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Impact of upstream oil extraction and environmental public health: a review of the evidence

Jill E. Johnston^{a,#}, Esther Lim^b, and Hannah Roh^a

^aDepartment of Preventive Medicine, Keck School of Medicine of University of Southern California, Los Angeles, CA

^bSouthern California Clinical and Translational Science Institute, University of Southern California, Los Angeles, CA

Abstract

Upstream oil extraction, which includes exploration and operation to bring crude oil to the surface, frequently occurs near human populations. There are approximately 40,000 oil fields globally and 6 million people that live or work nearby. Oil extraction can impact local soil, water, and air, which in turn can influence community health. As oil resources are increasingly being extracted near human populations, we highlight the current scope of scientific knowledge regarding potential community health impacts with the aim to help identify scientific gaps and inform policy discussions surrounding oil drilling operations. In this review, we assess the wide range of both direct and indirect impacts that oil drilling operations can have on human health, with specific emphasis on understanding the body of scientific literature to assess potential environmental and health risks to residents living near active onshore oil extraction sites. From an initial literature search capturing 2,236 studies, we identified 22 human studies, including 5 occupational studies, 5 animal studies, 6 experimental studies and 31 oil drilling-related exposure studies relevant to the scope of this review. The current evidence suggests potential health impacts due to exposure to upstream oil extraction, such as cancer, liver damage, immunodeficiency, and neurological symptoms. Adverse impacts to soil, air, and water quality in oil drilling regions were also identified. Improved characterization of exposures by community health studies and further study of the chemical mixtures associated with oil extraction will be critical to determining the full range of health risks to communities living near oil extraction.

Keywords

oil extraction; human health; petroleum; contamination; cancer

[#]To whom correspondence should be addressed: Jill E. Johnston, Division of Environmental Health, Department of Preventive Medicine, Keck School of Medicine of University of Southern California, 2001 N. Soto Street, MC 9237, Los Angeles, CA, 90089; telephone: 323-442-1099; jillj@usc.edu.

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1. Introduction

Modern oil extraction frequently occurs near human populations. Globally, there are an estimated 70,000 oil fields across ~100 countries with over 1600 billion barrels of known crude oil reservoirs (CIA 2017; Bentley 2002; Mead 1993). Existing oil fields have been estimated to potentially impact the health and environment of over 600 million people worldwide (O’Callaghan-Gordo et al. 2016). In the United States, the doubling of oil production in less than a decade and growth of new oil wells has raised new and longstanding public concerns about the health and safety of these nearby populations (EIA 2018; Tadeo 2017). Of the approximately 808,485 active oil wells located in the continental United States (US), an estimated 8 million people live near (<1600 m) an active oil extraction site (Czolowski et al. 2017).

Oil forms in sedimentary rocks two to four kilometers below the surface where there are high enough pressures and temperatures to transform organic matter into liquid hydrocarbons through thermogenic breakdown (J Li et al. 2016). Oil exploration, drilling, and extraction are the first phase—or the “upstream” phase—in the lifecycle of oil. Once an oil resource is identified, a single well typically operates for 20-30 years, with the region being occupied for multiple decades with associated activities such as construction, production, processing, and transportation. As oil extraction is becoming more common near where people live, work and play, such activities have the potential to affect public health.

While there have been recent epidemiological studies and scientific reviews on the environmental and human health risks related to unconventional natural gas extraction in the United States (Adgate et al. 2014; Saunders et al. 2016; Shonkoff et al. 2014), there is a lack of systematic analyses of the environmental or health impacts from oil exploration, drilling, and extraction (Lave and Lutz 2014). Various health impacts among exposed residents and cleanup workers of several large oil tanker or offshore oil spills have previously been reviewed with respect to acute physical, psychologic, genotoxic, and endocrine effects (Aguilera et al. 2010). The potential health impacts among residents living close to oil fields and potentially exposed for long periods of time have received less attention. In this review, we leverage existing scientific literature to assess the potential range of both direct and indirect impacts that oil drilling operations can have on local communities, with specific emphasis on understanding the body of scientific literature to assess potential environmental and health risks to residents living near oil extraction sites.

2. Methods

2.1 Scope of review

The production chain of oil development involves multiple steps, ranging from extraction to transportation, refinement, and combustion. For purposes of this review, we focused on the health implications of processes that happen upstream, that is, on-site at the well production pad or field, a current focus of public health policy and community concern (McKenzie et al. 2016). Studies with an experimental design, with measurements of exposures or health outcomes, were considered. In addition, we included toxicological or animal studies directly assessing potential ecological or health-related impacts of oil drilling activities or studies

employing risk assessment models estimating a health-related outcome based on measured exposure data. Occupational studies were eligible only if they covered onshore workers and addressed an environmental hazard.

2.2 Identification of relevant studies

Existing literature that is relevant to oil extraction, either using conventional or unconventional techniques, remains limited. We employed a broad search strategy using multiple databases including: Web of Science- Biosis Citation Index, Ovid- Global Health, EBSCO Host- Greenfile and Environment Index, EMBASE, and PubMed. In addition, we completed manual searches of references related to oil development from included peer-reviewed studies. No date restrictions were placed, and the last date of a search was on April 14, 2017.

We developed the search terms and identified databases most likely to hold studies applicable to our topic of review. Search terms used were similar for all databases except for the sub-database Global Health for Ovid, with terms including variations of oil drilling: (oilfield OR oil field OR petroleum extraction OR fossil fuel extraction OR oil drilling) AND (health OR disease) AND (human), to focus on human health effects. Global Health used slightly altered terms: (oil and gas industry OR petroleum industry) AND (oilfield OR oil drill OR petroleum drill) AND (health OR epidemiology).

2.3 Study selection criteria

Our primary interest was the identification of literature focused on chemical or health impacts of oil drilling and/or oil extraction. We focused on exposure pathways of greatest relevance to human health (e.g. air, water, soil) or epidemiological studies that included some metric for exposure to oil wells. We also included studies of animals (field-based and toxicological) directly related to oil drilling. Studies dealing with only natural gas extraction operations were not considered appropriate for this review and have been summarized elsewhere (Shonkoff et al. 2014). Further, we restricted the review to onshore (rather than offshore or ocean-based) drilling operations, as occupational health risks to off-shore workers have previously been reviewed (Gardner 2003). However, occupational studies were included if they were specific to upstream oil workers and assessed an environmental hazard. That is, studies that focused only on mechanical occupational hazards, such as repetitive stress injury or work patterns, were excluded. Commentaries and publications that reviewed existing literature were also excluded, but their reference lists were examined.

Abstracts and selected full-texts for each study were screened based on the eligibility criteria stated above, with two independent reviewers determining whether the study merited final inclusion. Any discrepancies during the screening phase were resolved by consensus through discussions between the two reviewers. All studies selected for review needed to have full-text available in either English or Spanish. Each full-text was first evaluated by one reviewer (EL) and extracted for information on study design, methodology, affected population, route of exposure, (health) effect, magnitude of effect, and country of study. A table of this information was then reviewed by the second reviewer (JJ). During this process, missing information was supplemented, and incorrect information was marked with corrections.

Afterwards, all changes were discussed between the two reviewers to reach consensus for inclusion in the final literature for review.

Quality assessments of individual studies were determined and labeled as either inadequate, fair, or good. A study meriting an “inadequate” rating had significant methodological faults or was unclear with details or rationale behind its methodological structure. In contrast, studies with a clear methodology, use of standardized measures, and a systematic collection of data were graded as “fair”. Conclusions also had to be supported by the results. Furthermore, “good” ratings were reserved for studies which, in addition to all the qualities of a “fair” study, also directly observed the relationship between oil drilling and human health, clearly defined the study design and measure, and conducted robust and appropriate statistical analyses. Overall, information on funding sources was also assessed and recorded to identify possible biases afforded by the study team and the research outcomes presented in the text.

3. Results

3.1 Study selection & characteristics

After screening (n=2236) and full-text review (n=214), 63 original peer-reviewed articles published between 1993 to 2017 were selected for inclusion in the qualitative synthesis (Figure 1). Each study was summarized by population, study design, exposure metric, health outcome, results, and quality (Table 1). This set of literature is international in scope with 20 countries represented: Australia (1), Bolivia (1), China (8), Colombia (1), Ecuador (9), India (1), Iran (1), Iraq (1), Italy (1), Kazakhstan (2), Kuwait (2), Nigeria (10), Oman (1), Peru (2), Russia (2), Trinidad and Tobago (1), Tunisia (1), and US (17) (Figure 2). Studies were identified as belonging in one of four broad categories: human health and community well-being (n=22), animal biomonitoring (n=5), exposure assessment (n=30), and experimental/toxicological (n=6). Furthermore, human health and well-being studies were divided into occupational and non-occupational studies, while sub-categories of environmental exposure pathways included air, soil, water, and waste products. Studies were included in more than one category if applicable.

3.2 Population health and oil extraction

3.2.1 Community health—Of the studies reviewed, we identified 15 studies that used epidemiological methods to assess health outcomes from non-occupational exposures associated with oil drilling (Table 1). The scope of health endpoints investigated varied substantially from chronic diseases to acute symptoms, including cancer, hospitalizations, liver damage, autoimmune disorders, allergies, respiratory symptoms, general well-being, and quality of life.

Cancer: Six studies assessed the association between cancer and oil extraction, the majority of which were based in the Amazon region of Ecuador. Comparing cancer incidence in a small Ecuadorian community in the Amazon basin impacted by oil extraction to a reference population, San Sebastián and colleagues found an excess of incidence and mortality for all types of cancer (San Sebastián et al. 2001). A subsequent study of 4 counties with at least 20

years of oil extraction also showed excess risk for cancer incidence, including an increase in childhood hematopoietic (blood stem cell) cancer (Hurtig and San Sebastián 2002). The same authors also identified a significantly elevated relative risk for leukemia (RR 3.48, 95% CI 1.25-9.67) among Ecuadorian children less than 14 years of age who lived in an oil extraction region compared to those who did not (Hurtig and San Sebastián 2004). In the US, a Colorado registry-based case-control study found that children (ages 5-24) diagnosed with acute lymphocytic leukemia were 4.3 times as likely as controls (children with non-hematologic cancers) to live near active oil and gas extraction wells (McKenzie et al. 2017). In this study, authors show a positive association even after adjusting for age, race, gender, socioeconomic status, and elevation, but did not distinguish between oil and gas extraction wells. However, other analyses did not observe a significant relationship between oil production and cancer mortality. In Ecuador, researchers relying on a national mortality dataset found comparable county-level cancer mortality rates between oil producing and non-oil producing regions (Kelsh et al. 2009). Another analysis of cancer mortality in Ecuador, funded in part by the Chevron Corporation, saw no difference in rates between oil-producing and other regions of the country even while incorporating oil production data (Moolgavkar et al. 2014). The studies with null findings regarding cancer and oil production relied on all-cause mortality datasets and did not look at incidence or prevalence data. In all cases, the reliance on datasets with incomplete information (such as the exact address or date of diagnoses) and missing cases may influence study findings.

Acute and non-cancer health outcomes.: Several studies identified multiple acute and chronic non-cancer health effects elevated in communities living near oil extraction, typically relying on a cross-sectional design. A study of a New Mexico community near an oil drilling site and an oil waste pit identified elevated prevalence of rheumatic disease, lupus, neurological and respiratory symptoms, and cardiovascular problems compared to a community farther away (Dahlgren et al. 2007). Multiple studies have found suggested evidence of alteration of immunological function in communities near oil extraction which may explain higher rates of lupus (Dahlgren et al. 2007), liver abnormality (Dey et al. 2015) and allergic disease (Yermukhanova et al. 2017). Adults living within 5 km of an oil field had significantly lower levels of 3 liver enzymes—alanine transaminase, aspartate transaminase, and alkaline phosphatase—as measured in blood when compared to adults living in a non-industrial region without oil drilling sites (Dey et al. 2015). School-age children (ages 7-11) in the oil-producing region in Kazakhstan found significant enlargement of thyroid volume in children living in the oil-producing regions, compared to those living in agricultural regions (Kudabayeva et al. 2014) and presence of allergic disease decreased with distance from the oil fields (Yermukhanova et al. 2017). All studies suggest that exposure to oil-related air pollutants may be adversely impacting immunological functions and driving the observed health differences.

A comparative study using a structured questionnaire among women living near oil wells in Ecuador identified higher prevalence of skin fungi, nasal irritation, and throat irritation (San Sebastián et al. 2001). A similarly designed questionnaire based study in rural Nigeria found significantly higher rates of neurological symptoms, including headache, dizziness, eye and skin irritation, and anemia after adjusting for age, sex, and smoking status (Kponee et al.

2015). No difference was found between communities for gastrointestinal symptoms, malaria, or general pain metrics. Using hospital records, numerous cases of asthma, bronchitis, eye, and skin infection were identified in 9 rural Nigerian communities near oil fields, although there was not a clear analysis of the association between exposure and hospital data, nor were these rates compared to an unexposed population (Ogbija et al. 2015). 95.2% of the participants reported experiencing environmental degradation of air, water, or land due to oil drilling operations, identifying oil spills and air pollution from flaring as important risk factors to environmental health (Ogbija et al. 2015).

Contamination of water has been identified as another possible mechanism for observations of health risks. Women relying on surface water for household needs and men working in oil spill remediation recorded the highest levels of urinary mercury in oil extraction regions of Ecuador and Peru (Webb et al. 2016). Overall, however, the urinary mercury levels in this population were consistent with global background levels, while 7% of participants exceeded World Health Organization background levels.

Only one study was found examining birth outcomes in relation to oil extraction. After adjusting for socioeconomic factors, women of child-bearing ages from exposed communities reported higher numbers of spontaneous abortions (OR: 2.47, 95% CI 1.61-3.79); however, no significant differences in stillbirth were observed (San Sebastian et al. 2002). This review did not identify any studies assessing birth outcomes, such as birth weight, pre-term birth, or birth defects.

3.2.2 Worker health—A total of five studies explored health outcomes for occupational exposures associated with working in the onshore oil drilling industry. Two studies explored cancer risk, while the other studies examined upper respiratory tract bleeding, silica related illnesses, and neurobehavioral impairment.

The Australian Health Watch cohort, consisting of workers in the petroleum industry (including both extraction and refining), was designed to track both cancer incidence and deaths that may be associated with occupational exposure to oil-related chemicals using a national cancer registry. Among the cohort there was an observed low standard mortality ratio (SMR 0.84), suggesting a presence of the “healthy worker effect,” lower cancer mortality and prolonged survival among this cohort (Gun 2004). The results for cancer from a 15-year follow up showed a non-significant increase in the incidence of all cancers (SIR 1.04, 95% CI 0.97-1.11). Melanoma occurred in significantly increased rates (SIR 1.54, 95% CI 1.30-1.81), while other types of cancers—bladder, prostate, and blood—were only found to be marginally significant. Among the results reported for only onshore oil extraction job types, there was no significant elevated incidence of cancer.

Paz-y-Miño et al. (2008) in Ecuador found that blood samples of oil workers showed increased DNA damage and cancer risk compared to urban control populations. Participants exposed to hydrocarbons were also more likely to report acute symptoms such as fatigue, headache, nausea, and diarrhea (Paz-y-Miño et al. 2008). The work suggests that populations exposed to hydrocarbons are more susceptible to developing DNA damage. However, the study lacked a detailed assessment of the degree of exposure among the study participants.

An observational study administered health questionnaires to employees presenting at an oil field clinic with symptoms associated with low-level exposure to hydrogen sulfide (H₂S) gas. Independent monitoring found H₂S gas levels to range between 4-50 ppm, with common symptoms reported by oil workers including bleeding of the nose, pharynx, gum, mouth, and tongue, during periods of elevated H₂S concentrations at drill sites (Mousa 2015).

Questionnaires were also utilized to exclude symptoms not associated with H₂S gas exposure (e.g. related to the flu or rhinitis); however, the exact degree of exposure per patient was not assessed, nor was the exact placement of the monitors detailed. Prolonged neurobehavioral impairment was also identified among workers experiencing the highest levels of H₂S (up to 50 ppm) (Mousa 2015). Further, a case report described that a 24-year-old oil tester with acute exposure to an estimated level of 14,000 ppm of H₂S exhibited declines in “cognitive function, memory, visual perceptual and coordination, intelligence, and neurophysiologic functions” 49 months after the initial exposure (Kilburn and Warshaw 1995).

Respirable crystalline silica was an occupational hazard presented to some oil field workers, which can cause silicosis, lung cancer, autoimmune disorders, and kidney disease (Castranova 2000). Crystalline silica, or “frac sand”, is injected along with water and chemicals into hydraulically fractured wells to open cracks and fissures underground to allow increased flowback of oil. Millions of pounds of sand may be used for a single well, with one study finding that 5 out of 11 US sites utilize hydraulic fracturing methods with a mixture of sand and water, exposing some workers to respirable silica levels 10 times greater than those deemed as safe by the US Occupational Safety and Health Administration (Esswein et al. 2013). However, individual levels of exposures were not assessed.

3.2.3. Community risk perception and environmental health—Two papers assessed the attitudes and beliefs of rural communities toward oil drilling and extraction activities using interviews and questionnaires designed to contextualize local residents’ experiences and concerns (Brown 2003). Among rural coastal communities of Trinidad, villagers living closest to oil extraction regions expressed the strongest belief that oil drilling harmed the nearby communities by causing health problems and damaging the wetland ecosystem (Baptiste and Nordenstam 2009). In Nigeria, residents reported adverse impacts of oil exploration on socio-economic livelihood and health. Residents believed that oil drilling was associated with decreased farmland productivity, decreased fish populations due to oil spills, adverse impacts on drinking water quality, and decreased animals for hunting due to noise (Okoli 2006).

3.3 Animal biomonitoring

The health and exposure of animals, including wildlife, pets, or livestock, can serve as sentinels to understand the potential cumulative impacts of exposure to human health. Biomonitoring of animals can also provide information about specific toxicants in exposed areas. Typically, animals are continually exposed to ambient air, soil, and surface water, have shorter life-spans, and have more frequent reproductive cycles when compared to humans.

Five studies investigated the exposure and biologic effects of living near an oil drilling operation among either livestock or native species (Table 2).

Bamberger and Oswald (2015) longitudinally investigated 21 cases related to animal health based on qualitative interviews. The animals lived within two miles of an intensively drilled region across five US states, with some animals directly exposed to drilling fluids and wastewater. In both companion and livestock animals, the most commonly reported health impacts were found in reproductive, neurologic, gastrointestinal, and respiratory systems, along with decreased growth and milk production. Reported symptoms were largely unchanged over the course of the study.

Two studies assessed heavy metals in organs of animals raised in oil producing regions and slaughtered for meat consumption. Researchers found that among sheep (but not cattle), proximity to oil wells was related to higher concentrations of Pb (liver) and Cd (kidney) and that levels of metals varied by geographic location of the livestock in southern Italy (Miedico et al. 2016). Among cattle in oil-producing regions in Colombia, Pb, Cd, and molybdenum were measured in the organs of slaughtered animals (Brown 2003). In both studies, many of the individual samples exceeded permissible Pb and Cd levels as established by the European Commission. In addition to potential pathways of exposure to humans, exposure to Pb and Cd adversely affect livestock animals' reproductive and immune systems, harming offspring and increasing susceptibility to infections (Cai et al. 2009).

Sand lizards in Kuwait were used as a bio-indicator to study the health hazards of pollution related to oil wells in the desert. Reptiles are exposed to pollutants primarily through ingestion, dermal contact, and inhalation. Lizards and ants from the oil-extraction region were found to have significantly higher concentrations of polycyclic aromatic hydrocarbons (PAHs) measured in tissue from the whole body compared to tissues of animals from a control region.

Specifically, phenanthrene, fluoranthene, and benzo[a]anthracene were found in both species found in the oil field region but not found in other sites (Al-Hashem 2011). They also identified higher numbers of dead and swollen cells with cytoplasmic degeneration in the analysis of liver tissue from lizards in this region (Al-Hashem et al. 2007). In addition, damage was greater in male than in female lizards, suggesting an overall impact to an organism's growth, survival, and reproduction with exposure.

3.4 Environmental exposures and oil extraction

The literature on environmental contamination associated with oil drilling that may impact human health is typically focused on a specific medium—air, soil, or water (Figure 3).

3.4.1 Air pollution—A single drill site typically operates for decades, and the extraction process itself produces emissions of multiple health-hazardous air pollutants, including chemicals such as benzene, toluene, ethylbenzene, xylene, formaldehyde, hydrogen sulfide, and methylene chloride (Field et al. 2014). Chemicals released into the air include particulate matter (PM), nitric oxides (NO_x), methanol, naphthalene, xylene, toluene,

ethylbenzene, formaldehyde, and sulfuric acid. Many of these compounds are known to be either toxic, carcinogenic, or associated with reproductive harm (Stringfellow et al. 2017). However, transport from the extraction site to human populations is less well-characterized, as understanding of the impact on local air quality is typically limited by the availability of existing monitoring networks. The emissions also likely depend on geographical location and state of drilling.

Organics.: Macey and colleagues (2014) leveraged community knowledge to identify and install air sampling equipment in particularly noxious locations near oil drilling sites across five states. Of the 75 volatile organic compounds analyzed, 8 were identified at concentrations exceeding the US Environmental Protection Agency chronic cancer-risk threshold (assuming >365 days of exposure): benzene, 1,3 butadiene, ethylbenzene, formaldehyde, n-hexane, hydrogen sulfide, toluene, and xylenes (Macey et al. 2014). Benzene, formaldehyde, and hydrogen sulfide were the most frequently detected at excess levels.

An analysis of the air quality in an oil-extraction region of Tatarstan Republic, Russia measured hydrogen sulfide, hydrocarbons, benzene, sulfur dioxide, and nitrogen oxide gas (Novikova et al. 2014). Benzene and hydrogen sulfide were the largest contributors to the total estimated non-carcinogenic risk for nearby populations, with the highest risk estimated for children. Elevated risk was further calculated for the respiratory and cardiovascular systems. However, the study lacked detailed information on both the procedural and analytic methods utilized for the conclusion.

Another set of researchers measured concentrations of sulfur dioxide (SO₂) in the desert oil fields of Oman attributed to the local flaring of gas (Abdul-Wahab et al. 2012). Flaring is a widely used practice for the disposal of natural gas during drilling and production in places where there is insufficient infrastructure for the utilization of the gas. At sites most impacted by flare emissions, the average monthly concentration of SO₂ gas was 80 µg/m³ with peaks exceeding 1300 µg/m³. The one-hour US National Ambient Air Quality Standard is 196 µg/m³. Inhalation of low concentrations of SO₂ for short-term exposures (1 hour) has been known to cause bronchoconstriction, shortness of breath, and wheezing (Reno et al. 2015). Oil field workers in particular could experience adverse, acute health effects even with short-term exposures to sulfur dioxide emissions (Abdul-Wahab et al. 2012).

3.4.2 Soil—Contamination of the earth occurs when drilling fluids are spilled during transport by truck or wastewater pipelines, failure of well casings, or leaks from tank pipes (Pichtel 2016). Polluted lands can then impact human health through direct ingestion, crops, dermal contact, indoor and outdoor inhalation of soil particulates, and/or migration to groundwater, with field workers and nearby communities at highest risk for exposure.

Organics.: Hydrocarbons, primarily measured as total petroleum hydrocarbons (TPH), comprise the major component of crude oil profiles, with hundreds of individual chemicals in a single TPH mixture. These profiles may vary between oil fields. A comparison of TPH soil concentrations between oil fields and farmlands in China found significantly higher concentrations in the oil fields, particularly in the top 15 cm of soil, likely as a result of

direct oil spills or leaks (Teng et al. 2013). Similar results were observed around oil production sites in Nigeria, where the TPH concentrations are expected to have adverse effects on soil quality and microorganism health (Olobaniyi and Omo-Irabor 2016). Naphthenic acids, for example, are a naturally occurring component of nearly all crude oils and can persist in water and accumulate in sediments. These compounds have been found to be toxic to microorganisms, aquatic organisms, birds, and mammals (Brown and Ulrich 2015). An investigation across four oil fields measured naphthenic acids in all samples, and many samples were found to be at concentrations that exceeded reported ecotoxicity thresholds (Jie et al. 2015).

Polycyclic aromatic hydrocarbons (PAHs), a group of environmentally toxic and persistent chemicals associated with crude oil, enter the environment through spillage or leaks from producing wells, storage tanks, transportation lines, and/or waste pits. In Texas, soil analysis of oil extraction sites found that 12-46% of the total PAH contaminants were comprised of known carcinogens (Bojes and Pope 2007). Furthermore, concentrations of these PAHs exceeded Texas residential soil standards by up to 59 times the limit and groundwater protective levels by 4 times the screening criteria. Another study characterizing the concentrations of PAHs in soil across an agricultural and industrial region in China found higher levels in oil extraction fields compared to other sites, suggesting the direct contamination of local soil by the surrounding oil drilling activities (Zhang et al. 2013), which based on a risk assessment model, may increase risk of cancer in the local population. A separate analysis of surface soil samples from four oil fields across China identified heavily contaminated soils with a petroleum related PAH-signature (Wang et al. 2015). The possibly carcinogenic PAHs accounted for 8-27% of total PAHs, with the authors finding a similar cancer risk to Zhang et al. (2013). In addition, a similar study of PAHs in Iraqi oil fields modeled a comparable, but slightly lower, potential cancer risk for exposures (Alawi and Azeez 2016).

Inorganics.: Concentrations of heavy metals in oil have also been assessed with respect to oil extraction. Crude oil contains metals such as Cd, Pb, nickel (Ni), and vanadium (V), and drilling fluids may additionally contain chromium (Cr) and zinc (Zn), although composition can vary by oil field (Lord 1991). In a soil content analysis for a Chinese oil field, the heavy metals Zn, Cd, and copper (Cu) were found to be significantly higher than background concentrations, with the highest concentrations being found near the oldest oil wells that were developed more than 40 years prior (Fu et al. 2014). The researchers concluded that Cd is the most bioavailable heavy metal in oil-polluted soils and the most threatening to the surrounding ecosystem. Similarly, an investigation in Nigeria identified elevated concentrations of Pb, Cd, Cr, and Zn when compared to background levels in soils (Asia et al. 2007).

Radioactive materials.: Others have investigated the relationship between oil extraction and the presence of naturally occurring radioactive materials (NORM, e.g. ^{226}Ra , ^{232}Th and ^{40}K) in surface soils. Exposure to such radioactive materials can cause cell damage, anemia, birth defects, and respiratory harm and is associated with the increased incidence of cancer (Rich and Crosby 2013). A comparison of soils in a region with untapped crude oil deposits

to oilfields with active oil exploration measured 2-10 times higher concentrations of natural radionuclides in the active exploration regions, suggesting that active oil exploration leads to increased radionuclide concentrations in surface soils (Ajayi and Dike 2016). While the population living near active oil exploration sites was estimated to have higher risk exposure to radiation hazards, that risk analysis did not exceed the maximum permissible limit established by the International Commission on Radiological Protection (ICRP 1999). Furthermore, another study in Nigeria also measured elevated radioactivity levels in the soil of 10 oil fields compared to background levels (Agbalagba et al. 2012). The authors in this study also concluded that the radioactivity levels did not pose an immediate health risk but suggested a potential for longterm effects for oil field workers and nearby residents.

3.4.3 Water—The quality of surface water is influenced by local land use and both point and non-point sources that discharge into the water basin. Several studies have evaluated the role of oil extraction on local surface and groundwater quality; particularly, research has focused on changes in the chemical composition of the water.

Surface water: A river basin in Western Siberia, home to over 112 oil fields and more than 70,000 drilled wells, measured elevated levels of chloride and higher salinity in the surface water, suggesting release of oil-related wastewater through leakage, dumping, or seepage from contaminated groundwater (Moskovchenko et al. 2009). A similar study in a small river basin in the Peruvian Amazon impacted by oil extraction also found that oil activity was responsible for 20% of the chloride and 12% of the sodium content in surface waters (Moquet et al. 2014). The authors concluded that oil extraction activities could not be considered as negligible in terms of the impact on surface water hydrochemistry, with increased risk following the populations in this region who are in frequent contact with the contaminated surface water. In the US, an Oklahoma groundwater study found higher levels of chloride, sodium, and other salts in shallow groundwater sources beneath oil production areas compared to areas of residential or agricultural land use, which was attributed to oil drilling wastewater (An et al. 2005). In China as well, an oil field with over 3,800 wells in the eastern Gansu Province found high salinity and TPH concentrations in the local ground and surface water, suggesting the significant degradation of water quality due to local oil drilling activities (Ma et al. 2011).

Drinking water: A group of studies assessed the presence of chemical contaminants in drinking water sources near oil fields. A study in southeastern Bolivia measured the levels of TPH, PAH, and 22 metals in the drinking water of residents living less than 30 km from an oil extraction field (Alonso; et al. 2010). With surface waters acting as the primary source of drinking water for these rural communities, the study found high levels of exposure: three-quarters of the samples were contaminated with concentrations exceeding the reference levels. The most frequently detected contaminants were TPH, PAH, arsenic (As), and manganese (Mn). In the US, an investigation in Colorado examined the association between groundwater methane concentrations, which can indicate a seepage pathway of natural gas due to hydraulic fracturing, and proximity to oil and gas production. While methane was identified in drinking water, there was not a strong association with proximity to extraction sites (Li and Carlson 2014). A further study looking at the transport pathways of

contaminants into aquifers from leaking well casings near oil and gas production regions also found no evidence of aqueous phase contamination; however, the authors suggest that the results are inconclusive due to data and methods limitations (H Li et al. 2016). In contrast, a groundwater TPH investigation in China found higher levels in a confined aquifer near an oil exploration field in comparison to that near a farmland, suggesting the direct contamination of the aquifer from exploratory wells, injection well leakages, and open well holes (Teng et al. 2013).

3.5 Drilling fluids, wastewater, and oilfield waste pits

The occurrence of spills is strongly associated with oil well density, indicating that areas with dense oil drilling are more likely to experience spills (Lauer et al. 2016).

Inorganics and organics.—Based on state government records, North Dakota was estimated to have had more than 8000 spills from 2008–2015, involving over 53 million liters of wastewater concentrated in the northwest oil fields (Cozzarelli et al. 2017). The wastewater was high in salts (chloride and sodium) and contained high concentrations of other toxic contaminants including barium (Ba), Cd, Ni, Mn Pb, selenium (Se) and V at amounts exceeding national ecological or drinking water regulations (Lauer et al. 2016). Accordingly, a detailed investigation of one major oil wastewater spill in North Dakota levels of chloride and sodium were 10–70 times greater than those found prior to the spill. Oil spills may introduce compounds into the ecosystem due to partitioning into the sediment layers, acting as long-term sources of contaminants for aquatic organisms (Cozzarelli et al. 2017).

Drilling fluids are injected into wells during the drilling process to aid in clearing, cooling the drill bit, and maintaining proper pressure during oil extraction. These oil- or water-based fluids can be discharged into oil field pits with the potential to leach directly into the soil or groundwater, which may in turn expose local populations. A study in Iran measured elevated concentrations of Cd, Cr, and Ni in the drilling fluids used in well sites, with significant concentration variations over an 8-month period (Shadizadeh and Zoveidavianpoor 2010). Kuang (2011) found that agricultural lands around the Zhongyuan oil field in China contained 435–4112 mg/kg total PAHs, with increasing concentrations with decreasing distance to the oil waste pits (Kuang et al. 2011).

Radioactive materials.—Human exposures to such contaminations could occur through the inhalation of radium from the surface, through ingestion of animals that grazed on the site, or through food grown in the contaminated soil. Elevated concentrations of radioactive materials, in addition to the heavy metals As and Pb, in areas which formerly served as waste pits and sludge ponds were measured on farmland from a former oil drilling site in Eastern Kentucky (Spitz 1997). A later investigation suggested that the leachability of radium and other radioactive contaminants on farmland is another important factor for estimating risks to human health as a result of legacy oil drilling activities (Rajaretnam and Spitz 2000). In Tunisia, waste samples from onshore oil field production regions had the highest levels of radium isotopes, with estimated annual effective radiation doses exceeding the levels deemed allowable by the United Nations Scientific Committee on the Effects of

Atomic Radiation (Hrichi et al. 2013). The same team also found that the radioactivity of the oil field directly increased along with the amount of wastewater being used in the processes. However, a Nigerian study measuring NORM levels in the soil waste stream did not pose a significant risk to workers or residents based on the calculated cancer mortality risk (Jibiri and Amakom 2010).

3.5.1 Toxicological studies of oil drilling related fluids—Researchers have investigated the toxicological profile of both the fluids used for injection into petroleum wells for stimulating production and the wastewaters collected from such extraction wells (Table 2). In a review of data collected by regulatory agencies on acidization, or the use of fluids for enhancement of oil production, Abdullah and colleagues identified 600 instances of acidizing over the course of 16 months in California (2016). Twenty-eight of the chemicals used recently by oil operators are known to be carcinogens, mutagens, reproductive and developmental toxins, endocrine disruptors, or other acutely toxic chemicals like xylene, hydrofluoric acid, methanol, and nitroacetic acid. Again, such compounds can enter the environment through spills, leaks, and volatilization, but in general are poorly characterized in terms of transport through and persistence in the environment (Stringfellow et al. 2017). Agriculture and fishing are sectors that are vulnerable to environmental pollution related to oil extraction because they are closely intertwined with our ecosystems. The biological impact to these sectors can result in not only economic declines but also the more direct impact to our health and well-being. For example, Akani and Obire (2014) simulated the impact of disposing wastewater into local surface water sources on the native catfish population. The study exposed African catfish to sub-lethal doses of raw wastewater effluent. In general, as the dose of wastewater increased, the bacterial counts on the skin, gills, and intestines of the fish also increased. The authors suggest that the presence of potential pathogens in the wastewater, including *Bacillus*, *E. coli*, and *Staphylococcus* could contribute to bacterial diseases for fish living in waters impacted by wastewater from oil drilling operations, leading to economic loss and public health hazards (Akani and Obire 2014).

The degree of contamination, toxicity, and phototoxicity caused by seepage from production pits and wastewater runoff in water sources was also assessed in the oil producing regions of the Ecuadorian Amazon (Wernersson 2004). TPH could be identified in rivers and ponds used for drinking water; however, the acute water toxicity was determined to be low when analyzed through bioassays. Others have investigated the genotoxicity of wastewater on native onion varieties, finding a negative dose-response relationship between root growth and oil wastewater concentration through root damage and growth inhibition (Odeigah et al. 1997). Root malformations and statistically significant chromosomal aberrations were also observed, indicating possible genotoxicity for exposed plant life.

Kassotis and colleagues (Kassotis et al. 2015; Kassotis et al. 2016) examined the endocrine-disrupting properties of chemicals used or produced during the petroleum extraction process to reduce friction, decrease drilling time, or enhance the recovery of oil (Wiseman 2009). Over 100 chemicals associated with oil or natural gas extraction are known or suspected to be endocrine disruptors. The studies investigated the potential range adverse reproductive and developmental health outcomes in mice after exposing them prenatally to a mixture of

23 chemicals prepared in the lab, in order to replicate the fluids used in unconventional oil and gas extractions. The results included decreased pituitary hormone levels, increased body weights, disrupted development of ovarian follicles, and altered uterine and ovary organ weights for female off-spring (Kassotis et al. 2016). Among their male counterparts, increased testes weights, serum testosterone, body weights, and cardiomyocyte size and decreased sperm counts were observed (Kassotis et al. 2015). For all exposed groups, adverse effects to fertility could be found, even for those exposed to the lowest doses, which suggests that any level of pollutants from extraction sites may prove to be hazardous—even those coming from wells near communities which are deemed to be low impact.

4. Discussion

Based on a review of existing scientific literature and peer-reviewed studies, current evidence suggests a potential wide range of risks associated with upstream oil drilling that occurs close to human and animal populations. Various pathways such as air, water, and soil have been found to transmit pollutants associated with oil drilling operations, and there are multiple studies suggested higher disease prevalence in communities near such operations. As oil extraction activities is expected to become more common near where people live, work and play, such exposure pathways may become an important public health consideration.

There are few epidemiological studies identified related to upstream oil extraction, with the majority located in the Amazon region of South America. The methods reviewed also typically made comparisons between an exposed and unexposed (or less exposed) group, which does not allow for a robust assessment of dose-response trends, specific exposure pathways, acute impacts, cumulative effects, or variation across oil extraction regions. There are multiple studies that suggest evidence of association with cancer, although the results are not always consistent and rely on secondary surveillance data. In most cases, studies were based on existing disease surveillance systems and did not directly measure exposure or disease status.

The health endpoints are generally non-specific, that is having multiple potential causes and only assessed at multiple time points. While community health studies can identify impacts on vulnerable populations (children, elderly, etc.), additional studies among workers could offer greater insights into the health implications of oil drilling since they are the first to be exposed and usually at the highest levels possible. Secondly, epidemiological studies routinely relied on residential proximity to gauge magnitude of exposure. Since intense drilling areas may have multiple drilling pads spaced closely together with potential for multiple exposure pathways (air, water, soil), distance is a reasonable proxy for potential cumulative exposure.

Nevertheless, the use of different approaches to defining the exposed make it difficult to determine a constant, since both the extent of exposure (over both space and time) and what this potential exposure means to humans and animals living nearby is variable. The limited range of studies also create a gap in understanding the episodic nature of potential exposures and how it may influence the indoor living environments of communities.

Among the studies considered in this review, there is a larger body of literature regarding exposure and environmental contamination associated with oil drilling when compared to epidemiological analyses. These studies typically assessed the behavior of one contaminant group in a single environmental medium. Despite varied methodological approaches and diverse oil field settings, a pattern of elevated heavy metal, hydrocarbon, and radioactive material (particularly in the soil) concentration emerged across the literature. However, the conclusions on the risk these elevated concentrations pose to human populations vary widely, depending on the exposure patterns specific to that community (e.g. drinking water source, local food, occupation, etc).

4.1 Future Research

There persist important limitations in the existing research and a need to extend the understanding regarding the public health dimensions of oil extraction processes. Therefore, larger studies therefore, with greater statistical power and more spatially refined exposure assessments are needed to better characterize impacts on mortality, morbidity, and mental health endpoints. Furthermore, there is a need for baseline data (prior to oil drilling), prospective exposure monitoring, and health surveillance of populations living near oil developments in order to better assess causality (Finkel and Hays 2015). While many health studies pointed to air pollution as a key driver for potential adverse health effects, few studies investigated the relationship between air quality and oil extraction. No studies reviewed to date have published longitudinal physiological measurements from a cohort near an oil extraction site, and few evaluate the potential impacts of unconventional extraction technologies or frequency of flaring.

Future research required to address the multiple gaps in understanding the upstream oil impacts will require the utilization of improved methodologies. For example, the use of multiple continuous monitors that use innovative, low-cost, and highly portable electrolytic sensors (Collier-Oxandale et al. 2018), capable of measuring in the parts-per-billion level range, can enable the use of temporal and spatial-scale data highly relevant to realistic patterns of human exposure to ambient air pollution (Clements et al. 2017). Technological advances allowing the capture of higher resolution data may better support epidemiological designs, even evaluating the dose-response relationship between exposure and health outcomes. Finally, there is a need for continued investigations into whether specific populations are more susceptible to or disproportionately impacted by oil drilling-related pollution than the general population (Johnston et al. 2016; McKenzie et al. 2016; O'Rourke and Connolly 2003). Susceptibility factors may relate to life stage, genetic predispositions, co-morbidities, socioeconomic status, race and/or ethnicity.

As unconventional techniques expand oil production globally into previously inaccessible sources within existing communities, more humans and animals will be exposed to oil-related contaminants. Unconventional drilling techniques are not only dramatically changing the geography of oil production but are also changing our estimates of oil and gas reserves (Lave and Lutz 2014). Global estimates for recoverable unconventional oil deposits order near 345 billion barrels, which suggest that oil drilling practices may not decrease anytime soon and may even become more harmful to public health (Jackson et al. 2014). In the US,

hydraulic fracturing accounted for less than 2% of total oil production in 2000 but has rapidly grown and accounted for nearly half of all oil extracted in the US in 2015 (EIA 2018).

Although we used a broad search strategy and consider this a substantive review of the available literature, there are limitations to this study. Some relevant publications or data could have been neglected in our search due to the search terms used for each database although efforts were made to be as inclusive as possible. Furthermore, there are many countries with high volumes of oil extraction and potentially high exposure levels such as Saudi Arabia, Mexico, or the United Arab Emirates, for which no studies were identified that met the criteria (e.g. peer reviewed paper in English or Spanish).

5. Conclusion

In this review, we focused on the peer-reviewed scientific literature addressing the various dimensions of upstream oil extraction activities on environmental health. There is growing evidence of health impacts in communities near oil extraction compared to other populations and potential for multiple pathways of exposure to oil-related chemicals. Although various impacts associated with exposure to oil drilling activities were identified, studies ranged in methodology and assessment of both exposures and effects. In order to more clearly assess the range of impact that oil drilling operations may have on public health, future studies will need to improve on defining related exposures, using better equipment and more consistent methodology.

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Highlights

- Identifies 63 studies on the exposure and health risks related to oil extraction.
- Examines the human health effects of oil drilling
- Discusses potential exposure pathways via include air, soil, water and waste fluids.

Figure 1.
PRISMA diagram with levels of screening and selection of literature at each stage

Figure 2. Geographical distribution of known oil fields, designated by yellow dots. Shaded countries designate location of studies reviewed.

Pathway	Inorganics	Organics	Radioactive
Air	SO ₂	Benzene, Formaldehyde, H ₂ S, VOCs	
Water	As, Cl ⁻ , Mn, Na	CH ₄ , PAHs, TPH	
Drilling waste	As, Ba, Cd, Cl ⁻ , Cr, Mn, Na, Ni, Pb, Se, V	PAHs	NORM, Radium
Soil	Cd, Cr, Cu, Pb, Zn	Naphthenicacids, PAHs, TPH	NORM

Figure 3.
Summary of potential exposure pathways and contaminants measured.

Table 1.

Summary of epidemiological studies on health outcomes from exposures associated with oil drilling

Author(s)	Year	Country	Study Design	Study Population and Sample Size (n)	Findings	Health Effect	Quality
<i>Cancer</i>							
San Sebastian et al.	2001	Ecuador	Cross-sectional	10 cases from ~1000 residents in San Carlos, 1989-98	Village near oil fields had to 3.6 times higher cancer incidence and mortality among males	Effect	Good
Hurtig and San Sebastian	2002	Ecuador	Cross-sectional	Cancer cases in 4 exposed (n=473) vs 11 unexposed (n=512) counties, 1985-1998	Significant increase in incidence of (1) stomach, rectum, skin, soft tissue, and kidney cancer for men, (2) cervical and lymph cancer for women, and (3) hematopoietic cancers for children < 10 in oil exploration regions	Effect	Good
Hurtig and San Sebastian	2004	Ecuador	Cross-sectional	91 cancer cases, 1985-2000	Significantly elevated risk of leukemia among children < 14 years living in an oil extraction region	Effect	Good
Kelsh et al.	2009	Ecuador	Ecological	7,713 deaths (of 2,569,685 person-years) in exposed vs 7,622 deaths (of 2,428,113 person-years) in unexposed regions, 1990-2005	No significant increase in county-level cancer mortality rates in oil producing regions	No effect	
Moolgavkar et al.	2014	Ecuador	Ecological	Population and mortality data, 1990-2010	No significant difference in cancer mortality rates between oil-producing and non-oil producing areas	No effect	Fair
McKenzie et al.	2017	United States	Case-control	743 children (ages 0-24) with hematologic cancers vs non-hematologic cancers, 2001-2013	Children ages 5-24 with acute lymphocytic leukemia were 4.3 times more likely to live in an area with the highest concentration of oil and gas wells	Effect	Good
<i>Birth & Reproductive Outcomes</i>							
San Sebastian et al.	2002	Ecuador	Cross-sectional	365 exposed compared to 283 non-exposed women (ages 17-45), 1998-99	Increased likelihood of pregnancy resulting in spontaneous abortion among	Effect	Good

Author(s)	Year	Country	Study Design	Study Population and Sample Size (n)	Findings	Health Effect	Quality
					women in exposed communities		
<i>Acute & non-cancer Outcomes</i>							
San Sebastian et al.	2001	Ecuador	Cross-sectional	368 exposed compared to 291 in non-exposed communities between 1998-99	Exposed women had significantly higher prevalence of nose and throat irritation. Headaches, earaches, eye irritation, diarrhea, and gastritis associated with nearness to oil wells.	Effect	Good
Dahlgren et al.	2007	United States	Cross-sectional	90 exposed vs 129 unexposed adults	Higher prevalence of rheumatic diseases, lupus, neurological symptoms, respiratory symptoms, and cardiovascular problems	Effect	Good
Kudabayeva et al.	2014	Kazhakstan	Cross-sectional	368 exposed children vs 447 unexposed	Higher prevalence of goiter in children ages 7-11 living in oil-producing regions	Effect	Fair
Dey et al.	2015	India	Cross-sectional	46 exposed vs 61 control participants	Higher levels of respirable PM and NO ₂ associated with long-term liver injury in exposed group	Effect	Good
Kponee et al.	2015	Nigeria	Cross-sectional	100 exposed vs 100 unexposed adults	Increased reports of neurological and hematological health problems among exposed residents	Effect	Good
Ogbija et al.	2015	Nigeria	Cross-sectional	373 participants living in oil-producing communities	Household survey to assess perception of environmental degradation and enumerate cases of diarrhea, asthma, skin infection and bronchitis.	---	Inadequate
Webb et al.	2016	Peru	Cross-sectional	76 participants (ages 15 and older)	No significant increase in mercury levels in urine in populations living near oil extraction sites.	No effect	Fair
Yermukhanov a et al.	2017	Kazhakstan	Cross-sectional	424 participants with immunodeficiency	Decrease prevalence of immunodeficiency	Effect	Fair

Author(s)	Year	Country	Study Design	Study Population and Sample Size (n)	Findings	Health Effect	Quality
				syndrome (stages 2 and 3)	decreased with increasing distance from oil fields		
<i>Occupational Health Studies</i>							
Esswein et al.	2013	United States	Cross-sectional	111 personal breathing zone samples from workers in 5 states	Silica levels of hydraulic fracturing oil workers were ~10 times higher than recommended levels	Effect	Good
Gun et al.	2004	Australia	Cohort	708 Australian petroleum industry employee deaths of 17,165 persons, 1981-96	No significant increase in cancer mortality among cohort of workers in petroleum industry	No effect	Good
Kilburn	1993	United States	Case Study	24-year old oil well tester exposed to 14,000 ppm hydrogen sulfide gas	Persistent and severe neurobehavioral symptoms after acute hydrogen sulfide gas exposure	Effect	Fair
Mousa	2015	Not Specified	Observational	34 male patients (ages 22-60) attending an oil field clinic, 2012-13	Oil field workers exposed to subchronic low levels of hydrogen sulfide reported upper respiratory tract bleeding	Effect	Inadequate
Paz-y-Miño et al.	2008	Ecuador	Cross-sectional	46 oil workers exposed to hydrocarbons vs 46 non-exposed	Increased risk of mutagenic and carcinogenic damage and increased symptoms of common illnesses among individuals exposed to petroleum hydrocarbons	Effect	Fair
<i>Community Risk Perception</i>							
Baptiste and Nordenstam	2009	Trinidad and Tobago	Cross-sectional	177 residents from 3 villages between, June to August 2006	Residents living closer to the drilling site had greater health and environmental concerns	Effect	Fair
Okoli	2006	Nigeria	Cross-sectional	42 rural participants	Rural communities affected by environmental degradation, pollution, job displacement and health concerns	Effect	Inadequate

Table 2.

Summary of animal biomonitoring, toxicological studies on health outcomes from exposures associated with oil drilling

Author(s)	Year	Country	Study Population	Findings	Health Effect	Quality
<i>Animal Biomonitoring Studies</i>						
Al-Hashem et al.	2007	Kuwait	<i>A. scutallatus</i> lizards	Higher numbers of cells with cytoplasmic degeneration and dead cells among lizards living in oil-extraction region	Effect	Inadequate
Al-Hashem and Mona	2011	Kuwait	<i>A. scutallatus</i> lizards	Greater hepatotoxicity among adults (particularly males) exposed to oil pollution	Effect	Inadequate
Bamberger and Oswald	2015	United States	Companion and food animals	No significant changes to health of animals living within 2 miles of oil/gas well after 15-34 months	No effect	Fair
Bustamante et al.	2015	Colombia	Cattle	Excess lead and cadmium levels in liver, kidney and muscle of cattle near oil extraction sites represents a human health risk	Effect	Fair
Miedico et al.	2016	Italy	Cows and sheep	Bovine and ovine liver samples collected near oil wells showed accumulation of 18 heavy metals	Effect	Fair
<i>Toxicological Studies</i>						
Odeigah et al.	1997	Nigeria	Onion (<i>A. cepa</i>)	Increasing concentrations of oil field waste water led to decreased root length and mitotic index, and increased morphological deformations	Effect	Fair
Wernerss on	2004	Ecuador	Aquatic ecotoxicity	Acute water toxicity at all sites was not significantly high	No effect	Fair
Akani and Obire	2014	Nigeria	African catfish (<i>C. gariepinus</i>)	Exposure to sub-lethal concentrations of oil field wastewater led to increased bacterial concentrations in skin, intestine, and gill tissues	Effect	Fair
Kassotis et al.	2015	United States	Male C57BL/6J mice	Prenatal exposure to hydraulic fracturing chemicals caused decreased reproductive health and increased body weight, heart size, thymus size, and serum testosterone	Effect	Good
Abdullah et al.	2016	United States	Drilling fluids	Identified 28 different chemicals used for acidization known to be toxins	Effect	Good
Kassotis et al.	2016	United States	Female C57Bl/6 mice	Prenatal exposure to hydraulic fracturing chemicals caused increased pituitary hormone levels and body weight and decreased reproductive health	Effect	Good

Table 3.

Summary of literature on environment exposures associated with oil drilling

Author(s)	Year	Country	Exposure	Findings	Quality
Abdul-Wahab et al.	2012	Oman	Air	Short-term levels of hydrogen sulfide gas from flaring exceeded acceptable standard	Fair
Macey et al.	2014	United States	Air	VOCs present near oil/gas drilling sites at levels above federal guidelines, concern to resident and worker health	Good
Novikova et al.	2014	Tatarstan Republic	Air	Significant correlation between pollutants in ambient air and number of diseases found in exposed population, suggesting delayed and cumulative effects of exposure	Poor
Spitz et al.	1997	United States	Drilling waste	Significantly higher levels of radium and other hazardous waste in former sludge pond and waste pit areas	Fair
Shadizadeh and Zoveidavianpoor	2010	Iran	Drilling waste	Heavy metal concentrations of reserve mud pit samples exceeded ACGIH standards	Fair
Hrichi et al.	2013	Tunisia	Drilling waste	Mean radium levels of oil fields above maximum safe standards	Fair
Rajaretnam and Spitz	2000	United States	Soil	About 1.3% of radium-226 in contaminated soil was found to leach into the environment	Good
Bojes and Pope	2007	United States	Soil	12-46% of total PAHs in soil near oil sites comprised of possible carcinogens, exceeding regulatory standards	Good
Jibiri and Amakom	2010	Nigeria	Soil	All radiation detected in crude oil sedimentation tank found to be derived from naturally occurring radionuclides	Fair
Kuang et al.	2011	China	Soil	Higher concentrations of PAH found with decreasing distance from the source of the oily sludge	Fair
Agbalagba et al.	2012	Nigeria	Soil	Radioactivity of oil field samples within allowable limits	Fair
Teng et al.	2013	China	Soil	Significantly higher concentrations of TPH in the oil field due to spills or leaks	Good
Fu et al.	2014	China	Soil	Cadmium is the most common, easily changing/mobile, and potentially harmful heavy metal found in oil-polluted soils	Good
Jie et al.	2015	China	Soil	Napthenic acid levels of oil fields exceeded ecotoxic levels	Fair
Wang et al.	2015	China	Soil	Varying concentrations of carcinogenic PAHs in soil from oil fields, low cancer risk	Fair
Ajayi and Dike	2016	Nigeria	Soil	Higher risk for radiation exposure near active crude oil exploration, but levels are within permissible limits	Fair
Alawi and Azeez	2016	Iraq	Soil	Cancer risk for all sites within acceptable levels specified by US EPA	Fair
Olobaniyi and Omo-Irabor	2016	Nigeria	Soil	Neutral pH, low TOC, highly variable TPH, and slightly elevated levels of nickel in soil	Poor
Zhang et al.	2013	China	Soil	Level of PAH concentrations higher near the oil wells, presents risk of cancer	Fair
Asia et al.	2007	Nigeria	Soil and water	High levels of heavy metals detected in soil and water samples, some above natural levels	Fair
An et al.	2005	United States	Water	Groundwater under oil production sites higher in chloride, sodium, salinity, and conductivity	Fair

Author(s)	Year	Country	Exposure	Findings	Quality
Moskovchenko et al.	2009	Russia	Water	Elevated concentrations of chloride, salinity, and total petroleum hydrocarbons	Fair
Alonso et al.	2010	Bolivia	Water	Contamination concentrations exceeded regulations in 76.19% of samples; contaminants included TPH, PAH, As, Mn and Fe	Fair
Ma et al.	2011	China	Water	Surface and groundwater quality severely impacted by pollution from petroleum drilling	Fair
Teng et al.	2013	China	Water	Higher TPH levels in aquifer near oil field from oil exploitation, transportation, and temporary storage	Good
Li and Carlson	2014	United States	Water	Methane in drinking water but not strongly associated with proximity to extraction sites	Good
Moquet et al.	2014	Peru	Water	Oil extraction activity significantly impacts concentrations of dissolved Na and Cl of the Amazon basin	Fair
Lauer et al.	2016	United States	Water	Occurrence of spills is strongly associated with oil well density, spill water violates regulations contaminant levels	Good
Li et al.	2016	United States	Water	No aqueous phase contamination of groundwater detected	Fair
Cozzarelli et al.	2017	United States	Water	Water Persistent pollution from oil/gas wastewater spill despite remediation efforts	Good