50 (96 h) = No information available Long-term, > 20 days:  Increase of EROD, HSP-70, and SDH activity; increase of pyrene metabolite and DNA damage (2)
Adults (Fish)	LC50 (96 h) = No information available  Long-term No information available	LC50 (96 h) = SP: 31,107 mg L <sup>-1</sup> (mar) 200,000 mg L <sup>-1</sup> (fsw) (3) SPP: 42,614 mg L <sup>-1</sup> (mar), 243,652 mg L <sup>-1</sup> (ben), 770,000 mg L <sup>-1</sup> (fsw) (3) OBF: 16,713 mg L <sup>-1</sup> (mar), 22,414 mg L <sup>-1</sup> (fsw), 167,340 mg L <sup>-1</sup> (ben) (3) Long-term No information available	LC50 (96 h) = 2,210 mg L <sup>-1</sup> (Parateq) (4), 37,550 mg L <sup>-1</sup> (SP), and 40,390 mg L <sup>-1</sup> (SPP) from the Indian well (5); 5.5% (Parateq) (6), 7.8% (XP-07) (7)  Long-term, 3 months: decrease in oocyte maturation; delayed spermatogenesis (6)

LC<sub>50</sub>: 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) Jagwaniet *al.*, 2011; (6) Vincent-Akpu and Chindah, 2009; (7) Vincent-Akpuet *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	NABFs	
		Natural OBFs	SBFs
Gametes (Echinodermata)	1 h: Fecundity inhibition 3,649 ± 400 mg L <sup>-1</sup> (1)	No information available	No information available
Post-larvae (Crustacea)	LC50 (96 h) = 4,224–26,635 ppm (2)	No information available	LC50 (96 h) = 40,781–308,248 ppm (2)
Juveniles (Crustacea)	No information available	No information available	LC50 (96 h) = SPP: 12,000–1,000,000 ppm (3)
(Mollusca)	LC50 (96 h) = 9,113–50,446 ppm (4)	LC50 (96 h) = No information available	LC50 (96 h) = 40,500 – > 1,000,000 ppm (4)
(Mollusca)	Long-term, 30 days: Toxic effect on survival and growth	Long-term: No information available	Long-term, 30 days: Toxic effect on survival and growth
Adults (Crustacea)	LC50 (96 h) = 320 mg L <sup>-1</sup> (5)	LC50 (96 h) = 2,825 mg kg <sup>-1</sup> (6) 6,200 – 17,200 mg L <sup>-1</sup> (7)	LC50 (96 h) = 101 mg kg <sup>-1</sup> (Glycol™) (8) 210 – 620 mg kg <sup>-1</sup> (lubricants) (9) 200 – 1,500 mg kg <sup>-1</sup> (E, IO, paraffin) (10) 1,600 – 3,720 mg kg <sup>-1</sup> (IOBF) (6)
(Mollusca)	No information available	No information available	LC50 (96 h) = 20,000 mg kg <sup>-1</sup> (EBF, IOBF, and paraffin) (10)
(Spongia)	12 h: Decrease in lysosomal membrane stability 50–100 mg L <sup>-1</sup> (11)	No information available	No information available
(Nematoda)	Long-term: 10 days: LC <sub>50</sub> (10 d) = 8.82 ppm Ba; decrease of population size: 400–2,000 ppm Ba and 2.40–2.68 ppm Cd (12)	Long-term: No information available	Long-term: No information available
(Mollusca)	4 – 19 days Std. particulate barite and ilmenite: 100% dead, gill ctenidia severely damaged (13)	No information available	No information available
(Spongia)	14 days: Decrease of lysosomal membrane stability at 30 mg L <sup>-1</sup> (11)	No information available	No information available
(Foraminifera)	30 days: Decreased pseudopodal activity at ≥ 100 mg L <sup>-1</sup> (14)	30 days: Decreased pseudopodal activity at ≥ 100 mg L <sup>-1</sup> (14)	No information available

LC<sub>50</sub>: 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) Rodríguez-Santizábalet *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  $\mu\text{m}$ ) and ilmenite (12.8  $\mu\text{m}$ ) 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  $\geq 100 \text{ mg L}^{-1}$ , with effects only seen for OBF when the concentration was  $\geq 500 \text{ mg L}^{-1}$  (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 ( $\text{LC}_{50}$  [96 h] = 125  $\text{mg L}^{-1}$ ) than did OBFs. OBFs showed less toxicity to juvenile fish ( $\text{LC}_{50}$  [96 h] = 6,000  $\text{mg L}^{-1}$ ), and even less to adult marine fish ( $\text{LC}_{50}$  [96 h] = 16,713  $\text{mg L}^{-1}$ ); however, marine fish were the most sensitive to drilling fluids when compared to freshwater and benthic fish.

Glycol™ (101  $\text{mg kg}^{-1}$ ) and Parateq (2,210  $\text{mg L}^{-1}$ ) in adult invertebrates and vertebrates, respectively, were the most toxic SBF. In mollusks, standard-sized barite (20.1  $\mu\text{m}$ ) and ilmenite (12.8  $\mu\text{m}$ ) WBFs were the most toxic because of their long-term physical interference with gill function. Juvenile mollusks (min.  $\text{LC}_{50}$  [96 h] = 40,500 ppm) and adult mollusks (20,000  $\text{mg kg}^{-1}$ ) were less sensitive to SBFs than were juvenile crustaceans (min.  $\text{LC}_{50}$  [96 h] = 12,000 ppm) and adult crustaceans (3,720  $\text{mg kg}^{-1}$ ).

### 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.

## REFERENCES

- BAKHTYAR, S. & GAGNON, M.M. 2012. Toxicity assessment of individual ingredients of synthetic-based drilling muds (SBMs). *Environ. Monit. Assess.*, 184 (9): 5311–5325. <http://dx.doi.org/10.1007/s10661-011-2342-x>.
- BARLOW M.J. & KINGSTON, P.F. 2001. Observations on the effects of barite on the gill tissues of the suspension feeder *Cerastoderma edule* (Linné) and the deposit feeder *Macomabalthica* (Linné). *Mar. Pollut. Bull.*, 42(1): 71–76. [http://dx.doi.org/10.1016/S0025-326X\(00\)00117-X](http://dx.doi.org/10.1016/S0025-326X(00)00117-X)
- BENAVIDES, S.M., BENAVIDES, S.M.C., SANTOS-ACEVEDO, M., CERÓN, A.E.G., OSPINA-SALAZAR, G.H., FIGUEROA, M.A. I. & GÓMEZ-LEÓN, J. 2014. Acute toxicity assessment of an offshore exploration fluid for the fertilization sea Urchin *Lytechinus*

- Variegatus*. Bol. Investig. Mar. Costeras, 43(2): 383–405.
- BRITISH PETROLEUM (BP). 2018. BP Statistical Review of World Energy. 67th Edition. <https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review/bp-stats-review-2018-oil.pdf>. Accessed 6th November 2018.
- CONTRERAS-LEÓN, G.J., RODRIGUEZ-SATIZÁBAL, S.A., CASTELLANOS-ROMERO, C.M., FRANCO-HERRERA, A. & SERRANO-GÓMEZ, M. 2013. Acute toxicity of drilling muds on *Litopenaeus vannamei* (Boone, 1931) postlarvae. Cienc. Tecnol. Futuro, 5(3): 127–138. <http://dx.doi.org/10.29047/01225383.52>
- DENOYELLE, M., GESLIN, E., JORISSEN, F.J. & CAZES, L. 2012. Innovative use of foraminifera in ecotoxicology: a marine chronic bioassay for testing potential toxicity of drilling muds. Ecol Indic, 12(1): 17–25. <https://doi.org/10.1016/j.ecolind.2011.05.011>
- EDGE, K.J., JOHNSTON, E.L., DAFFORN, K.A., SIMPSON, S.L., KUTTI, T. & BANNISTER, R.J. 2016. Sub-lethal effects of water-based drilling muds on the deep-water sponge *Geodiabarretti*. Environ. Pollut., 212: 525–534. <https://doi.org/10.1016/j.envpol.2016.02.047>
- FARKAS, J., BÅDSVIK, C.Y., ALTIN, D., NORDTUG, T., OLSEN, A.J. & HANSEN, B.H. 2017. Acute and physical effects of water-based drilling mud in the marine copepod *Calanus finmarchicus*. J Toxicol Env Heal A, 80(16–18): 907–915. <https://doi.org/10.1080/15287394.2017.1352197>
- GAGNON, M.M. & BAKHTYAR, S. 2013. Induction of fish biomarkers by synthetic-based drilling muds. PLoS ONE, 8(7): e69489. <https://doi.org/10.1371/journal.pone.0069489>
- GALVÃO T.F. & PEREIRA, M.G. 2014. Revisões sistemáticas da literatura: passos para sua elaboração. Epidemiol. Serv. Saúde, 23(1): 183–184. <http://dx.doi.org/10.5123/S1679-49742014000100018>
- GANDHI, S.M. & SARKAR, B.C. 2016. Essentials of Mineral Exploration and Evaluation. Chapter 8: Drilling. Elsevier, New York, p. 199–234.
- GOMES, I.S. & CAMINHA, I.O. 2014. Guia para estudos de revisão sistemática: uma opção metodológica para as ciências do movimento humano. Movimento, 20(1): 395.
- HOLDWAY, D.A. 2002. The acute and chronic effects of wastes associated with offshore oil and gas production on temperate and tropical marine ecological processes. Mar. Pollut. Bull., 44(3): 185–203. [https://doi.org/10.1016/S0025-326X\(01\)00197-7](https://doi.org/10.1016/S0025-326X(01)00197-7)
- IMARHIAGBE, E.E. & ATUANYA, E.I. 2017. Assessment of biodegradation and toxicity of drill-muds used in an onshore active field located in Edo State, Nigeria. Jordan J. Biol. Sci., 10(2): 63.
- JAGWANI, D., SHUKLA, P., KULKARNI, A., RAMTEKE, D.S. & JUNEJA, H.D. 2011. Organ specific distribution of PAHs in a carnivorous fish species following chronic exposure to used synthetic-based drilling mud. PolycyclAromatCompd, 31(4): 227–242. <https://doi.org/10.1080/10406638.2011.585371>
- LIRA V.F., SANTOS, G.A.P., DERYCKE, S., LARRAZABAL, M.E.L., FONSÊCA-GENEVOIS, V.G. & MOENS, T. 2011. Effects of barium and cadmium on the population development of the marine nematode *Rhabditis (Pellioditis) marina*. Mar. Environ. Res., 72(4): 151–159. <https://doi.org/10.1016/j.marenvres.2011.07.003>
- MAGALHÃES, D.P. & FERRÃO-FILHO, A.S.A. 2008. Ecotoxicologia como ferramenta no biomonitoramento de ecossistemas aquáticos. Oecol. Aust., 12(3): 355–381.
- OGELEKA, D.F. & TUDARARO-AHEROBO L.E. 2011. Short-term toxicity of oil-based drilling fluid to the brackish-water shrimp *Palaemonetes africanus*. Afr. J. Mar. Sci., 36(1): 109–112. <https://doi.org/10.2989/16085914.2011.559707>
- OKOGBUE, C.O., ANYIAM, O.A. & ADUN, A.A. 2016. Impact assessment of drilling waste generated in “Eden Field” offshore, Niger Delta, Nigeria. Arab J Geosci, 538: 1–9. <https://doi.org/10.1007/s12517-016-2568-6>
- OTAIGBE, J.O.E., OSUJI, L.C. & AZUBIKE, A.N. 2006. Quantal response of *Palaemonetes africanus* in locally formulated drilling mud lubricants. Toxicol. Environ. Chem., 88(4): 719–727. <https://doi.org/10.1080/02772240600903029>
- RAND, G.M., WELLS, P. & MCCARTY, L.S. Introduction to aquatic toxicology. In: Rand, G.M. (Ed) Fundamentals of Aquatic Toxicology: Effects, Environmental Fate and Risk Assessment. Washington: Taylor & Francis, 1995.
- RODRÍGUEZ-SATIZÁBAL, S.A., CASTELLANOS, C., CONTRERAS, G., FRANCO, A. & SERRANA, M. 2015. Efectos letales y subletales en juveniles de *Argopecten nucleus* expuestos a lodos de perforación. Bol. Investig. Mar. Costeras, 44(2): 303–326.
- SANZONE, D.M.; VINHAEIRO, N. & NEFF, J.M. 2018. Environmental fates and effects of ocean discharge of drill cuttings and associated drilling fluids from offshore oil and gas operations. Technical Report. Available at: <[https://www.researchgate.net/publication/299285673\\_Environmental\\_Fates\\_and\\_Effects\\_of\\_Ocean\\_Discharge\\_of\\_Drill\\_Cuttings\\_and\\_Associated\\_Drilling\\_Fluids\\_From\\_Offshore\\_Oil\\_and\\_Gas\\_Operations](https://www.researchgate.net/publication/299285673_Environmental_Fates_and_Effects_of_Ocean_Discharge_of_Drill_Cuttings_and_Associated_Drilling_Fluids_From_Offshore_Oil_and_Gas_Operations)>. Accessed on: January 2018.
- SIL, A. et al. 2012. Toxicity characteristics of drilling mud and its effect on aquatic fish populations. J. Hazard. Toxic Radioact. Waste, 16(1): 51–57.
- STILL, I.; RABKE, S.; CANDLER, J. 2000. Development of a standardized reference sediment to improve the usefulness of marine benthic toxicity testing as a regulatory tool. Environ. Toxicol., 15(5): 406–416. [https://doi.org/10.1002/1522-7278\(2000\)15:5<406::AID-TOX8>3.0.CO;2-%23](https://doi.org/10.1002/1522-7278(2000)15:5<406::AID-TOX8>3.0.CO;2-%23)
- STRACHAN, M.F. & KINGSTON, P.F.A. 2012. Comparative study on the effects of barite, ilmenite and bentonite on four suspension feeding bivalves. Mar. Pollut. Bull., 64 (10): 2029–2038. <https://doi.org/10.1016/j.marpolbul.2012.06.023>
- TERZAGHI, C., BUFFAGNI, M., CANTELLI, D., BONFANTI, P. & CAMATINI, M. 1998. Physical-chemical and ecotoxicological evaluation of water based drilling fluids used in Italian off-shore. Chemosphere, 37(14–15): 2859–2871. [https://doi.org/10.1016/S0045-6535\(98\)00328-2](https://doi.org/10.1016/S0045-6535(98)00328-2)
- TSVETNENKO Y.B., BLACK, A.J. & EVANS, L.H. 2000. Development of marine sediment reworker tests with western Australian species for toxicity assessment of drilling mud. Environ. Toxicol., 15(5): 540–548. [https://doi.org/10.1002/1522-7278\(2000\)15:5<540::AID-TOX26>3.0.CO;2-A](https://doi.org/10.1002/1522-7278(2000)15:5<540::AID-TOX26>3.0.CO;2-A)
- VINCENT-AKPU, I.F., ALLISON, M.E. & SIKOKI F.D. 2010. Survival and gill morphology of different life stages of “*Tilapia guineensis*” exposed to the drilling fluid XP-07. Ciênc. Rural, 40(3): 611–616.
- VINCENT-AKPU, I.F. & CHINDAH, A.C. 2009. Gonad histology in post fingerling of *Tilapia guineensis* exposed to Parateq. Rev. Cient. UDO Agríc., 9(3): 672–680.
- VINCENT-AKPU, I.F. & SIKOKI F.D. 2013. Toxicity of drilling Fluid Parateq on Microbial Load and Survival of *Oreochromis niloticus* Fingerlings. J Fish Aquat Sci, 8: 218–222. <https://doi.org/10.3923/jfas.2013.218.222>
- YAN, T., ZHOU, M., TAN, Z., LI, Z., LI, J., YU, R. & WANG, L. 2003. Application of *Neomysis awatschensis* as a standard marine toxicity test organism in China. J EnvironSci, 15(6): 791–795.
- ZAGATTO, P.A.; BERTOLETTI, E. 2008. Ecotoxicologia aquática: princípios e aplicações. RiMa, São Carlos.
- ZHU, H.; LIU, X. 2015. Application of microtox biological toxicity testing technique in drilling fluid analysis. Drill. Fluid Complet. Fluid, 32(1): 53–56.