Polycyclic Aromatic Hydrocarbon (PAH) Pollution and its Associated Human Health Risks in the Niger Delta Region of Nigeria: A Systematic Review

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Abstract

The frequent incidents of oil spills and other forms of pollution arising from crude oil exploration and exploitation (OEE) in the Niger Delta have caused several investigations on Polycyclic Aromatic Hydrocarbons (PAHs) pollution. This study aimed at developing a comprehensive report on PAH pollution and its human health risks recorded in the Niger Delta. Studies were extracted from Google Scholar, PubMed, and ResearchGate using a defined selection criterion. The quality of each study was assessed using the Newcastle – Ottawa Scale. Thirty-eight studies were selected with the majority reporting on PAH pollution in aquatic environments. Across all the selected studies, the total number of PAHs recorded ranged from 7 to 28 PAH congeners. Also, PAH potential sources reported in the studies were of pyrogenic and petrogenic sources. PAH concentrations recorded in water, sediment, aquatic organisms (fish and shrimp), soil, dust, and crop samples ranged from below detection limit (BDL) to 450 ± 117.9 mg/L, BDL to 1821.5 mg/kg, 0.005 to 1.098 mg/kg, ND to 4154 ± 3461 mg/kg, 165.1 to 1012 mg/kg, and 0.020 to 3.37 mg/kg, respectively. Majority of the selected studies reported PAH levels which were higher than the permissible limits. Incremental Lifetime Cancer Risk (ILCR) assessment of PAHs in samples ranged from low to high via ingestion and dermal routes of exposure to humans. It is recommended that the Federal Government of Nigeria promotes environmentally friendly operations of OEE. Future studies should focus on PAH pollution in farmlands, ambient air and the associated human and ecological health risks.

Keywords: Oil exploration and exploitation, Gas flaring, Environmental pollution, PAH sources, Incremental lifetime cancer risk

Highlights

- The Niger Delta is one of the most polluted regions on earth with high international recognition.

- Most PAH records in its aquatic and terrestrial environments are higher than permissible limits.

- PAH pollution poses low to high cancer risks to humans via ingestion and dermal exposure routes.

1.0 Introduction

Nigeria is known to be the leading producer of oil across the African continent since 2019 with a production amount of 101.4 million metric tonnes (Faria 2020) which occurs in the Niger Delta. The country also holds the eleventh position of the top crude oil-producing countries in the world (Nriagu et al. 2016). Nigeria's Niger Delta is identified as the largest delta in Africa, which is also listed as the third-largest delta in the world (Obida et al. 2018). The Niger Delta is situated in southern Nigeria with its main water source being the River Niger, which also originates from the central part of Nigeria. As part of ten major marine and wetland ecosystems in the world, the Niger Delta is known to possess several creeks, lakes, rivers, estuaries, mangrove ecosystems, forests, and other ecological features (Obida et al. 2018). There are also human settlements in the Niger Delta including states, metropolis, cities, and local government areas (LGAs) (Ofori et al. 2020a).

The Niger Delta is identified as the main region noted for the production of oil and gas in Nigeria (Fig. 1). The exploration of oil in the Niger Delta commenced in the year 1956 when the first oil well was drilled at Oloibiri (Sojinu et al. 2010). Oil exploration and exploitation (OEE) operations currently occur in more than 50% of Niger Delta's total area (Nriagu et al. 2016). These operations which generate major foreign exchange and revenue for the country, have led to a profusion of access roads, oil pipelines, oil wells, gas flaring, wastes generated from dredging, and flow stations that are commonly found close to homesteads, schools, and farms within or close to hosting communities (Nriagu et al. 2016).

Fig. 1 here

It is common to find oil spill sites in the Niger Delta where in most cases are reported to be caused by multinational oil companies (MNOCs) involved in major OEE operations and vandalism of oil pipelines occurring in the region (Amnesty International 2018). Oil spills that occurred in the Niger Delta during the last five decades are estimated to be over two billion litres of oil (Agbonifo 2016). This implies that in each of these years, about 40 million litres of oil were released into the Niger Delta environment area through incidences of oil spills (Agbonifo 2016). Besides, natural gas which is a by-product of petroleum production is also frequently flared into the atmosphere (Ite and Ibok 2013), contributing greatly to the pollution levels in the region. Subsequently, the Niger Delta is identified in the list of the top five oil-polluted regions in the world (Obida et al. 2018; Amnesty International 2018).

The operations related to the exploration and exploitation of oil in the Niger Delta are indicated as those that pose significant negative impacts on the natural environment and society (Ite et al. 2013). These negative impacts

include: (i) atmospheric pollution related to the burning and venting of natural gas (Ite et al. 2013); (ii) marine ecosystem pollution resulting in negative impacts on biota, and indirect impacts on tourism, fisheries and other livelihoods of the host communities (Iniaghe et al. 2013; Osuagwu and Olaifa 2018); (iii) surface and groundwater pollution (Ite et al. 2018); (iv) introduction of socio-economic issues and degradation of the cultural values and resources of host communities (Iniaghe et al. 2013); (v) degradation of lands, issues of food quality and decline in agricultural activities (Inoni et al. 2006); and vi) increased cases of disease symptoms and environmental distress (Nriagu et al. 2016).

The pollution events occurring as a result of the OEE operations in the Niger Delta have led to the release of harmful chemicals such as Total Petroleum Hydrocarbons (TPHs), Polycyclic Aromatic Hydrocarbons (PAHs), heavy metals, and other persistent organic pollutants into its terrestrial and aquatic environments. This situation has largely presented environmental and human health issues of global concern (Emoyan et al. 2008a, b; United Nations Environment Programme 2011).

Aside from the OEE operations, which are considered as the major sources of pollution in the Niger Delta, there has been an increase in the number of allied industries and other anthropogenic activities. These include the production of chemical fertilisers, processing of rubber and asphalt, and activities of landfill sites, petrochemical industries, power stations, urbanisation, among others. These activities together with the OEE operations have greatly promoted several studies on the increased levels of PAH pollution in the Niger Delta since the year 2005 (Abbas and Brack 2005; Inam et al. 2015; Dosunmu et al. 2016; Ofori et al. 2020a).

PAHs are described as a group of organic compounds which are formed and released into the natural environment during incomplete combustion of organic materials such as crude oil, coal, wood, and even smaller organic molecules such as methane (Russell 2013; Ofori et al. 2020a, b). PAHs are frequently present across various components of the natural environment (soil, air, water, biota) with their traces also recorded in different food items. Hence, they are classified as ubiquitous chemicals in the environment (Ofori et al. 2020a, b). There are over 100 PAH congeners (including parent PAHs and alkylated derivatives) identified in the environment. The United States Environmental Protection Agency (USEPA 2014) has, however, indicated 16 of them as priority pollutants under its Clean Water Act (1977) due to the possible risks they pose to human and ecological health. They are chrysene, acenaphthylene, acenaphthene, phenanthrene, anthracene, fluoranthene, fluorene, pyrene, naphthalene, benzo[*b*]fluoranthene, benzo[*k*]fluoranthene, benzo[*a*]pyrene, benzo[*a*]anthracene, dibenz[*a,h*]anthracene, benzo[*g,h,i*]perylene, and indeno[*1,2,3-cd*]pyrene (USEPA 2014). The European

Commission (EC 2013) however includes eight (naphthalene, benzo[*b*]fluoranthene, benzo[*k*]fluoranthene, benzo[*a*]pyrene, anthracene, fluoranthene, indeno[*1,2,3-cd*]pyrene, and benzo[*g,h,i*]perylene) of these PAH congeners as priority substances under its Water Framework Directive.

The properties of PAHs are determined by the number of benzene rings and their molecular mass (Stogiannidis and Laane 2015). PAH congeners that possess four or more benzene rings are described as high molecular weight (HMW) PAHs, while congeners with two or three benzene rings are described as low molecular weight (LMW). For instance, anthracene, phenanthrene, naphthalene, fluorene, which possess less than four benzene rings are categorised as LMW PAHs, whereas benzo[*a*]pyrene, benz[*a*]anthracene, pyrene, chrysene, and indeno[*1,2,3-cd*]pyrene with four or more benzene rings are described as HMW PAHs (Stogiannidis and Laane 2015; Ofori et al. 2020a, b). Benzo(*a*)pyrene [B(a)P], a well-known PAH congener, is used to represent PAHs as it is considered by the International Agency for Research on Cancer (IARC) as a known carcinogen, implying its harmful effects on human and animal health (IARC 2016). Also, since PAHs are commonly occurring in the environment as mixtures, an identification of B(a)P in a sample or product can be used to describe the existence of other PAHs (German Federal Environment Agency 2012).

In aquatic environments, sediments and aquatic organisms are mostly described as the eventual sinks of PAHs (Mekonnen et al. 2015). Since PAHs are lipophilic with high chemical stability, they can find their way into organs of aquatic organisms such as fish and molluscs through their ingestion of PAH-polluted organic matter or dermal contact with sediments polluted with PAHs, thereby accumulating in their fatty tissues. Fish and molluscs are therefore used as suitable indicators of PAH pollution in aquatic environments (Nyarko et al. 2011; Ofori et al. 2020a).

In terrestrial environments, cities and communities with increasing growth in the human population and urbanisation are reported to also experience an increase in vehicular traffic and industries resulting in a high degree of PAH pollution in the environment (Safo-Adu et al. 2014; Chen et al. 2017). Moreover, vehicles without proper maintenance are generally identified to release increased levels of especially HMW PAHs through exhaust fumes which readily adsorb onto soil particles (Obiri et al. 2011).

The widespread characteristic of PAHs and their ability to cause cancer or toxic effects on living organisms in the environment constitute a significant risk to human health. The release of PAHs can result in their uptake into the body of humans and other mammals through ingestion of contaminated food or water, inhalation of polluted air, and dermal contact with polluted soil. The toxic effects that may occur as a result of public exposure to PAHs are

short- and long-term health effects, which are commonly associated with breathing and cardiovascular disorders (Błaszczyk et al. 2016; Ofori et al. 2020b).

Due to the high levels of PAH pollution occurring in the Niger Delta and their associated health risks, several studies have been conducted by collecting samples from different environments of the Niger Delta. Most of these environments include rivers, creeks, dumpsites, OEE sites, automobile repair shops, agricultural farms, and other urban areas (Abbas and Brack 2005; Ana et al. 2009; Sojinu et al. 2010; Nganje et al. 2011; Olawoyin et al. 2012; Oyo-Ita et al. 2012; Adedosu et al. 2012; Osuji et al. 2012; Nduka et al. 2013; Nganje et al. 2014; Ogoko 2014; Asagbra et al. 2015; Inam et al. 2015; Nwineewii and Marcus 2015; Davies and Abolude 2016; Dosunmu et al. 2016; Nwaichi et al. 2016; Iwegbue et al. 2016; Ekanem et al. 2019; Ihuoma et al. 2020).

It is commendable to see that several studies have addressed PAH pollution in the Niger Delta, however, these studies are isolated. This situation limits the ease of access and use of these studies by the public and even the scientific community, and further breeds a lack of general understanding of PAH pollution in the Niger Delta. It is, therefore, timely and important to address the above issues through a systematic review. The current study serves as a comprehensive report on the degree of PAH pollution in the Niger Delta and its associated human health risks. It also critically reviews the quality of data presented by the various selected studies, and also provides recommendations necessary for tackling this environmental issue in the Niger Delta.

2.0 Methods

2.1 Criteria for Search and Selection of PAH-related Studies

The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) methodology developed by Moher et al. (2009) was used in the preparation of this systematic review (Fig. 2). The search for studies and their selection took place from February to September 2020 using the databases: Google Scholar, PubMed and ResearchGate. The search and selection process extracted studies that have been published from 2005 to 2020. The keywords used in the search process were: "PAHs or Polycyclic Aromatic Hydrocarbons in Niger Delta, Nigeria".

Based on the different studies that were extracted from the databases, the following categories of studies were used to aid in the selection process: PAHs in aquatic environments, PAHs in dust and soil, and PAHs in crops. TheThe extracted studies were then assessed for relevance or not. Studies that only looked at bioremediation and

other management strategies of PAHs were not considered relevant since such studies did not present the objective of assessing the concentrations of PAHs in samples. Concerning studies that were published twice, researchers decided to choose the one that was most recently published with adequate information on identified PAHs (Fig. 2).

Fig. 2 here

2.2 Data Extraction and Quality Assessment

After suitable studies were selected, a set of information describing each study was extracted: authors, year of publication, aim of study, area of study, period of sampling, type(s) and number of samples collected, analytical technique, number and concentrations of PAHs identified, and potential sources of PAH pollution in the study area.

The quality process was conducted then by adapting the Newcastle–Ottawa Scale (NOS) developed by Wells et al. (2009) to suit the scope of this study. A set of eight signalling questions were used to provide an overall quality score for each study that was selected (Table 1). The signalling questions inquired whether selected studies reported on period of sampling, control samples, sampling technique, clean-up process, QA/QC methods, all objectives achieved, PAH sources, and mean PAH levels. For each signalling question, a "Yes" or "No" response was given on behalf of each of the selected studies.

3.0 Results

3.1 Study Selection and Quality Assessment

The criteria employed in selecting and excluding the extracted studies is summarised using an adapted PRISMA flow diagram (Fig. 2). The number of studies that were extracted was 59 in total. Among these, 38 studies were selected as suitable for this analysis while the remaining 21 were excluded. Among the 21 studies that were excluded, three were duplicate studies, while nine were found to be unrelated to this work after their abstracts were reviewed. The remaining nine studies were also excluded since they did not meet the criteria used in selecting suitable studies.

The results of the signalling questions used in assessing the quality of the selected studies are presented in Table 1 and Fig. 3. Table 1 provides the individual scores for each study that was selected, while Fig. 3 presents the percentage of selected studies that responded with a "Yes" or a "No" to each of the signalling questions. The majority of the selected studies responded a "Yes" to six of the signalling questions: i.e., period of sampling indicated, clean-up process conducted, QA/QC conducted, all objectives achieved, reports on PAH sources, and reports on mean PAH levels (Fig. 3). However, considering the individual scores of the selected studies, ten studies answered "Yes" to 6-7 out of the 8 signalling questions (i.e., scoring 5/8 - 7/8), while 28 studies answered "Yes" to 2-5 out of the 8 signalling questions (i.e., scoring 2/8 - 5/8).

Table 1 and Fig. 3 here

3.2 Sources and Levels of PAHs in the Niger Delta

3.2.1 PAHs in Aquatic Environments

Results of selected studies that reported on PAH pollution in different aquatic environments are provided in Table 2. The USEPA under the National Primary Drinking Water Act sets a legally permissible limit on the level of benzo[*a*]pyrene in drinking water to be 0.002 mg/L (USEPA 2009). The Agency for Toxic Substances and Disease Registry (ATSDR) sets a permissible range limit on the level of PAHs occurring in surface water samples to be 0.004 to 0.024 mg/L (ATSDR 1995). The EC (2006) has also established a permissible limit for the levels of benzo[*a*]pyrene and the sum of 4 PAHs present in fresh molluscs to be 0.005 mg/kg and 0.030 mg/kg, respectively. For fresh fish samples, a permissible limit of 0.002 mg/kg of benzo[*a*]pyrene was implemented (EC 2006). Out of the 20 studies that reported on PAH pollution in aquatic environments (water, fish, and shrimps), 19 of them recorded PAH concentrations which were higher than the permissible limits provided by USEPA (2009), ATSDR (1995) and the EC (2006) (Fig. 4).

Table 2 here

3.2.2 PAHs in Dust and Soil

Table 3 provides a summary of the selected studies that reported on PAH pollution in dust and soil samples in the Niger Delta. The Federal Soil Protection and Contaminated Sites Ordinance (FSPCSO 1998) of Germany introduced a precautionary value for benzo[*a*]pyrene in agricultural soils to be 1 mg/kg (GFEA 2012). For urban

area soils (commercial, industrial, and recreational facilities), a test value range of 10 - 12 mg/kg for benzo[*a*]pyrene is used as a basis for controlling pollution of urban soils (GFEA 2012). Out of the 18 studies that reported on PAH pollution in dust and soil samples, 10 of them recorded PAH concentrations which were higher than the permissible limits provided by the FSPCSO (1998) (Fig. 4).

Table 3 here

3.2.3 PAHs in Crops

The results of studies reporting on PAH levels in crops collected from agricultural lands located nearby oil exploration sites are provided in Table 4. The European Commission (EC) under the Regulation No. 1881/2006 (EC 2006) implemented a permissible limit of 0.001 mg/kg for PAH contamination in ready-to-eat food items (European Food Safety Authority 2008). All three studies which reported on PAH contamination in crops recorded PAH concentrations which were higher than the permissible limits provided by the EU (Fig. 4).

Table 4 and Fig. 4 here

3.3 Human Health Risk Assessment of PAH Pollution in the Niger Delta

Among the several PAHs identified in the environment, the 16 USEPA PAHs indicated by the USEPA as priority pollutants have been used in several studies for assessing human health risks of PAH exposure in samples. Since PAHs are ubiquitous, the models used in human health risk assessments pay attention to the major pathways (ingestion, inhalation, and dermal contact) through which PAHs get into the human body.

Most studies report on either one or both of non-carcinogenic (toxic) and carcinogenic risks of PAHs on human health. For carcinogenicity risks of PAHs on human health, it is common to find that majority of studies use the Incremental Lifetime Cancer Risk (ILCR) model developed by the USEPA in 1991 (Ofori et al. 2020a). The model depends on some factors such as type of sample, pathways of exposure, concentrations of individual PAHs, carcinogenic equivalents, particle emission factor, exposure duration, exposure frequency, dermal adherence factor, slope factor, ingestion rate, inhalation rate, average lifetime, body weight, and age of the individual, among others (Yang et al. 2015; Ofori et al. 2020b). The USEPA defines an ILCR guideline range between 10^{-6} and 10^{-4} to be indicative of potential risk (Ofori et al. 2020a).

Studies that focus on non-carcinogenic effects of PAH exposure to human health make use of hazard quotient (HQ) and hazard index (HI) which depends on the estimated/chronic daily intake (EDI or CDI) and reference dose (RfD) of PAHs in samples. The EDI or CDI employs most of the factors used in the ILCR except the slope factor. When the HI, which is the summation of individual HQs, is greater than one, it indicates a potential non-carcinogenic human health risk (Inam et al. 2015; Tongo et al. 2017). The results of carcinogenic (ILCR) and non-carcinogenic (HI) risks of PAH exposure to human health reported in the selected studies are recorded in Table 5.

Table 5 here

4.0 Discussion

4.1 Summary of Major Findings

The current study presents a systematic review of a total of 38 selected studies conducted on the occurrence of PAH pollution in the Niger Delta. All selected studies reported varying levels of PAHs in samples. Most of the studies went further to assess the potential sources of PAHs identified in the collected samples. Generally, the total number of PAH congeners identified in samples across all studies ranged from seven to 28. Twenty-five studies out of the 38 that were selected reported on the 16 USEPA PAHs recorded in aquatic environments, dust and soil and crops, making the 16 USEPA PAHs the most identified set of PAHs present in the Niger Delta (Fig. 5).

Fig. 5 here

The majority (53%) of selected studies reported on PAH pollution occurring in aquatic environments such as rivers, creeks, lakes, and estuaries. The samples collected in the studies included water, sediments, fish and shrimps. For water and sediment samples, studies reported levels of PAHs ranging from BDL to 450 ± 117.9 mg/L and BDL to 1821.5 mg/kg, respectively. PAH concentrations recorded for fish and shrimps ranged from 0.005 to 0.1098 mg/kg across the selected studies.

Considering studies conducted on PAH pollution occurring in dust and soil samples collected from various regions of the Niger Delta, 18 (including 3 already reported studies in the category of aquatic environments) out of the 38 studies were identified. The majority of the studies focused on PAH pollution occurring in soil samples collected from oil spill sites, leaking pipelines, and polluted farm/forest lands. The total PAH concentrations recorded across these sampling sites ranged from ND to 4154 ± 3461 mg/kg. Out of the 38 selected studies, three reported on PAH

contamination occurring in crops (cassava tubers, African oil bean, and mushrooms) harvested from farmlands located within areas with reported incidences of oil spills or pipeline leakages. The total PAH concentrations recorded ranged from 0.020 to 3.37 mg/kg.

The use of PAH isomeric/molecular ratios and other methods (like Principal Component Analysis, cross plots, and the percentage of LMW and HMW PAHs) by the various studies in assessing the potential sources of PAHs in the aquatic environments and dust and soil samples showed that the major sources of the PAH pollution were of petrogenic (petroleum) and pyrogenic (combustion) origins. Studies conducted on PAH contamination in crops did not report on the potential sources of PAHs in samples. Petrogenic sources included incidences of oil spills and oil pipeline leakages arising from either OEE operations, inland port and harbour activities, and vandalising and illegal bunkering of crude oil. For pyrogenic sources, the flaring of natural gas associated with crude oil was implicated as the major contributor.

Eight of the selected studies conducted a human health risk assessment of PAH pollution in samples for both children and adult populations. Out of the 8 studies, five used soil and/or dust, two used water, sediment, and fish samples, and one used mushrooms, as samples. Only three of the eight studies reported on both carcinogenic and non-carcinogenic risks of PAH pollution to human health (Table 5). Considering non-carcinogenic risks, 2 studies recorded an HI which was less than one. For carcinogenic risks, the range of ILCR via the inhalation pathway of exposure for children and adult populations across all the studies was from 8.79×10^{-15} to 2.17×10^{-8} and from 3.53×10^{-14} to 2.39×10^{-8}, respectively. For dermal pathway of exposure, the ILCR recorded for children and adult populations across all the studies ranged from 8.19×10^{-12} to 8.9×10^{-2} and from 7.28×10^{-6} to 8.74×10^{-3}, respectively. The range of ILCR via the ingestion exposure pathway recorded for children and adult populations across the studies were from 3.16×10^{-7} to 3.54×10^{-2} and from 4.35×10^{-11} to 1.69×10^{-2}.

In reference to the ILCR guideline (10^{-6} to 10^{-4}) defined by the USEPA (1991), it can be deduced that PAH exposure via inhalation as recorded across the eight selected studies does not present any carcinogenic risks. However, considering ingestion and dermal contact as pathways of PAH exposure, the recorded ILCRs in most of the selected studies presented low to high carcinogenic risks (Table 5).

4.2 Discussion of Major Findings

In assessing the quality of studies using the Newcastle – Ottawa Scale (NOS), limitations of the studies mainly resulted from the sampling technique, the analytical techniques and reported results (Table 1 and Fig. 3). It was

found that about 42% of the selected studies during their sampling process only collected single samples instead of duplicates or triplicates from each sampling point. Using a single sample per sampling point does not provide representative information of the PAH pollution occurring at a sampling point (Zhang 2006). In this way, such studies could not provide mean values of the total concentration of PAHs identified in collected samples. Moreover, some studies did not provide comprehensive information on how the sampling process was undertaken. For instance, about 50% of the selected studies did not state how long sampling lasted. Moreover, about 74% of the selected studies did not include control samples in their sampling process. Sixty-six per cent of the selected studies did not indicate the type of sampling technique that was employed in their sampling process. All of these brings about the lack of power to find significance in reported PAH concentrations in samples (Zhang 2006).

It was found that about 79% of the selected studies conducted a clean-up process for sample extracts before PAH analysis. A clean-up process on sample extracts helps to remove co-extractives or unwanted particles which may cause changes in the actual concentrations of the identified PAHs in the samples (Zhang 2006). Also, about 42% of the selected studies did not conduct QA/QC measures during sample analysis. QA/QC measures are known to be relevant in promoting the accuracy and precision of studies, and thus, renders studies without it untrusted (Zhang 2006). The use of PAH isomeric ratios and multivariate analysis for the assessment of PAH sources in samples are useful in understanding the occurrence and levels of PAHs in the environment. About 61% of the selected studies reported the potential sources of PAHs in collected samples.

To assess the degree of PAH pollution occurring in the selected studies, the recorded range of PAH concentrations for each of the sample categories reported in this study were compared to regulatory limits provided by different governmental organisations (Fig. 4). Considering water samples, the recorded range of PAH concentrations (BDL to 450 ± 117.9 mg/L) was about 15,000 times higher than the permissible limit (0.004 to 0.024 mg/kg) indicated by the ATSDR (1995). For fish and shrimp samples, the recorded range of PAH concentrations (0.005 to 0.1098 mg/kg) was 1000 times higher than the permissible limits set by the EC for benzo[a]pyrene and 4 PAHs in fish and molluscs samples. For dust and soil samples, the range of PAH concentrations (ND to 4154 ± 3461 mg/kg) recorded in this study was over 300 times higher than the permissible limits (10 - 12 mg/kg) defined by the FSPCSO (1998). Lastly, the range of PAH concentrations in crops (0.020 to 3.37 mg/kg) reported in this study was over 3000 times higher than the permissible limit (0.001 mg/kg) defined by the EC (2006) for PAH contamination in ready-to-eat food items.

The outcomes of the comparisons conducted for the levels of PAHs in each of the sample categories with the permissible limits defined by the governmental organisations reveals that there is a high degree of PAH pollution occurring in the Niger Delta. The human health risk assessment conducted by some of the selected studies also revealed that the public was exposed to low to high cancer risks via dermal and ingestion pathways of exposure (Table 5). This implies that the continual exposure of high PAH levels experienced by individuals located in the Niger Delta has the potential to lead to toxicological and carcinogenic effects on their health.

4.3 Limitations of Study

There were only three categories from which this systematic review of the selected studies was prepared. They included PAHs in aquatic environments, PAHs in dust and soil, and PAHs in crops. Researchers were not able to identify any PAH-related study in the Niger Delta that focused on PAH pollution occurring in other sample categories such as indoor/outdoor air and ready-to-eat food items. Such studies were not available in the databases searched. Out of the 38 selected studies, 20 were in the category of PAHs in aquatic environments, 15 in the category of PAHs in dust and soil, and three in the category of PAHs in crops. The few numbers of studies recorded under the category of PAHs in crops makes it inefficient to provide a general idea of PAH levels present in crops cultivated in the Niger Delta.

Considering the number of PAH congeners reported by the selected studies, the majority (25 out of 38) identified the 16 USEPA PAHs (USEPA 2014) in their samples, with the remaining focusing on other groups of PAHs. The 16 USEPA PAHs are identified as the most reported PAHs across different studies in the world. This is a result of their potential to present toxic and carcinogenic effects on living organisms, persistence in the environment, and the ease of analysing and identifying them in samples (Hussar et al. 2012; Andersson and Achten 2015a). However, as relevant as the 16 USEPA PAHs may be, many researchers in the ecotoxicology of Polycyclic Aromatic Compounds (PACs) have pointed out that focusing only on the 16 USEPA PAHs may limit our ability to adequately assess and comprehensively describe the fate and behaviour of PAHs in different components of the environment (Andersson and Achten 2015a). Considering then this remark by Andersson and Achten (2015b), it is relevant to point out that the majority of the selected studies in this systematic review may have missed out on providing sufficient data on the issue of PAH pollution in the Niger Delta.

Most of the results of total PAHs concentrations recorded in samples were reported in diverse measuring units. For instance, studies which recorded PAHs in soil or sediment samples reported the total concentrations in either

ng/g or mg/kg or µg/kg, and studies which recorded PAHs in water samples reported them in either mg/L or ng/L or µg/L. These differences in units of measurements make the extensive comparison between studies less efficient as readers would have to make conversions of recorded values beforehand. It is also key to indicate since a high number (42%) of the selected studies did not follow QA/QC protocols during sample analysis, their results may be rendered less reliable.

The assessment of the potential sources of PAHs recorded in samples were conducted using different indices of PAH source identification which included PAH diagnostic/isomeric ratios, Principal Component Analysis, and the predominance of either LMW or HMW PAHs. PAH isomeric ratios or the predominance of LMW/HMW PAHs are proven to be simple methods for assessing the potential sources of PAHs. However, PAH ratios do change remarkably from the source of pollution to the environmental media under study through existing differences in water solubility and volatility between two PAHs of the same molecular weight, thus making the identified sources less accurate (Biache et al. 2014; Wang et al. 2016). This situation is also common with the use of LMW/HMW PAH diagnostic ratios, as LMW PAHs are known to be very unstable due to the influence of environmental factors such as photodegradation and volatilization, making them highly affected by flow mechanisms in the aquatic environment (Adeniji et al. 2017). These factors, therefore, make the PAH sources identified by studies which used PAH diagnostic ratios less robust.

Moreover, each of the selected studies presented different techniques in sample extraction, sample clean-up and PAH analysis in sample extracts. Sample extraction methods used by the different selected studies included: Accelerated Solvent Extraction, Ultrasonication Extraction, Microwave Extraction, Liquid to Liquid Extraction, and Soxhlet Extraction, among others. The methods used for PAH analysis included: Gas Chromatography – with Flame-Ionization Detection (GC-FID) and Gas Chromatography-Mass Spectrometry (GC-MS). Each of these methods operates differently with distinct levels of accuracy. For instance, ultrasonication extraction is a quick extraction method, however, its efficiency is typically low when used for studies which require a high extraction efficiency of samples with a very low concentration of PAHs (Wang et al. 2016).

5.0 Conclusions

This study reports on relevant information on the occurrence, concentrations, sources and associated potential human health risks of PAHs in the Niger Delta using reported results from selected studies. Majority of the selected studies reported PAH pollution occurring in water, sediments, fish and shrimp samples from the aquatic

environment of the Niger Delta. The PAHs identified in samples from the aquatic environments were of both petrogenic and pyrogenic sources. Moreover, higher concentrations of PAHs recorded across the sample categories were above the permissible limits indicated by governmental organisations. The studies which reported on ILCR of PAHs in samples recorded low to high cancer risks via ingestion and dermal routes of exposure. This indicates the urgency needed by the Federal Government of Nigeria in collaboration with the National Oil Spill Detection and Response Agency (NOSDRA), the Niger Delta Development Commission (NDDC), Department of Petroleum Resources (DPR), Nigerian Federal and States' Ministry of Environment, and other NGOs involved in environmental conservation to pay adequate attention to the pollution arising from OEE operations in the Niger Delta. It is further recommended that research studies on PAHs in the Niger Delta are extended to farmlands (crops, livestock) and the ambient air, within the vicinities of oil exploration companies, with a greater focus on the assessment of potential ecological and human health risks. Researchers are encouraged to report more on the other PAH groups such as alkylated PAHs, considering their potential environmental relevance, since using only the 16 USEPA PAHs does not provide a complete view of the environmental and human health impacts of PAH pollution. Researchers in this field of study are also urged to make use of two or more indices (including multivariate analysis) for PAH source identification and also develop the practice of including QA/QC measures in their studies to promote the robustness and confidence of their results.

Declaration

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1   **Tables**

2   **Table 1** Quality assessments of selected studies using Newcastle-Ottawa Scale

Authors (year)	Period of sampling indicated	Control samples included	Sampling technique indicated	Clean-up process conducted	QA/QC conducted	All objectives achieved	Report on PAH sources	Report on mean PAH levels	Overall quality score
Olajire et al. (2005)	No	No	Yes	Yes	No	Yes	Yes	Yes	5/8
Orgi et al. (2006)	No	No	No	Yes	No	Yes	No	No	2/8
Inengite et al. (2010)	Yes	No	No	Yes	Yes	Yes	Yes	No	5/8
Sojinu et al. (2010)	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	7/8
Ekpo et al. (2011)	No	No	No	Yes	Yes	Yes	Yes	Yes	5/8
Oyo-Ita et al. (2012)	No	No	No	No	Yes	Yes	Yes	Yes	4/8
Asagbra et al. (2015)	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	7/8
Inam et al. (2015)	Yes	No	Yes	No	Yes	Yes	No	Yes	5/8
Nwineewii and Marcus (2015)	No	No	No	Yes	No	Yes	No	No	2/8
Dosunmu et al. (2016)	Yes	No	Yes	Yes	Yes	Yes	No	Yes	6/8
Davies and Abolude (2016)	Yes	No	No	No	No	Yes	Yes	Yes	4/8
Obinaju et al. (2015)	No	No	No	Yes	Yes	Yes	No	No	3/8
Ikue et al. (2016)	No	No	No	Yes	No	Yes	No	Yes	3/8
Tongo et al. (2017)	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	7/8

Inam et al. (2018)	Yes	No	No	Yes	Yes	Yes	Yes	No	5/8
Ihunwo et al. (2019)	Yes	No	Yes	No	No	Yes	Yes	Yes	5/8
Effiong et al. (2016)	Yes	No	No	Yes	Yes	Yes	Yes	Yes	6/8
Uzoekwe and Ikpesu (2020)	Yes	No	Yes	Yes	No	Yes	No	No	4/8
Abbas and Brack (2005)	Yes	No	No	Yes	No	Yes	Yes	Yes	5/8
Nganje et al. (2011)	No	Yes	No	Yes	Yes	Yes	Yes	Yes	6/8
Oyo-Ita et al. (2011)	Yes	No	No	No	Yes	Yes	Yes	Yes	5/8
Nganje et al. (2014)	Yes	No	No	No	Yes	Yes	Yes	No	4/8
Iwegbue and Obi (2016)	No	No	No	Yes	Yes	Yes	Yes	No	4/8
Iwegbue et al. (2016)	No	No	No	Yes	Yes	Yes	Yes	No	4/8
Nduka et al. (2013)	Yes	Yes	No	No	No	Yes	No	No	3/8
Adedosu et al. (2013)	No	No	No	Yes	No	Yes	Yes	Yes	4/8
Ogoko (2014)	Yes	Yes	No	Yes	No	Yes	No	No	4/8
Olawoyin et al. (2012)	Yes	No	Yes	Yes	No	Yes	No	Yes	5/8
Osuji et al. (2012)	No	Yes	Yes	Yes	No	Yes	Yes	No	5/8
Ugochukwu et al. (2018)	No	Yes	Yes	Yes	Yes	Yes	No	No	5/8
Ekpete et al. (2019)	No	No	Yes	Yes	No	Yes	Yes	No	4/8
Emoyan et al. (2020)	Yes	No	No	Yes	Yes	Yes	Yes	Yes	6/8

Emoyan (2020)	No	Yes	No	Yes	Yes	Yes	Yes	Yes	6/8
Nwankwoala et al. (2020)	No	Yes	Yes	Yes	Yes	Yes	No	Yes	6/8
Owhoeke et al. (2020)	No	Yes	No	No	No	Yes	Yes	Yes	4/8
Nwaichi et al. (2016)	No	Yes	Yes	Yes	Yes	Yes	No	Yes	6/8
Igbiri et al. (2017)	Yes	No	No	Yes	Yes	Yes	No	No	4/8

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4

5   **Table 2** PAHs in aquatic environments

Sample category	Reference	Type of sample/sampling area	Polluting activity	Extraction method	Analytical technique	PAH concentration	Number of PAHs and potential sources
Aquatic environments	Olajire et al. (2005)	Sediments	Incidents of oil spill	Soxhlet extraction with Dichloromethane (DCM)	GC-MS	0.02 – 0.072 mg/kg	16 PAHs of petrogenic sources from six rivers of the Niger Delta
	Orgi et al. (2006)	Sediments	Effluent discharge from agricultural and industrial activities, incidents of oil spill, and shipping activities	Soxhlet extraction with a mixture of DCM and methanol (60:40, v/v)	GC-FID	2.38 – 5.18 mg/kg	16 PAHs from the Great Kwa River
	Inengite et al. (2010)	Sediments (dry season)	Gas flaring	Filtration method with 10 mL of Pentane	GC-FID	0 – 0.350 mg/kg	16 PAHs of pyrogenic sources from the Kolo Creek
		Sediments (rainy season)				0.22 – 0.470 mg/kg	
	Sojinu et al. (2010)	Sediments	Incidents of oil spill	Soxhlet extraction with 200 mL of DCM	GC-MS	0.65 – 0.331 mg/kg	28 PAHs of petrogenic sources from five waterbodies of the Niger Delta

Nganje et al. (2011)	Water	Incidents of oil spill	Accelerated solvent extraction	GC-MS	0.37 – 99.3 mg/L	16 PAHs of petrogenic and pyrogenic sources within the vicinity of a leaking pipeline at Esuk Utan
Ekpo et al. (2011)	Sediments	Effluent discharge from agricultural and industrial activities, incidents of an oil spill, and shipping activities	Soxhlet extraction with 200 ml of Hexane/Acetone (1:1, v/v)	GC-MS	Anthropogenic PAH (0.004 – 0.027 mg/kg) Biogenic PAHs (0.05 – 9.77 mg/kg)	PAHs of petrogenic sources from the Cross River estuary
Olawoyin et al. (2012)	Sediments	Processing of petrochemicals	Soxhlet extraction with 200 ml of Hexane/Acetone (1:1, v/v)	GC-MS	6 – 132 ± 28.7 mg/L	17 PAHs from four regions in the Niger Delta
	Water				119.8 – 450 ± 117.9 mg/L	
Oyo-Ita et al. (2012)	Sediments	Dotting of jetties and extensive fishing	Sonication extraction with DCM/Methanol (2:1, v/v)	GC-MS	1.67 – 20.1 mg/kg	26 PAHs of petrogenic sources from the Calabar River
Asagbra et al. (2015)	Sediments	Incidents of oil spill	Homogenisation method with DCM	GC-MS	4.587 mg/kg	11 and 9 PAHs of petrogenic sources from the Warri river
	Water				0.034 mg/L	
	Fish				1.098 mg/kg	
Inam et al. (2015)	Sediments	Agriculture, rubber and asphalt processing, solid waste combustion	Soxhlet extraction with DCM	GC-MS	1.099 mg/kg	16 PAH of pyrogenic sources from the Ikpa River Basin
	Water				0.926 mg/L	
Nwineewii and Marcus (2015)	Water	Processing of petrochemicals, agriculture, wood combustion	Liquid-liquid extraction with DCM	GC-FID	0.008 – 0.249 mg/L	16 PAHs from Eleme Creeks
	Sediments			GC-MS	0.482 mg/kg	

Dosunmu et al. (2016)	Shrimps	Processing of fertilizers and petrochemicals	Sonication extraction with 15 mL of Acetone/n-Hexane (1:1, v/v)		0.460 ± 0.33 mg/kg	16 PAHs from the Imo river
Davies and Abolude (2016)	Water	OEE operations, effluent discharge	Not defined	Not defined	0 – 0.018 mg/L	16 PAHs of anthropogenic or natural sources from the Oburun lake
Obinaju et al. (2015)	Water	Incidents of oil spill	Solid-phase extraction with 10 ml of DCM	GC-MS	0 – 1.055 mg/L	16 PAHs from the Ovia river
Ikue et al. (2016)	Fish muscle (Bodo city)	Incidents of oil spills	Filtration method with 10 ml of DCM	GC-FID	0.009 mg/kg	17 PAHs from landing beaches of Bodo City and Kaa waterside
	Fish muscle (Kaa)				0.005 mg/kg	
	Fish gills (Bodo city)				0.181 mg/kg	
	Fish gills (Kaa)				0.006 mg/kg	
Tongo et al. (2017)	Sediments	Incidents of oil spill	Sonication method with mixture of DCM and n-Hexane (2:3, v/v)	GC-MS	0.005 – 0.573 mg/kg	17 PAHs of pyrogenic and petrogenic sources from the Ovia River
	Water		Soxhlet extraction with 20 mL of n-Hexane and DCM (3:1, v/v)		0.002 – 0.025 mg/L	
	Fish		Soxhlet extraction with mixture of DCM and n-Hexane		0.010 – 0.914 mg/kg	
Inam et al. (2018)	Sediments (Ikpa River Basin)	Agriculture, rubber and asphalt processing, solid waste combustion	Soxhlet extraction with DCM/n-Hexane as solvent (7:3, v/v)	GC-MS	1.055 mg/kg	16 PAHs from the Ikpa River Basin, the Eniong River, and the Douglas/Stubbs Creek
	Sediments (Eniong River)				0.011 mg/kg	
	Sediments (Douglas/Stubbs Creek)				0.014 mg/kg	
Ihunwo et al. (2019)	Sediments	Incidents of oil spill	Not defined	GC-MS	687.93 – 1821.5 mg/kg	10 and 15 PAHs of petrogenic and pyrogenic sources from the Woji Creek
	Water				6.029 – 29.257 mg/kg	

	Effiong et al. (2016)	Silver catfish (Bonny River)	Effluent discharge from agricultural and industrial activities, incidents of oil spill, and shipping activities	Ultrasonication extraction with 30 mL of n-Hexane and DCM (1:1, v/v)	GC-MS	0.106 – 0.491 mg/kg	16 PAHs of pyrogenic sources from the Bonny and Cross River estuaries
		Giant African threadfin fish (Bonny River)				0.043 – 1.734 mg/kg	
		Tongue sole (Bonny River)				0.096 – 0.937 mg/kg	
		Silver catfish (Cross River)				0.020 – 0.975 mg/kg	
		Giant African threadfin fish (Cross River)				0.247 – 0.506 mg/kg	
		Tongue sole (Cross River)				0.025 – 0.387 mg/kg	
	Uzoekwe and Ikpesu (2020)	Sediments	Gas flaring	Filtration method with 10 mL of Hexane	GC-FID	0 – 0.374 mg/kg	16 PAHs from the Kolo Creek
		Water				BDL – 0.009 mg/L	

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8   **Table 3** PAHs in dust and soil

Sample category	Reference	Type of sample/sampling area	Polluting activity	Extraction method	Analytical technique	PAH concentration	Number of PAHs and potential sources
Dust and Soil	Abbas and Brack (2005)	Soil	Incidents of oil spill	Soxhlet extraction with DCM	GC-MS	0.154 – 0.750 mg/kg	16 PAHs of petrogenic sources from major ports in the Niger Delta
	Sojinu et al. (2010)	Soil	OEE operations	Soxhlet extraction with 200 mL of DCM	GC-MS	0.024 – 0.12 mg/kg	28 PAHs of pyrogenic sources from communities close to oil installations
	Nganje et al. (2011)	Soil	Petroleum handling facilities, fuel distributors, vehicle repairs, small scale motor mechanics,	Accelerated solvent extraction with Water, Acetone, Cyclohexane, and Toluene	GC-MS	0.016 – 25.548 mg/kg	16 PAHs from spill sites of Esuk Utan community and environs

		vehicle overhaul services				
Oyo-Ita et al. (2011)	Soil (forest)	Wood combustion and power generation	Sonication extraction with DCM/Methanol (2:1, v/v)	GC-MS	0.002 – 0.005 mg/kg	10 PAHs of petrogenic sources from polluted forest land and a point source in the Niger Delta
	Soil (pollution source)				0.011 – 0.047 mg/kg	
Nganje et al. (2014)	Soil	Incidents of oil spill	Accelerated solvent extraction	GC-MS	4.28 – 29.77 mg/kg	16 PAHs of petrogenic and pyrogenic sources from two spilt sites in Calabar Metropolis
Iwegbue and Obi (2016)	Dust	Incidents of oil spill	Ultra-sonication method with 50 mL of hexane/DCM (1:1, v/v)	GC-MS	165.1 – 1012 mg/kg	16 PAHs of pyrogenic sources from Warri and its environs
Iwegbue et al. (2016)	Soil	Incidents of oil spill	Accelerated Solvent Extraction with hexane and DCM (1:1, v/v)	GC-MS	0.188 – 0.684 mg/kg	16 PAHs of pyrogenic sources from Warri and its environs
Nduka et al. (2013)	Soil	Solid waste combustion	Soxhlet extraction with 100 mL of DCM	GC-MS	ND – 2392.06 mg/kg	16 PAHs from refuse dumpsites at Awka
Adedosu et al. (2013)	Soil	Gas flaring facilities	Soxhlet extraction with DCM	GC-FID	0.0074 – 0.078 mg/kg	16 PAHs of pyrolytic sources from gas flaring sites in Etche and Obio Akpor LGA
Ogoko (2014)	Soil	Pipeline transport of petroleum products	Microwave extraction with 25 mL n-Hexane and Acetone (7:3, v/v)	GC-MS	6.3 – 7.4 mg/kg	PAHs from oil depots in Aba city
Olawoyin et al. (2012)	Soil	Processing of petrochemicals	Soxhlet extraction with 200 mL of Hexane/Acetone (1:1, v/v)	GC-MS	297 – 4080.6 ± 546.3 mg/kg	7 PAHs from a petroleum region
Osuji et al. (2012)	Soil	Production of asphalt in Hot Mix Asphalt (HMA) plants	Shake extraction with 10 mL of DCM	GC-FID	117.67 – 2226.44 mg/kg	16 PAHs of pyrogenic sources from the vicinity of a Hot Mix Asphalt (HMA) plant
Ugochukwu et al. (2018)	Soil	Incidents of oil spill	Agitation extraction with 100 mL DCM/acetone (1:1, v/v)	GC-MS	1.9 – 461.3 mg/kg	16 PAHs from oil spill sites in the Obuaku wetland

	Ekpete et al. (2019)	Soil	Solid waste combustion	Soxhlet extraction with 10 mL of methanol and 25 mL of DCM	GC	21.987 – 60.958 mg/kg	16 PAHs of pyrogenic sources from three waste dumpsites in Port Harcourt
	Emoyan (2020)	Soil	Incidents of diesel oil spills and/or emission of gaseous particles from telecom masts	Soxhlet extraction with 100 mL Methylene – Chloride	GC-FID	0.236 – 10.622 mg/kg	16 PAHs of pyrogenic sources from the areas of some telecom masts
	Emoyan et al. (2020)	Soil (Topsoil-Dry season)	Vehicular emissions	Sonication method with 50 mL of hexane/dichloromethane (DCM) (1:1, v/v)	GC-FID	0.664 – 0.269 mg/kg	16 PAHs of pyrogenic sources from vehicle parks
		Soil (Subsoil-Dry season)				212.1 to 1.343 mg/kg	
		Soil (Topsoil-Wet season)				0.366 – 1.066 mg/kg	
		Soil (Subsoil-Wet season)				0.143 – 5321.9 mg/kg	
	Nwankwoala et al. (2020)	Soil	Incidents of oil spill	Liquid to liquid extraction with 20 mL of DCM	GC-MS	0.02 – 28.49 mg/kg	16 PAHs from a spill site in Bonny Island
	Owhoeke et al. (2020)	Soil	Incidents of oil spill	Not defined	GC-FID	354.7 ± 360.7 – 4154 ± 3461 mg/kg	16 PAHs of pyrogenic and petrogenic sources from crude oil contaminated farmland in Egi

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11   **Table 4** PAHs in crops

Sample category	Reference	Type of sample/sampling area	Polluting activity	Extraction method	Analytical technique	PAH concentration	Number of PAHs and potential sources
Crops	Nwaichi et al. (2016)	Cassava tubers (Ekore)	Incidents of oil spill	Filtration method with 10 mL of DCM	GC-FID	0.504 mg/kg	17 PAHs from crude oil polluted farm crops in Ughevwughe community
		African oil bean (Ekore)				0.447 mg/kg	

					1.001 mg/kg	
	Cassava tubers (Uduvwoku)				1.001 mg/kg	
	African oil bean (Uduvwoku)				0.496 mg/kg	
Igbiri et al. (2017)	Mushroom	Incidents of oil spill	Ultrasonication extraction with a mixture of Acetone and Methylene Chloride (50:50)	GC-FID	0.002 – 3.370 mg/kg	16 PAHs from polluted mushrooms cultivated in Port Harcourt
Ihuoma et al. (2020)	Cassava tubers	Incidents of oil spill	Filtration method with 10 mL DCM	GC-FID	0.007 – 0.012 mg/kg	9 PAHs from four polluted farm crops in Rivers State

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14 **Table 5** Results of human health risk assessment reported by some selected studies

Sample category	Sample	Hazard Index (HI)			Mean ILCR (mg/kg/day)						References
					Children			Adult			
		Ingestion	Inhalation	Dermal	Ingestion	Inhalation	Dermal	Ingestion	Inhalation	Dermal	
Dust and Soil	Soil	-	-	-	2.25×10^{-5}-1.90×10^{-3}	2.12×10^{-13}-5.70×10^{-12}	8.19×10^{-12}-6.91×10^{-4}	1.41×10^{-4}-1.91×10^{-3}	1.06×10^{-12}-2.85×10^{-11}	7.28×10^{-6}-6.14×10^{-4}	Iwegbue et al. (2016)
	Soil	-	-	-	-	-	4.55×10^{-4}	-	-	5.07×10^{-4}	Olawoyin et al. (2012)
	Dust	-	-	-	3.16×10^{-7} - 6.38×10^{-4}	8.79×10^{-15} - 6.35×10^{-12}	9.12×10^{-8} - 8.34×10^{-4}	1.52×10^{-4} - 1.14×10^{-3}	3.53×10^{-14}-1.33×10^{-11}	1.34×10^{-6}-5.93×10^{-4}	Iwegbue and Obi (2016)
	Soil	<1	<1	<1	$4.36x10^{-3}$ - $2.45x10^{-3}$	$3.84x10^{-10}$ - $2.17x10^{-8}$	$1.59x10^{-3}$ - $8.9x10^{-2}$	$3.01x10^{-4}$ - $1.69x10^{-2}$	$4.23x10^{-10}$-$2.39x10^{-8}$	$1.56x10^{-4}$-$8.74x10^{-3}$	Emoyan (2020)
	Soil	-	-	-	4.31×10^{-3} - 3.54×10^{-2}	-	-	5.99×10^{-4} - 8.90×10^{-3}	-	-	Owhoeke et al. (2020)
Crops	Mushroom	-	-	-	-	-	-	$1.56x10^{-8}$ - $1.73x10^{-6}$	-	-	Igbiri et al. (2017)

Aquatic Environments	Water	<1	-	-	-	-	1.87×10^{-5} - 2.06×10^{-5}	-	-	2.85×10^{-5}- 3.14×10^{-5}	Inam et al. (2015)
	Sediments	-	-	>1	-	-	2.73×10^{-5} - 3.23×10^{-3}	-	-	5.03×10^{-4}- 5.95×10^{-3}	
	Fish (*C. gariepinus*)	<1	-	-	-	-	-	4.35×10^{-11} - 3.01×10^{-8}	-	-	Tongo et al. (2017)

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16   **Figures**

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19   **Fig. 1** Map of Niger Delta showing the various Local Government Areas

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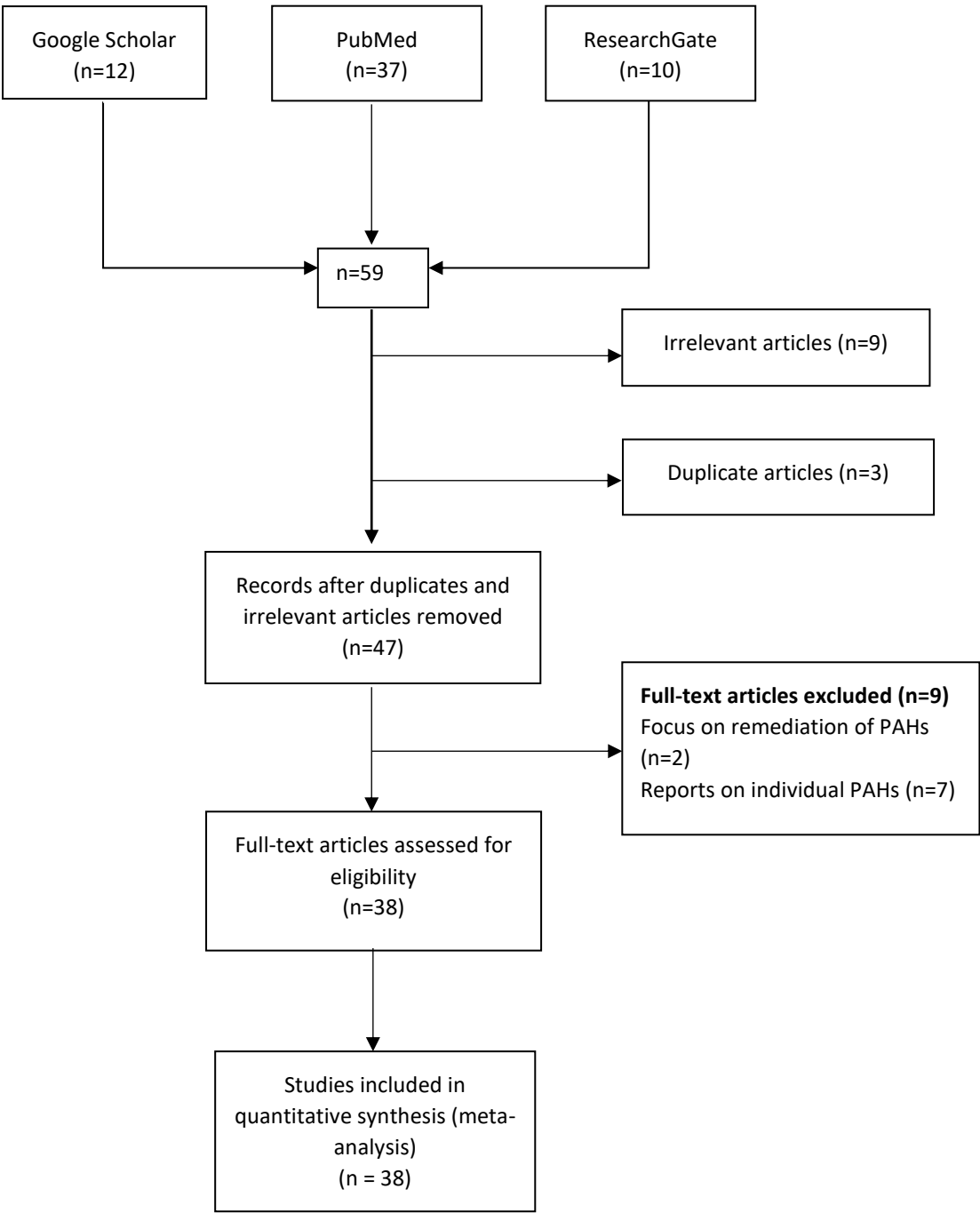22   **Fig. 2** Flow chart of article selection (Adapted from Moher et al. 2009)

23

Quality Assessment of Selected Studies
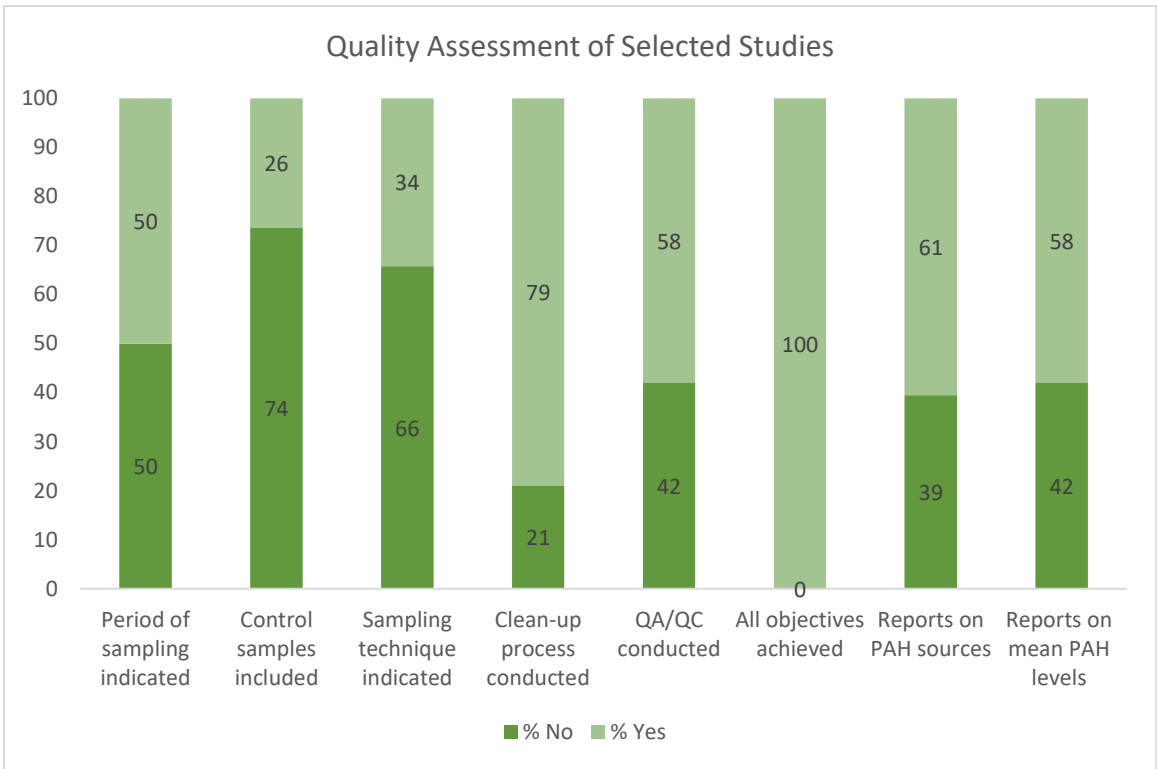
Fig. 3 Quality assessment of selected studies

25   **Fig. 3** Quality assessment of selected studies

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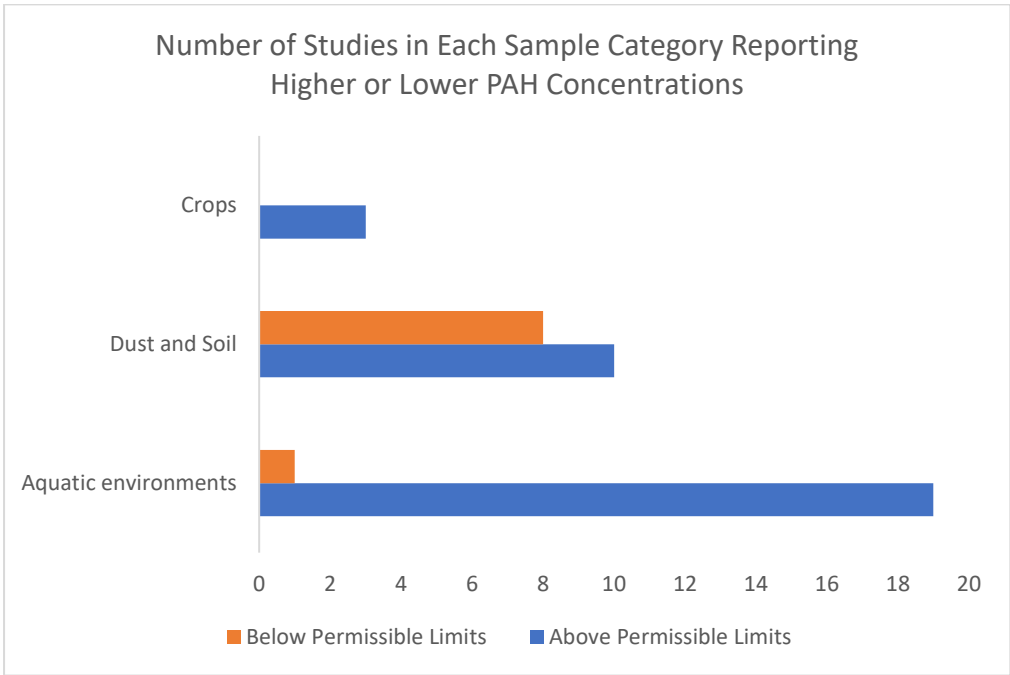**Number of Studies in Each Sample Category Reporting Higher or Lower PAH Concentrations**

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29   **Fig. 4** Number of studies in each sample category reporting higher or lower PAH concentrations as compared to
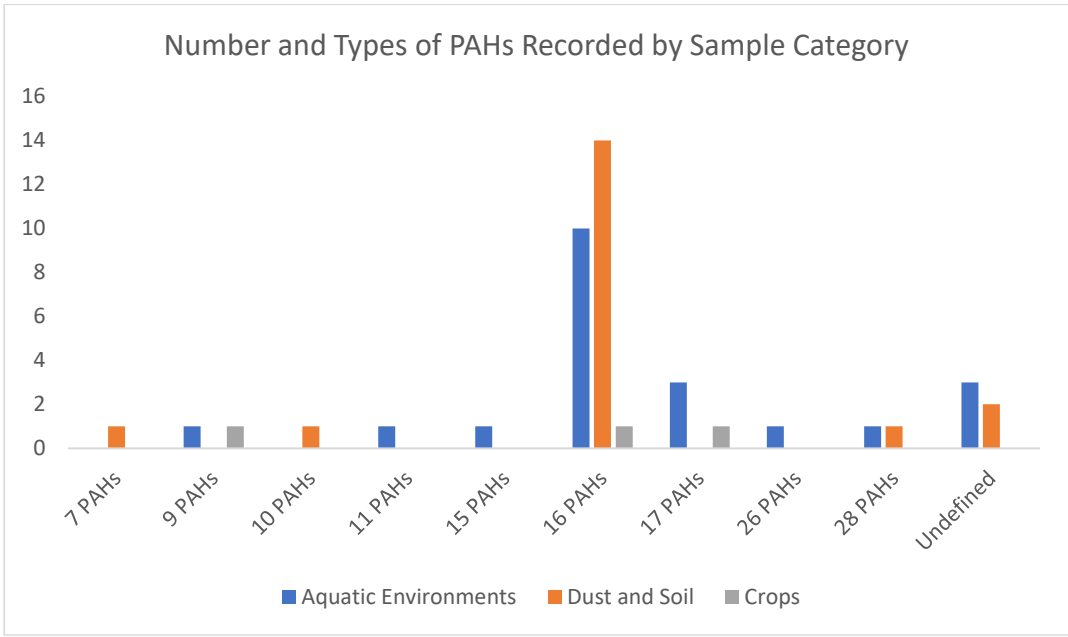
30   the permissible limits

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32   **Fig. 5** Number and types of PAHs recorded by each sample category

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