Risk Assessment and Source Identification of some Phenolic Endocrine-disrupting Chemicals in Water, Sediment, and Clarias gariepinus from Okrika Axis of Bonny River

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ABSTRACT

This study investigated phenolic EDCs in surface water, sediment and Clarias gariepinus (African Sharptooth Catfish) from four sampling locations along the Okrika axis of Bonny River, Rivers State, Nigeria. Fish were obtained from local fishermen and water and sediment samples were collected from representative stations. Ten phenolic EDCs (including Phenol, 3-chlorophenol, 3-methylphenol, 2, 3-dimethylphenol, 2,4-dimethylphenol, 2,5-dimethylphenol, 2-cyclohexyl-4,6-dinitrophenol, nonylphenol (NP), octylphenol (OP), and bisphenol A (BPA)) were analyzed by Gas Chromatography–Mass Spectrometry (GC-MS). EDCs in water ranged from 0.81±0.01 to 4.72±0.02, in sediment from 0.44 ± 0.02 to 20.84 ± 0.03, and in Clarias gariepinus from 0.71±0.02 to 4.81±0.01. Concentration data were evaluated using contamination factor (CF) and pollution load index (PLI); accumulation was assessed by bioaccumulation factor (BAF) and biota–sediment accumulation factor (BSAF); and human/ecological risk was estimated via estimated daily intake (EDI), hazard quotient (HQ) and hazard index (HI). Results showed widespread contamination of the Bonny River by both EDCs. Phenolic compounds, particularly nonylphenol, octylphenol and bisphenol A—were pervasive in water, sediments and fish, and CF/PLI metrics flagged these chemicals as primary contributors to local pollution. Collectively, the data indicated that Bonny River is chemically stressed by mixed inputs from oil-related activities, industrial effluents and domestic discharges. The concurrence of elevated contamination indices, strong bioaccumulation and HI exceedances highlights an urgent need for monitoring and regulatory enforcement.

Keywords: *Risk assessment, source identification, phenolic EDCs, water and sediment*

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INTRODUCTION

Water pollution has emerged as a pressing global environmental concern, particularly in regions undergoing rapid industrialization and urban expansion. The infiltration of organic contaminants into aquatic ecosystems not only degrades water quality, but also threatens aquatic life and human health. Among these contaminants, phenolic

endocrine-disrupting chemicals (EDCs) are of special concern due to their persistence, bioaccumulative nature, toxicity, and ability to interfere with hormonal systems in organisms. Phenolic EDCs such as bisphenol A, nonylphenol, and other alkylphenols are widely used in industrial applications and consumer products, and have been frequently detected in various environmental matrices (Weldeslassie et al., 2017).

The Bonny River, located in the Niger Delta region of Nigeria, constitutes an ecologically and socio-economically significant waterway that supports diverse aquatic life and provides vital resources for local communities. Within this system, the Okrika Axis has experienced increasing anthropogenic pressures from oil and gas activities, industrial discharges, urban runoff, and domestic waste inputs. These activities are known to introduce complex mixtures of chemical pollutants into the river, raising concerns about the environmental quality and safety of biological resources harvested from this region (Babatunde, 2020).

Fish species such as *Clarias gariepinus* (the African sharp-tooth catfish) are key biological indicators of aquatic ecosystem health due to their wide geographic distribution, benthic feeding habits, and ability to accumulate contaminants in their tissues. Given the reliance of local communities on fish from the Bonny River as a source of protein and livelihood, there is a critical need to evaluate the extent of contamination and associated health risks (Kadye & Booth, 2012).

Effective environmental management requires a comprehensive understanding of both the levels of contaminants present and their potential sources. Risk assessment of phenolic EDCs in water, sediment, and biota provides essential insights into exposure pathways, toxicological implications, and the potential threat to ecological integrity and public health. Source identification further enables policymakers and stakeholders to trace pollutant origins, prioritize mitigation strategies, and implement targeted interventions (Diao et al., 2017).

Despite growing awareness of chemical pollution in the Niger Delta, data on the occurrence, distribution, and risk profile of phenolic EDCs in the Bonny River particularly within the Okrika Axis—remain limited. Many previous studies have focused on either water or sediment quality, with comparatively fewer investigations incorporating integrated assessments that include aquatic organisms. This knowledge gap hinders the development of evidence-based strategies for environmental protection and sustainable resource use in the region.

Therefore, this study aims to assess the levels of selected phenolic EDCs in water, sediment, and tissues of *Clarias gariepinus* from the Okrika Axis of the Bonny River; to evaluate the associated ecological and human health risks; and to identify potential sources of contamination. Through this integrated approach, the research seeks to generate critical baseline data, enhance our understanding of pollutant dynamics in tropical aquatic systems, and contribute to informed environmental management and policy formulation.

Study area

The Bonny River is a socio-economic lifeline for surrounding communities. It serves as a major transportation route for people and goods, while also supporting fishing, small-scale commerce, and industrial activities (Figure 1). Fishing remains the primary livelihood of local inhabitants, with tilapia and other aquatic species forming both dietary staples and commercial commodities. According to the 2006 Nigerian National Population Census, Okrika Local Government Area has a population of approximately 222,026 people, most of whom depend directly on the river for domestic water supply, food, transportation, and income (Jumbo & Ihuah, 2024). Despite its ecological and economic importance, the Bonny River system faces increasing environmental pressures. Boat repair and maintenance along its banks contribute significant pollution, as petroleum diesel and antifouling paints containing organotins and alkylphenols are discharged into the river. Informal metal scrap yards further contribute contamination, with corroding metallic parts leaching heavy metals such as cadmium, lead, and mercury into the aquatic system. Domestic waste disposal, including untreated sewage and household refuse, exacerbates the pollution load. These wastes often contain pharmaceuticals, synthetic detergents, and microplastics, introducing endocrine-disrupting chemicals such as nonylphenol, bisphenol A (BPA), and triclosan into the river. Given the heavy reliance of the local population on the river for food, water, and livelihood, understanding the distribution and risks associated with these contaminants is essential for biodiversity conservation.

METHODOLOGY

A random composite sampling approach was adopted in this study to obtain representative concentrations of endocrine-disrupting chemicals (EDCs) across the Okrika axis of Bonny River. Four stations were strategically selected, namely Ibaka (Station 1), George Ama (Station 2), Ogoloma (Station 3), and Ekerekana (Station 4), each reflecting different levels of anthropogenic influence such as industrial discharges, agricultural runoff, urban settlements, and relatively undisturbed areas that served as comparative controls. At each station, several sub-samples were collected randomly within a one-kilometer radius and homogenized to form a composite sample. This approach reduced localized variability and provided a more accurate reflection of average contamination levels at each site.

To ensure precision and reproducibility, triplicate

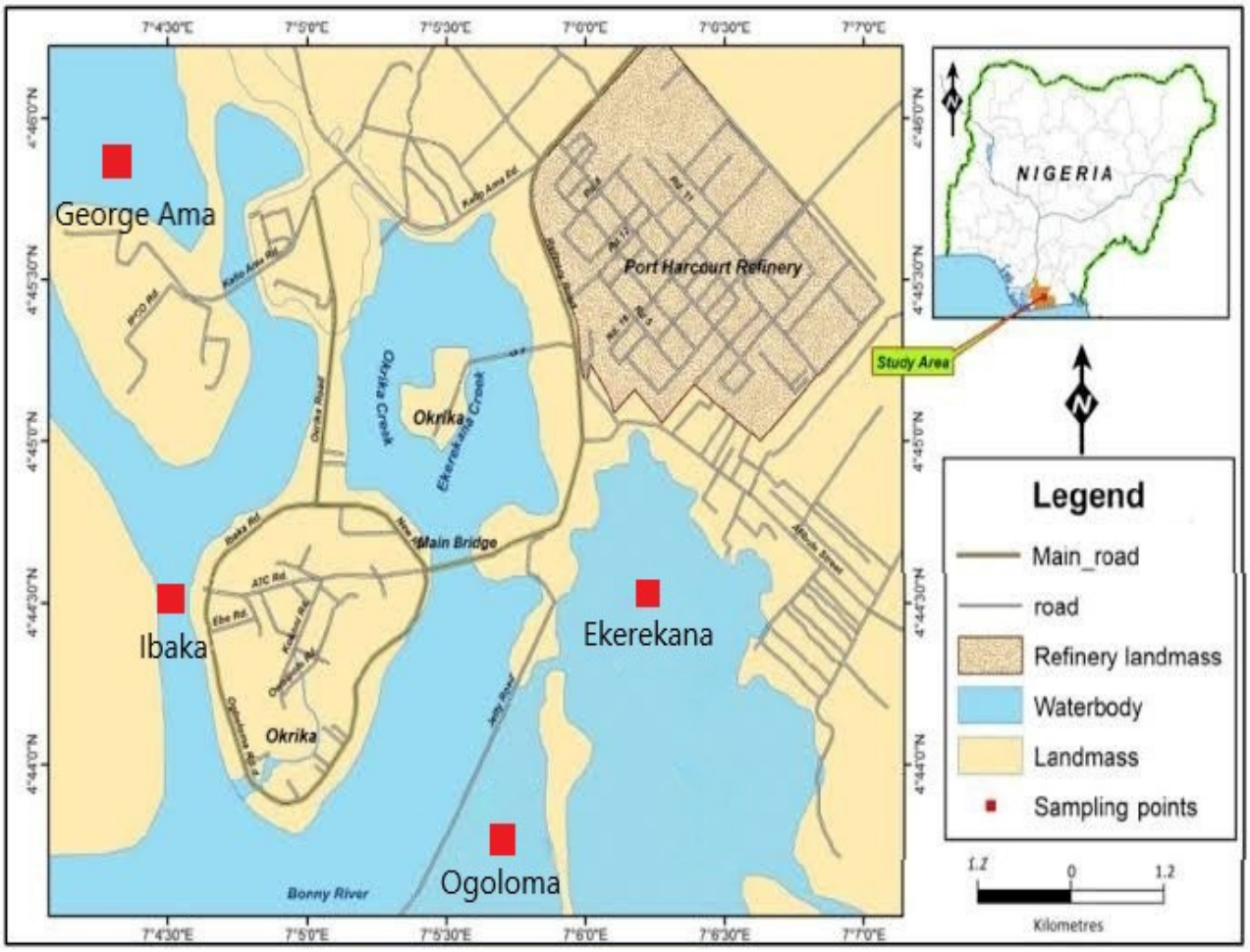

Figure 1: Map of Bonny River showing sampling locations

extractions were performed for each composite sample. The analytical determination of both EDCs was conducted using gas chromatography–mass spectrometry (GC–MS). Prior to instrumental analysis, samples underwent standard extraction and clean-up procedures to remove interferences and concentrate target compounds. Sample preparation and analysis employed standard laboratory-grade reagents. Acid digestion and stabilization involved the use of hydrochloric acid (HCl), nitric acid (HNO_3), perchloric acid ($HClO_4$), and sulfuric acid (H_2SO_4). Organic solvents such as methanol, acetone, and n-hexane were used for compound extraction.

Samples were collected in pre-cleaned amber glass bottles to prevent photodegradation, immediately preserved at 4 °C in ice-filled coolers, and transported to the laboratory for analysis within recommended holding times. Blanks, duplicates, and spiked samples were included in each analytical batch, and calibration was performed using certified reference standards to ensure accuracy and reliability. Triplicate analyses of each sample further minimized experimental errors and strengthened statistical robustness.

Sample collection

Sampling was carried out from four (4) designated locations - Ibaka, George Ama, Ogoloma, and Ekerekana, in the Bonny River and adjoining creeks within Okrika, Rivers State, using a boat to navigate between the sampling stations. For EDCs, water samples were collected at low tide using amber glass bottles from each of the four sampling locations. A composite sampling approach was employed by collecting water from three points at each location and combining them to obtain a representative sample that accounted for spatial variability. The amber bottles were pre-cleaned with acetone, rinsed with deionized water, and finally conditioned with river water at the sampling site before collection. To preserve the samples and prevent microbial degradation of phenolic compounds such as nonylphenol, octylphenol, and bisphenol A, the water was immediately

kept in ice below 6°C. Sediment samples for EDC analysis were also collected at low tide from depths of over 20 cm using a grab sampler. Three sub-samples were taken from each site and composited to provide a representative sample. The sediments were placed in pre-cleaned polyethylene bags, previously washed with dilute HCl and rinsed with deionized water. To ensure stability of organic contaminants, 1g of sodium azide (NaN_3) was added to each sample to inhibit microbial growth. Biota samples (*Clarias gariepinus*) were purchased from local fishermen at the river banks. These organisms were immediately wrapped in clean aluminum foil, labeled, and stored in coolers containing ice packs to minimize decomposition prior to analysis.

All collected samples water, sediment, and *Clarias gariepinus*—were carefully labeled with sampling date, time, location, and sample type. They were stored in coolers containing ice packs and transported immediately to the laboratory for extraction and instrumental analysis.

Sample preparation and analysis

Preparation of standards

The preparation of standards for GC-MS analysis of endocrine-disrupting chemicals (EDCs) involved selecting certified reference materials (CRMs) with high purity (≥ 98%) for target compounds.

Preparation of water samples for phenolic EDCs analysis

For water samples, liquid-liquid extraction was employed to isolate the endocrine-disrupting chemicals (EDCs). The water samples were first filtered through glass fiber filters to remove suspended particles and debris, ensuring only dissolved analytes remained. The extraction cartridges were prepared by rinsing with 3 mL of methylene chloride (CH_2Cl_2) to clean the packing material, followed by drying. Subsequently, the cartridges were rinsed with 3 mL of methanol to condition the packing, ensuring it remained moist during subsequent steps. To acidify the samples and stabilize the target analytes, the cartridges were washed with 0.05 N hydrochloric acid (HCl). Before the dilute acid level dropped below the packing edge, the vacuum was turned off to prevent drying, and an additional 3 mL of 0.05 N HCl was added to maintain an acidic environment. A transfer tube was attached, and the vacuum was turned on to facilitate solvent passage through the cartridge.

The sample bottles were rinsed with 10 mL of methylene chloride (CH_2Cl_2) to recover any residual analytes adhering to the bottle walls. The water samples were then added to the extraction system slowly, and a vacuum was used to pull the solvent through the transfer tube and cartridge, allowing the target analytes to adsorb onto the packing material. To enhance extraction efficiency, an additional 3 mL of methylene chloride (CH_2Cl_2) was added dropwise to the cartridge using a disposable pipette. The solvent was drawn through the cartridge at low vacuum, ensuring a steady dropwise flow. The eluate containing the extracted analytes was passed through a drying column packed with 5g of anhydrous sodium sulfate (Na_2SO_4) to remove any remaining moisture. The sodium sulfate column was then washed with 2 mL of methylene chloride (CH_2Cl_2), and the combined extract was collected in a clean tube. The collected extract was concentrated to approximately 0.9 mL in a warm (40°C) water bath under a gentle stream of nitrogen gas, taking care not to reduce the volume below 0.5 mL to prevent analyte loss. Methylene chloride (CH_2Cl_2) was then added to adjust the final volume to 1 mL. The prepared extract was sealed and transported for analysis using a Gas Chromatograph-Mass Spectrometer (GC-MS) system. This meticulous process ensured efficient extraction and preservation of EDCs and POPs for accurate analysis.

Preparation of sediment samples for phenolic EDCs analysis

The sediment samples were initially ground and homogenized using a mortar and pestle in the presence of anhydrous sodium sulfate to ensure uniformity and to remove moisture. 5g of the homogenized sample was accurately weighed using an analytical balance and transferred into a centrifuge tube. To facilitate the extraction of target compounds, 25mL of a solvent mixture consisting of dichloromethane and hexane in a 2:1 ratio was added to the tube. The mixture was then subjected to ultrasonication for 15 minutes to enhance the extraction efficiency by disrupting the matrix and releasing the analytes. Following ultrasonication, the tube was centrifuged at 1500rpm for 5 minutes to separate the extract from the sediment residue. The extraction process was repeated using an additional 10mL of the solvent mixture to ensure maximum recovery of the target analytes. The resulting extracts from both extractions were combined and concentrated to approximately 2mL using a rotary evaporator or under a gentle stream of nitrogen gas to avoid loss of volatile analytes. The concentrated extract was then dried over anhydrous sodium sulfate to remove any residual moisture. The final extract was transferred into a clean vial and sealed. It was subsequently sent for analysis using a Gas Chromatograph-Mass Spectrometer (GC-MS) system to identify and quantify the target EDCs present in the samples.

Preparation of *Clarias gariepinus* samples for phenolic EDCs analysis

The preparation of *Clarias gariepinus* samples for the analysis of phenolic endocrine-disrupting chemicals (EDCs) was conducted using an optimized solvent

extraction method adapted for biological tissues. Freshly procured fish samples were first rinsed with deionized water to remove external contaminants such as sediments and debris. The muscle tissues, considered the primary site for accumulation of EDCs, were carefully filleted using stainless-steel scalpels to avoid cross-contamination. The tissues were homogenized using a laboratory blender and freeze-dried to reduce moisture content while preserving the integrity of analytes. Approximately 5g of the homogenized, dried tissue sample was weighed using an analytical balance and placed into a centrifuge tube. To facilitate efficient extraction of the target phenolic EDCs such as nonylphenol (NP), octylphenol (OP), and bisphenol A (BPA), 20 mL of a solvent mixture comprising dichloromethane and hexane in a 2:1 ratio (v/v) was added. The mixture was subjected to ultrasonication for 20 minutes to enhance solvent penetration, disrupt tissue matrices, and improve the release of analytes into the solvent phase.

Following ultrasonication, the sample was centrifuged at 1500 rpm for 10 minutes, and the supernatant extract was carefully decanted into a clean flask. The extraction process was repeated with an additional 10 mL of solvent to maximize recovery, and the combined extracts were concentrated to approximately 2 mL using a rotary evaporator under reduced pressure. The concentrated extract was dried over anhydrous sodium sulfate (Na_2SO_4) to remove residual water.

A cleanup step was performed to eliminate residual lipids and co-extracted organic material. This was achieved using a silica gel column preconditioned with hexane. The extract was loaded onto the column and eluted with a mixture of hexane and dichloromethane (9:1 v/v). The purified eluate was collected in a clean vial and further concentrated to a final volume of 1 mL using a gentle stream of nitrogen gas at 40°C. The final extract was transferred into amber glass vials with Teflon-lined caps to prevent photodegradation and contamination. The vials were stored at 4°C until analysis by Gas Chromatograph-Mass Spectrometer (GC-MS), which provided sensitive and accurate quantification of phenolic EDCs in fish tissues.

Contamination Factor (CF)

The Contamination Factor (CF) is a key metric used to evaluate the extent of pollution by specific contaminants, such as heavy metals, in environmental matrices like water, sediment, and biota. It provides a quantitative measure of how much a particular contaminant exceeds its natural or background levels in a given sample. Although originally developed for heavy metals, the CF approach can be adapted to assess contamination by other pollutants, including EDCs, in relevant environmental samples (Table 1).

Table 1: Intervals of Contamination Factor.

Degree	Contamination factor
Low contamination	CF < 1
No contamination	CF = 1
Moderate contamination	**1 ≤ CF < 3**
Considerable contamination	3 ≤ CF < 6
Very high contamination	CF ≥ 6

$$\text{Contamination factor (CF)} = \frac{Cs}{Cb} \quad (1)$$

Where Cs = concentration of the contaminant in the sample, and
Cb = background or reference concentration of the contaminant from known standards.

Pollution load index (PLI)

The Pollution Load Index (PLI) is a valuable tool in environmental studies for assessing the cumulative pollution status of an area by integrating multiple contamination factors into a single index. By providing an overview of pollution levels, it aids in understanding the overall environmental quality and helps in identifying areas that require remediation efforts. It is a composite index that takes into account multiple pollutants and their concentrations. The Pollution Load Index is particularly useful in evaluating the cumulative impact of various pollutants on the environment. The PLI was determined as the nth root of the product of nCFs, as calculated based on the formula by Ranjani et al. (2021).

$$PLI = \sqrt[n]{CF1 \times CF2 \times CF3 \times \ldots.. CFn} \quad (2)$$

Where n is the number of variables, and CF are the calculated contamination factors for each target metal in the river.
PLI = 0 indicates environmental quality is within standard limits and there is only baseline level of contaminants, and PLI > 1 indicates that the area is polluted. The higher the PLI, the higher the degree of pollution.
The PLI evaluated the overall toxicity status of the samples.

Hazard quotient (HQ) and Hazard Index (HI)

The Hazard Quotient (HQ) is a quantitative tool used in risk assessment to evaluate the potential non-carcinogenic health risks posed by exposure to a chemical contaminant. It compares the level of exposure to a contaminant with a reference level known to be safe. HQ is widely employed in environmental studies to assess the risks associated

with contaminants in water, sediment, or biota.

$$HQ = \frac{E}{RfD} \quad (3)$$

Where:

Ex: Exposure level to the contaminant (e.g., daily intake via ingestion or dermal absorption, typically expressed in mg/kg/day).
RfD: Reference Dose, a safe exposure level for the contaminant (in mg/kg/day), provided by regulatory agencies such as the U.S. Environmental Protection Agency (USEPA).
The Estimated Daily Intake (EDI) was calculated for each chemical and used to quantify HQ for both exposure pathways. Hazard assessment was based on RfD values reported by the U.S.EPA and WHO for chemicals with established limits:

EDCs

- Phenol: 0.3 mg/kg/day
- 3-Methylphenol: 0.05 mg/kg/day
- 2,4-Dimethylphenol: 0.02 mg/kg/day
- Octylphenol (OP): 0.17 mg/kg/day
- Bisphenol A (BPA): 0.05 mg/kg/day

Source: USEPA

The Estimated Daily Intake (EDI) was first determined for both drinking water and fish consumption pathways using the following equations:

$$\text{EDIwater} = \frac{Cwater \times IRwater}{BW} \quad (4)$$

$$\text{EDIfish} = \frac{Cfish \times IRfish}{BW} \quad (5)$$

where C_{water} is the contaminant concentration in water (µg·L^{-1}), IR_{water} is the daily water ingestion rate (L·day^{-1}), C_{fish} is the contaminant concentration in fish (µg·kg^{-1} wet weight), IR_{fish} is the daily fish ingestion rate (kg·day^{-1}), and BW is the body weight (kg).

HQ Interpretation

HQ < 1: Indicates that the exposure level is below the reference dose, suggesting no significant risk of adverse effects.
HQ ≥ 1: Suggests potential non-carcinogenic risks to human health; the higher the HQ value, the greater the likelihood of adverse effects.

Bioaccumulation and Biota-Sediment Accumulation of Phenolic EDCs

To further understand the environmental dynamics of EDCs in Bonny River, bioaccumulation and biota-sediment accumulation factors were calculated. These indices are useful for assessing how pollutants partition between environmental compartments and the potential for transfer through the food chain. The Bioaccumulation Factor (BAF) was calculated using the formula:

$$\text{BAF} = \frac{\text{Cbiota}}{Cwater} \quad (6)$$

where C_{biota} is the concentration of the compound in fish (µg/kg wet weight) and C_{water} is the concentration in water (µg/L). BAF expresses the degree to which an organism can accumulate contaminants directly from its surrounding water through respiration or passive diffusion.

The Biota-Sediment Accumulation Factor (BSAF) was calculated as:

$$\text{BSAF} = \frac{Cbiota}{Csediment} \quad (7)$$

where $C_{sediment}$ is the concentration of the pollutant in sediment (µg/kg dry weight). BSAF describes bioaccumulation through dietary exposure pathways, reflecting the ability of organisms to assimilate contaminants from sediments either directly or via benthic food sources.

RESULTS AND DISCUSSION

Mean levels of phenolic Endocrine-disrupting chemicals (EDCs) in water of Bonny River

The mean concentrations of phenolic EDCs in water samples from Bonny River varied across the four sampling stations, with values ranging between 1.42 ± 0.72 µg/L and 3.60 ± 1.18 µg/L for most of the phenols, and higher levels for Bisphenol A (3.25 ± 0.96 µg/L), Nonylphenol (3.24 ± 0.67 µg/L) and Octylphenol (2.49 ± 0.47 µg/L) (Table 2). The presence of these compounds highlighted the contribution of anthropogenic activities such as oil exploration, industrial discharges, municipal wastes, and detergent residues, which are common in the Niger Delta environment.

Phenol, a priority pollutant according to both WHO and USEPA, recorded a mean concentration of 3.13 ± 1.21 µg/L across the four stations. Although WHO does not provide a strict maximum permissible limit for phenol in surface waters, the USEPA drinking water limit is 1.0 µg/L, while FEPA guideline values for industrial effluents are also in the range of 1 µg/L. The observed concentration in this study therefore exceeds recommended values, which suggested potential ecological and health risks, especially for communities that depend on Bonny River as a water source. Phenol contamination in aquatic systems is associated with industrial waste, petroleum refining, and microbial breakdown of organic matter, and its chronic

Table 2: Mean concentration of phenolic EDCs in water of Bonny River.

Parameter	Station 1	Station 2	Station 3	Station 4	Mean ± SD
Phenol	3.73 ± 0.16	1.63 ± 0.01	4.41 ± 0.03	2.73 ± 0.02	3.13 ± 1.21
3-Chlorophenol	2.44 ± 0.02	1.83 ± 0.03	1.84 ± 0.02	2.62 ± 0.01	2.18 ± 0.41
3-Methylphenol	1.80 ± 0.09	3.72 ± 0.02	4.05 ± 0.03	1.34 ± 0.02	2.73 ± 1.36
2,3-Dimethylphenol	1.93 ± 0.03	1.73 ± 0.01	2.22 ± 0.12	1.99 ± 0.02	1.97 ± 0.20
2,4-Dimethylphenol	0.81 ± 0.01	2.20 ± 0.02	1.87 ± 0.02	0.81 ± 0.01	1.42 ± 0.72
2,5-Dimethylphenol	1.94 ± 0.02	3.79 ± 0.04	4.72 ± 0.02	1.94 ± 0.02	3.60 ± 1.18
2-Cyclohexyl-4,6-dinitrophenol	2.43 ± 0.02	1.36 ± 0.05	3.73 ± 0.01	2.43 ± 0.02	2.43 ± 0.98
Nonylphenol (NP)	2.87 ± 0.35	3.87 ± 0.15	3.74 ± 0.12	2.87 ± 0.35	3.24 ± 0.67
Octylphenol (OP)	2.41 ± 0.04	1.98 ± 0.02	2.44 ± 0.05	2.41 ± 0.04	2.49 ± 0.47
Bisphenol A (BPA)	3.25 ± 0.12	3.12 ± 0.02	2.15 ± 0.02	3.25 ± 0.12	3.25 ± 0.96

Legend:
Station 1 – Ibaka
Station 2 – George Ama
Station 3 – Ogoloma
Station 4 – Ekerekana

exposure has been linked with liver and kidney damage (Anku et al., 2017).

3-Chlorophenol and 3-Methylphenol also showed considerable levels, with mean concentrations of 2.18 ± 0.41 µg/L and 2.73 ± 1.36 µg/L respectively. The USEPA and EU have classified chlorophenols and cresols as priority pollutants due to their persistence, toxicity, and bioaccumulative properties (Adeola, 2018). Both compounds have documented endocrine-disrupting and mutagenic potentials, yet their detected levels in Bonny River are higher than concentrations reported in relatively less industrialized water bodies. For instance, Dibofori-Orji et al. (2019) reported lower levels (< 1 µg/L) of phenolic pollutants in Woji Creek, while concentrations in Bonny River appear significantly elevated, possibly due to direct inputs from petrochemical and shipping activities.

Bisphenol A (BPA), Nonylphenol (NP), and Octylphenol (OP) are among the most studied endocrine-disrupting phenols. In this study, their mean concentrations were 3.25 ± 0.96 µg/L, 3.24 ± 0.67 µg/L, and 2.49 ± 0.47 µg/L respectively. These values are considerably higher than the 1 µg/L screening values recommended by the EU Water Framework Directive for NP and OP. BPA has no set WHO guideline, but the US FDA and EU have set tolerable daily intake (TDI) values for dietary exposure. The occurrence of these compounds in Bonny River is worrisome because NP and OP are widely recognized for their estrogenic effects in aquatic organisms, leading to feminization of male fish, reduced fertility, and disruption of hormone regulation (Soares et al., 2008). The fact that NP and OP levels in Bonny River exceed European environmental quality standards underscores the vulnerability of the aquatic ecosystem and the need for local monitoring frameworks.

In contrast, compounds such as 2,3-Dimethylphenol (1.97 ± 0.20 µg/L), 2,4-Dimethylphenol (1.42 ± 0.72 µg/L), 2,5-Dimethylphenol (3.60 ± 1.18 µg/L), and 2-Cyclohexyl-4,6-dinitrophenol (2.43 ± 0.98 µg/L) currently lack specific WHO, EPA, or FEPA permissible limits in water. The absence of regulatory guidelines does not imply safety; rather, it reflects a gap in monitoring of these emerging contaminants. Previous studies have highlighted the toxic and mutagenic potentials of dimethylphenols, which can persist in sediments and biomagnify through food chains (Hammam et al., 2015). The detection of 2,5-Dimethylphenol at a relatively high mean concentration (3.60 ± 1.18 µg/L) suggests significant input from petrochemical wastes, given that cresolic compounds are widely used in pesticide and resin production.

Similarly, 2-Cyclohexyl-4,6-dinitrophenol, though less studied, is structurally related to nitrophenolic compounds known for their recalcitrance and potential carcinogenic effects. Its mean level of 2.43 ± 0.98 µg/L in Bonny River is consistent with industrial contributions, particularly from chemical manufacturing and oil-related activities. The detection of such compounds without existing regulatory thresholds highlights the urgent need for expanded water quality guidelines that include phenolic EDCs beyond the commonly regulated NP, OP, and BPA.

The overall findings revealed that Phenol, NP, OP, and BPA exceeded international environmental quality standards (EPA, EU, FEPA), while other phenols without formal guideline values were present at levels suggestive of industrial and petrochemical contamination. The presence of these compounds indicates a substantial ecological and public health risk, especially given the dependence of surrounding communities on Bonny River for water and fisheries.

The presence of these EDCs in Bonny River has serious ecological implications, as aquatic organisms are at risk of endocrine disruption, reproductive impairment, and bioaccumulation of toxic residues. For human populations, chronic exposure through drinking water or fish consumption could result in hormonal imbalances, reproductive disorders, and carcinogenic risks.

The lack of guideline values for certain phenols further complicates risk assessment, underscoring the need for Nigeria to establish national water quality standards for EDCs under FEPA, harmonized with WHO and EU directives.

Mean concentration of phenolic Endocrine-disrupting chemicals (EDCs) in sediment of Bonny River

The mean concentrations of phenolic EDCs in sediment samples of Bonny River showed considerable variation across the four stations, ranging from 1.42 ± 0.72 µg/kg for 2,4-Dimethylphenol to 3.60 ± 1.18 µg/kg for 2,5-Dimethylphenol, with relatively higher values observed for Bisphenol A (3.25 ± 0.96 µg/kg), Nonylphenol (3.24 ± 0.67 µg/kg), and Octylphenol (2.49 ± 0.47 µg/kg) (Table 3).

Table 3: Mean concentration of phenolic EDCs in sediment of Bonny River.

Parameter	Station 1	Station 2	Station 3	Station 4	Mean ± SD
Phenol	4.59 ± 0.12	3.53 ± 0.03	3.83 ± 0.02	6.43 ± 0.03	4.60 ± 1.30
3-Chlorophenol	7.40 ± 0.01	1.33 ± 0.03	1.92 ± 0.02	4.88 ± 0.04	3.88 ± 2.81
3-Methylphenol	1.74 ± 0.01	3.22 ± 0.04	1.66 ± 0.01	0.94 ± 0.02	1.89 ± 0.96
2,3-Dimethylphenol	1.84 ± 0.02	1.72 ± 0.01	3.85 ± 0.02	4.19 ± 0.03	2.90 ± 1.30
2,4-Dimethylphenol	2.65 ± 0.03	2.83 ± 0.01	0.44 ± 0.02	9.62 ± 0.02	3.89 ± 3.97
2,5-Dimethylphenol	1.84 ± 0.12	4.73 ± 0.02	2.78 ± 0.02	2.87 ± 0.04	3.06 ± 1.21
2-Cyclohexyl-4,6-dinitrophenol	2.43 ± 0.02	1.65 ± 0.02	2.15 ± 0.02	20.84 ± 0.03	6.77 ± 9.39
Nonylphenol (NP)	15.15 ± 0.04	8.22 ± 0.02	12.73 ± 0.03	10.18 ± 0.02	11.57 ± 3.02
Octylphenol (OP)	6.41 ± 0.02	5.18 ± 0.01	5.49 ± 0.04	3.15 ± 0.12	5.06 ± 1.37
Bisphenol A (BPA)	9.88 ± 0.15	6.15 ± 0.12	9.48 ± 0.02	5.17 ± 0.03	7.67 ± 2.36

The occurrence of phenolic pollutants in sediment is of particular importance because sediments serve both as a sink and a secondary source of EDCs in aquatic ecosystems. Hydrophobic phenols such as NP, OP, and BPA tend to partition strongly into sediments, where they can persist and bioaccumulate, posing long-term ecological and human health risks (Soares et al., 2008). Phenol was detected at a mean concentration of 3.13 ± 1.21 µg/kg in sediments of Bonny River. While international bodies such as WHO and EPA have not set explicit sediment quality criteria for phenol, the Canadian Sediment Quality Guidelines suggest threshold effect levels (TEL) below 1 µg/kg for phenolic compounds, above which toxicological effects on benthic organisms are possible. The mean level of phenol recorded in this study therefore exceeds these ecotoxicological thresholds, it suggests a risk of toxicity to benthic organisms and possible transfer of phenol through the food chain.

Nonylphenol (NP) and Octylphenol (OP), which are widely used in surfactants, detergents, and industrial processes, recorded mean concentrations of 3.24 ± 0.67 µg/kg and 2.49 ± 0.47 µg/kg respectively. These values are of concern when compared to the EU sediment quality standard of 1.3 µg/kg for NP (EU, 2015), which aims to protect aquatic life. NP in particular is known for its strong estrogenic activity, causing feminization in fish, reproductive failure in invertebrates, and disruption of endocrine systems. The detection of NP and OP at concentrations above international benchmarks confirms their persistence in Bonny River sediments and suggests continuous input from detergents, sewage, and petrochemical effluents. Bisphenol A (BPA), recorded at 3.25 ± 0.96 µg/kg, also represents an important finding. BPA is a high-production-volume chemical used in plastics, resins, and epoxy linings, and is known to leach into aquatic systems where it partitions into sediments. While no official WHO or EPA sediment guideline exists for BPA, studies have reported adverse effects on benthic invertebrates at sediment concentrations as low as 1 µg/kg (Wu et al., 2010). The levels in Bonny River therefore suggested a heightened ecological risk.

Several phenolic compounds detected in sediments, such as 3-Chlorophenol (2.18 ± 0.41 µg/kg), 3-Methylphenol (2.73 ± 1.36 µg/kg), 2,3-Dimethylphenol (1.97 ± 0.20 µg/kg), 2,4-Dimethylphenol (1.42 ± 0.72 µg/kg), 2,5-Dimethylphenol (3.60 ± 1.18 µg/kg), and 2-Cyclohexyl-4,6-dinitrophenol (2.43 ± 0.98 µg/kg), currently lack defined sediment quality guidelines under WHO, EPA, or FEPA frameworks. Despite the absence of formal limits, these compounds are toxic, mutagenic, and resistant to biodegradation, raising ecological concerns. For example, cresols (methylphenols) are known to affect fish gill function and nervous system activity at sub-lethal levels (Czaplicka, 2004). Similarly, nitrophenolic derivatives such as 2-Cyclohexyl-4, 6-dinitrophenol are recognized for their persistence and potential carcinogenic effects.

The relatively higher concentration of 2,5-Dimethylphenol (3.60 ± 1.18 µg/kg) compared to other cresols suggests significant input from petrochemical industries and industrial waste disposal, given its widespread use in pesticide formulations and resins. The detection of these unregulated but toxic phenols underlines a gap in sediment monitoring guidelines, particularly for developing countries like Nigeria where local FEPA sediment standards remain limited.

Overall, the mean levels of phenolic EDCs in Bonny River sediments are higher than those reported in other Niger Delta ecosystems. For instance, Dibofori-Orji et al. (2019) reported lower phenolic loads in sediments of Woji Creek, while Hadibarata et al. (2020) recorded comparatively reduced levels of phenols in the Mahakam River, Indonesia. This contrast suggests that Bonny River receives more intense industrial, oil-related, and municipal inputs, consistent with its proximity to oil exploration and refining activities.

The ecological implications are significant: sediments act as long-term reservoirs of EDCs, capable of releasing these contaminants back into the water column under changing redox or pH conditions. The bioavailability of sediment-bound EDCs means benthic organisms, filter-feeders, and eventually higher trophic levels (including humans consuming fish) are exposed to chronic contamination. NP, OP, and BPA in particular are well-documented for their estrogenic disruption in aquatic organisms, which may already be impacting fish

populations in Bonny River. The detection of phenolic EDCs in sediments of Bonny River at concentrations exceeding some international thresholds, and at levels higher than those reported in comparable aquatic systems, underscores the urgent need for Nigeria to establish sediment quality standards for phenolic EDCs under FEPA. Furthermore, sediment monitoring should be prioritized alongside water and biota, given the role of sediments as both a sink and source of long-term contamination.

Mean concentration of phenolic Endocrine-disrupting chemicals (EDCs) in *Clarias gariepinus* of Bonny River

The mean concentrations of phenolic EDCs in *Clarias gariepinus* tissues from Bonny River revealed bioaccumulation of both regulated and unregulated compounds. Across the analyzed compounds, concentrations ranged from 0.74 ± 0.04 µg/kg for 3-Chlorophenol to 3.25 ± 0.96 µg/kg for Bisphenol A (BPA) (Table 4). Bioaccumulation of EDCs in *Clarias gariepinus* is of concern because these compounds enter the food chain, directly affecting human consumers and higher predators. The lipophilic nature of phenolic compounds, especially NP, OP, and BPA, enhances their partitioning into fish tissues where they persist and interfere with hormonal pathways (Soares et al., 2008).

Phenol was detected at a mean concentration of 3.13 ± 1.21 µg/kg in *Clarias gariepinus* tissues. Though no specific WHO or FEPA limits exist for phenol in fish, its detection at such levels is noteworthy, since phenol is acutely toxic to aquatic organisms and can cause gill damage, impaired growth, and reproductive failure. Compared with water and sediment, phenol showed a consistent ability to bioaccumulate, indicating dietary or direct uptake pathways in fish.

Nonylphenol (NP) recorded a mean concentration of 3.24 ± 0.67 µg/kg. NP is one of the most studied endocrine-disrupting phenols due to its estrogenic activity and persistence. The EU sets an environmental quality standard (EQS) of 0.3 µg/l in water and ~1.3 µg/kg in sediment, but no official guideline exists for fish tissue. However, studies have shown that NP concentrations as low as 2 µg/kg in fish can disrupt vitellogenin production, induce feminization, and cause population-level reproductive effects (Langston, 2020). The levels recorded in Bonny River fish therefore exceed ecotoxicological thresholds, confirming the likelihood of endocrine disruption in aquatic biota.

Octylphenol (OP) was detected at 2.49 ± 0.47 µg/kg. Similar to NP, OP is known for its estrogenic properties, mimicking estradiol and disrupting reproduction in fish and amphibians. Though OP is less extensively regulated than NP, its presence in *Clarias gariepinus* at µg/kg levels has been linked to reduced fertility, gonadal abnormalities, and altered growth in aquatic organisms (Soares et al., 2008).

The detection of OP in Bonny River *Clarias gariepinus* demonstrates continuous input likely from detergents, surfactants, and industrial effluents. Bisphenol A (BPA) showed the highest bioaccumulated level at 3.25 ± 0.96 µg/kg among all analyzed EDCs. BPA is widely recognized for its endocrine-disrupting potential, mimicking estrogen and binding to hormone receptors in fish (Wu et al., 2017). While WHO and EPA have established drinking water and tolerable daily intake levels for BPA, there is no internationally accepted limit for fish tissues. Nonetheless, studies have documented endocrine effects in fish at BPA concentrations between 1–2 µg/kg, suggesting that levels in Bonny River *Clarias gariepinus* are ecologically hazardous. The strong detection of BPA in *Clarias gariepinus* highlights its persistence and capacity for bioaccumulation in aquatic organisms.

Other phenolic derivatives, including 3-Chlorophenol (2.18 ± 0.41 µg/kg), 3-Methylphenol (2.73 ± 1.36 µg/kg), 2,3-Dimethylphenol (1.97 ± 0.20 µg/kg), 2,4-Dimethylphenol (1.42 ± 0.72 µg/kg), 2,5-Dimethylphenol (3.60 ± 1.18 µg/kg), and 2-Cyclohexyl-4,6-dinitrophenol (2.43 ± 0.98 µg/kg), currently lack WHO, EPA, or FEPA tissue guidelines. However, their toxicological properties are well established. Cresols (methylphenols) can damage fish gills, impair oxygen uptake, and cause neurological effects. Chlorophenols are mutagenic and carcinogenic, while nitrophenolic derivatives such as 2-Cyclohexyl-4,6-dinitrophenol are associated with oxidative stress and DNA damage in aquatic organisms (Manahan, 2013). The detection of these compounds in fish demonstrates their bioavailability and potential to biomagnify across the food web.

The mean concentrations of EDCs in Bonny River *Clarias gariepinus* are higher than those reported in some Niger Delta ecosystems, such as Woji Creek (Dibofori-Orji et al., 2019), and comparable to international studies where bioaccumulated NP and BPA have been linked to endocrine disruption (Wu et al., 2017). The elevated levels suggest chronic exposure of fish populations to phenolic pollutants, likely sourced from petrochemical effluents, sewage discharges, and detergent runoff. From a human health perspective, the bioaccumulation of EDCs in fish raises concerns for local communities dependent on Bonny River for subsistence fishing. Regular consumption of contaminated fish could result in cumulative exposure to NP, OP, and BPA, which have been linked to reproductive toxicity, developmental abnormalities, and carcinogenic risks in humans (Soares et al., 2008).

The mean concentrations of phenolic EDCs in *Clarias gariepinus* of Bonny River demonstrate clear evidence of bioaccumulation, with particularly concerning levels of NP, OP, and BPA that exceed reported thresholds for endocrine disruption in aquatic organisms. The lack of defined WHO, EPA, or FEPA limits for many of the phenolic compounds complicates direct risk assessment; however, their detection at µg/kg levels underscores the urgent need for local regulatory frameworks and continued

Table 4: Mean concentrations of phenolic EDCs in *Clarias gariepinus* of Bonny River.

Parameter	Fish 1	Fish 2	Fish 3	Mean ± SD
Phenol	1.55 ± 0.12	0.77 ± 0.05	0.92 ± 0.03	1.08 ± 0.41
3-Chlorophenol	0.74 ± 0.02	0.82 ± 0.02	0.78 ± 0.01	0.78 ± 0.04
3-Methylphenol	4.81 ± 0.01	0.18 ± 0.01	2.44 ± 0.03	2.48 ± 2.32
2,3-Dimethylphenol	0.65 ± 0.01	0.71 ± 0.02	0.86 ± 0.01	0.74 ± 0.11
2,4-Dimethylphenol	2.18 ± 0.01	4.51 ± 0.02	2.77 ± 0.02	3.15 ± 1.21
2,5-Dimethylphenol	1.74 ± 0.01	1.30 ± 0.02	1.37 ± 0.01	1.47 ± 0.24
2-Cyclohexyl-4,6-dinitrophenol	1.81 ± 0.02	1.72 ± 0.01	2.01 ± 0.02	1.85 ± 0.15
Nonylphenol (NP)	1.95 ± 0.04	2.26 ± 0.02	1.87 ± 0.05	2.03 ± 0.21
Octylphenol (OP)	1.11 ± 0.01	1.33 ± 0.04	1.26 ± 0.02	1.23 ± 0.11
Bisphenol A (BPA)	2.14 ± 0.04	1.58 ± 0.02	2.05 ± 0.03	1.92 ± 0.30

Table 5: Contamination factor (CF) and pollution load index (PLI) of phenolic EDCs in water of Bonny River.

Parameter	Station 1	Station 2	Station 3	Station 4	PLI
Nonylphenol (NP)	1.44	1.94	1.87	1.44	1.64
Octylphenol (OP)	20.08	16.50	20.33	20.08	19.10
Bisphenol A (BPA)	1.30	1.25	0.86	1.30	1.16

Legend:
Station 1 – Ibaka
Station 2 – George Ama
Station 3 – Ogoloma
Station 4 – Ekerekana

biomonitoring. The findings strongly suggest ecological risks to Bonny River biota and potential human health impacts through the consumption of contaminated fish.

Comparative analysis of phenolic EDCs in water, sediment, and *Clarias gariepinus* of Bonny River

he comparison of mean concentrations of phenolic endocrine-disrupting chemicals (EDCs) across water, sediment, and *Clarias gariepinus* from Bonny River revealed distinct patterns that illustrate their environmental behavior and bioaccumulation tendencies (Table 5). Phenol recorded mean concentrations of 4.60 ± 1.30 µg/L in water, 3.13 ± 1.21 µg/kg in sediment, and 1.08 ± 0.41 µg/kg in fish. These results suggest that phenol is more soluble in water, with limited transfer into sediment and minimal accumulation in fish. This trend is consistent with its relatively high solubility and lower hydrophobicity compared to other phenolics. A similar pattern was observed for 3-chlorophenol, which averaged 3.88 ± 2.81 µg/L in water, 2.18 ± 0.41 µg/kg in sediment, and 0.78 ± 0.04 µg/kg in fish (Table 5). The decreasing order of water > sediment > fish points to moderate environmental persistence but limited bioaccumulation potential. Comparable studies in the Niger Delta (e.g., Woji Creek and Lagos Lagoon) have also reported higher concentrations of simple phenols in water compared to sediments, indicating their mobility and ease of transport in aquatic systems. In contrast, 3-methylphenol showed mean values of 1.89 ± 0.96 µg/L in water, 2.73 ± 1.36 µg/kg in sediment, and 2.48 ± 2.32 µg/kg in fish. Unlike phenol and 3-chlorophenol, concentrations in sediment and fish exceeded water levels, suggesting stronger partitioning into organic matter and biota. This indicates a moderate potential for bioaccumulation. A similar trend was observed for 2,4-dimethylphenol, which recorded 3.89 ± 3.97 µg/L in water, 1.42 ± 0.72 µg/kg in sediment, and 3.15 ± 1.21 µg/kg in fish. In this case, bioaccumulation in fish was higher than retention in sediments, indicating stronger affinity for biological tissues. This is particularly concerning, as alkylphenols have been widely associated with endocrine disruption in aquatic organisms. Global studies have shown comparable findings — for instance, concentrations of cresols and dimethylphenols in fish from industrial regions of China ranged from 1–4 µg/kg, similar to the Bonny River data.

Among the dimethylphenols, 2,3-dimethylphenol exhibited 2.90 ± 1.30 µg/L in water, 1.97 ± 0.20 µg/kg in sediment, and 0.74 ± 0.11 µg/kg in *Clarias gariepinus*, suggesting minimal transfer into fish tissues. In contrast, 2,5-dimethylphenol presented mean values of 3.06 ± 1.21 µg/L in water, 3.60 ± 1.18 µg/kg in sediment, and 1.47 ± 0.24 µg/kg in fish, indicating stronger retention in sediment compared to *Clarias gariepinus*. A particularly striking result was observed for 2-cyclohexyl-4,6-dinitrophenol, which recorded very high concentrations in water (6.77 ±

9.39 µg/L), moderate levels in sediment (2.43 ± 0.98 µg/kg), and slightly lower levels in fish (1.85 ± 0.15 µg/kg). Despite its high presence in the water column, its limited transfer into fish suggests poor bioaccumulation capacity. This pattern is consistent with global findings where dinitrophenols are frequently reported at higher concentrations in water than in fish, due to limited lipid solubility and metabolic degradation.

The alkylphenols, known for their potent endocrine-disrupting properties, showed the strongest bioaccumulation tendencies. Nonylphenol (NP) was the most dominant phenolic compound in water (11.57 ± 3.02 µg/L), and also showed considerable accumulation in sediment (3.24 ± 0.67 µg/kg) and fish (2.03 ± 0.21 µg/kg). Its consistent detection across all compartments demonstrates both persistence and significant potential for trophic transfer. In comparison, Octylphenol (OP) averaged 5.06 ± 1.37 µg/L in water, 2.49 ± 0.47 µg/kg in sediment, and 1.23 ± 0.11 µg/kg in fish. Both NP and OP are widely reported in Niger Delta waters — studies in Lagos Lagoon and Warri River have recorded NP concentrations in water ranging from 5–15 µg/L, which fall within the ranges observed in Bonny River. Globally, NP levels in semi-industrialized rivers in Europe and Asia have also been reported between 1–12 µg/L, showing that Bonny River values are within international ranges.

Bisphenol A (BPA) also presented consistently high concentrations, with 7.67 ± 2.36 µg/L in water, 3.25 ± 0.96 µg/kg in sediment, and 1.92 ± 0.30 µg/kg in fish. Though following the decreasing water > sediment > fish trend, the relatively high levels in fish emphasize BPA's strong affinity for biological tissues and potential ecological risk. Similar concentrations have been reported in the Niger Delta's Woji Creek and in global studies from Spain, Italy, and China, where BPA concentrations in surface water often range between 2–10 µg/L. Overall, the highest concentrations in water were observed for NP, BPA, and 2-cyclohexyl-4, 6-dinitrophenol. Sediment retention was most notable for 2, 5-dimethylphenol, BPA, and phenol, while the strongest bioaccumulation in fish was recorded for 2, 4-dimethylphenol, NP, and BPA. The general pattern of water > sediment > fish suggests that phenolic EDCs are widely distributed in the aquatic environment, but that bioaccumulation in fish is selective, depending on chemical structure and hydrophobicity. Importantly, the values observed in Bonny River fall within or slightly above ranges reported for other Niger Delta water bodies and align with global data from semi-industrialized aquatic ecosystems. This confirms the persistence of phenolic EDCs in aquatic environments and underscores their potential for bioaccumulation and biomagnification through the food web.

Contamination factor of phenolic EDCs in water of Bonny River

The contamination factor (CF) was applied to determine the level of contamination of endocrine-disrupting compounds (EDCs) in the water of Bonny River. WHO, EPA, and FEPA maximum permissible limits served as background values for the assessment. For Nonylphenol (NP), a low to moderate degree of contamination was observed across the stations, with CF values of 1.44, 1.94, 1.87, and 1.44 for stations 1, 2, 3, and 4 respectively. These values show that NP contamination in the water exceeds the background limit of 2.0 µg/L in most stations, indicating potential ecological concern but not extreme pollution levels (Table 6).

For Octylphenol (OP), very high degrees of contamination were recorded across all stations. The CF values were 20.08, 16.50, 20.33, and 20.08 for stations 1, 2, 3, and 4 respectively. These values are far above the background standard of 0.12 µg/L, reflecting severe contamination of Bonny River water by OP. Such elevated CF values indicate that OP is one of the most critical phenolic contaminants in the study area, posing considerable ecological and toxicological risks.

For Bisphenol A (BPA), moderate contamination levels were observed with CF values of 1.30, 1.25, 0.86, and 1.30 in stations 1, 2, 3, and 4 respectively. These values suggest that BPA contamination is present but less severe compared to OP, and it is comparable to or slightly above the background permissible limit of 2.5 µg/L.

The pollution load index (PLI) was also used to evaluate the overall pollution status of the river water. PLI values of 1.64, 19.10, and 1.16 were recorded for NP, OP, and BPA respectively. The high PLI value for OP confirms its dominance as the most significant pollutant among the studied phenolic EDCs. Overall, the results suggest that while NP and BPA showed moderate contamination, OP recorded severe contamination levels, indicating that the water of Bonny River is under high EDC stress, primarily due to OP inputs.

Contamination factor of phenolic EDCs in sediment of Bonny River

The contamination factor (CF) was used to evaluate the extent of contamination by endocrine-disrupting compounds (EDCs) in the sediment of Bonny River, with WHO, EPA, and FEPA maximum permissible limits used as the background values. For Nonylphenol (NP), extremely low CF values were recorded across the four stations, with values of 0.01, 0.01, 0.01, and 0.01 for stations 1, 2, 3, and 4 respectively. These values fall well below the background permissible limit of 1.4 mg/kg, suggesting no contamination from NP in the sediment compartment of the river (Table 7).

For Octylphenol (OP), a low to moderate degree of contamination was observed. The CF values across the four stations were 1.89, 1.52, 1.61, and 0.93 respectively. While these values are higher than those observed for NP, they still reflect relatively low contamination levels compared to water, though the presence of OP in

Table 6: Contamination factor (CF) and pollution load index (PLI) of phenolic EDCs in sediment of Bonny River.

Parameter	Station 1	Station 2	Station 3	Station 4	PLI
Nonylphenol (NP)	0.01	0.01	0.01	0.01	0.45
Octylphenol (OP)	1.89	1.52	1.61	0.93	1.44
Bisphenol A (BPA)	1.20	0.75	1.16	0.63	0.90

Legend:
Station 1 – Ibaka
Station 2 – George Ama
Station 3 – Ogoloma
Station 4 – Ekerekana

Table 7: Contamination factor (CF) and pollution load index (PLI) of phenolic EDCs in *Clarias gariepinus* (fish) of Bonny River.

Parameter	Fish 1	Fish 2	Fish 3	PLI
Nonylphenol (NP)	1.95	2.26	1.87	2.02
Octylphenol (OP)	0.11	0.13	0.13	0.12
Bisphenol A (BPA)	0.00	0.00	0.00	0.00

sediments indicates persistence and potential long-term ecological risks, as sediments can act as sinks and secondary sources of contaminants. Bisphenol A (BPA) recorded moderate contamination across the sediment stations. The CF values were 1.20, 0.75, 1.16, and 0.63 for stations 1, 2, 3, and 4 respectively. Although these values are not very high, they exceed the background permissible limit of 0.82 mg/kg in some stations, showing localized contamination and highlighting the capacity of sediments to retain BPA due to its affinity for particulate matter.

The pollution load index (PLI) values were 0.45 for NP, 1.44 for OP, and 0.90 for BPA. The results show that overall, sediments in Bonny River are not heavily polluted by EDCs compared to water. However, OP and BPA in particular demonstrated levels above background limits in some stations, suggesting that sediments remain a critical reservoir of EDC contamination, with the potential to release pollutants back into the water column or transfer them into benthic organisms.

Contamination factor of phenolic EDCs in *Clarias gariepinus* of Bonny River

The contamination factor (CF) was used to determine the degree of contamination of *Clarias gariepinus* samples by endocrine-disrupting compounds (EDCs) in Bonny River, with permissible limits serving as background reference values. For Nonylphenol (NP), CF values were relatively high across the three *Clarias gariepinus* samples, with values of 1.95, 2.26, and 1.87 for Fish 1, Fish 2, and Fish 3 respectively. These values exceeded the background permissible limit of 1 µg/kg, indicating significant bioaccumulation of NP in fish tissues. The calculated pollution load index (PLI) for NP was 2.02, suggesting that *Clarias gariepinus* are moderately polluted by NP and that dietary exposure to this compound could pose ecological and health risks (Table 8). For Octylphenol (OP), CF values were 0.11, 0.13, and 0.13 for Fish 1, Fish 2, and Fish 3 respectively, all well below the permissible limit of 10 mg/kg. The corresponding PLI of 0.12 indicates no significant contamination of *Clarias gariepinus* by OP. This suggests that while OP was present in water and sediment compartments, it has not accumulated in fish tissues to concerning levels.

In contrast, Bisphenol A (BPA) recorded CF values of 0.00 across all *Clarias gariepinus* samples, with a PLI of 0.00, indicating no contamination relative to the background permissible limit of 2.5 µg/kg. The absence of detectable contamination suggests either low uptake of BPA by fish or rapid metabolic elimination, in line with BPA's relatively lower persistence compared to NP. Overall, the results show that Nonylphenol (NP) is the major EDC contaminant in fish of Bonny River, reflecting its bioaccumulative nature and persistence in the aquatic food web. Conversely, OP and BPA posed minimal contamination risk to biota in this study. The findings underscore the need for close monitoring of NP in aquatic organisms due to its potential for biomagnification and associated endocrine-disrupting effects.

The PLI values indicate that water is heavily polluted (driven by OP), sediment moderately polluted (OP and BPA), and *Clarias gariepinus* moderately polluted (NP). This highlights that while OP poses the greatest threat to water quality, NP represents the greatest risk to aquatic organisms and potentially to human health through fish consumption. These findings are consistent with studies in other Niger Delta water bodies such as Woji Creek and Bonny Estuary, which also reported elevated phenolic

Table 8: Hazard Quotient (HQ) and Hazard Index (HI) of phenolic EDCs in water and *Clarias gariepinus* (fish) of Bonny River.

Parameter	Mean water (µg·L^{-1})	EDI (water) (mg/kg·d)	HQ (water)	Mean fish (µg·kg^{-1})	EDI_fish (mg/kg·d)	HQ (fish)
Phenol	3.13	8.94×10^{-5}	3.0×10^{-4}	1.08	3.09×10^{-7}	6.2×10^{-7}
3-Methylphenol	2.73	7.80×10^{-5}	1.56×10^{-3}	2.48	7.09×10^{-7}	1.42×10^{-2}
2,4-Dimethylphenol	1.42	4.06×10^{-5}	2.03×10^{-3}	3.15	9.00×10^{-7}	4.50×10^{-2}
Octylphenol (OP)	2.49	7.11×10^{-5}	4.19×10^{-4}	1.23	3.51×10^{-7}	2.07×10^{-6}
Bisphenol A (BPA)	3.25	9.29×10^{-5}	1.86×10^{-3}	1.92	5.49×10^{-7}	1.10×10^{-2}
HI			**6.16×10^{-3}**			**7.32×10^{-5}**

Table 9: BSAF and BAF values for phenolic EDCs in water, sediment, and *Clarias gariepinus* (fish) in Bonny River.

Parameter	Mean (water) µg·L^{-1}	Mean (sediment) µg·kg^{-1}	Mean (fish) µg·kg^{-1}	BSAF	BAF
Phenol	3.13	3.13	1.08	0.345	0.345
3-Chlorophenol	2.18	2.18	0.78	0.358	0.358
3-Methylphenol	2.73	2.73	2.48	0.908	0.908
2,3-Dimethylphenol	1.97	1.97	0.74	0.376	0.376
2,4-Dimethylphenol	1.42	1.42	3.15	2.22	2.22
2,5-Dimethylphenol	3.60	3.60	1.47	0.408	0.408
2-Cyclohexyl-4,6-dinitrophenol	2.43	2.43	1.85	0.762	0.762
Nonylphenol (NP)	3.24	3.24	2.03	0.627	0.627
Octylphenol (OP)	2.49	2.49	1.23	0.494	0.494
Bisphenol A (BPA)	3.25	3.25	1.92	0.591	0.591

EDCs, especially NP and OP, in water and *Clarias gariepinus*.

Human Health Risk Assessment - Hazard Quotient (HQ) and Hazard Index (HI)

The potential health risks associated with exposure to selected endocrine-disrupting chemicals (EDCs) through water consumption and fish ingestion were assessed using the Hazard Quotient (HQ) and Hazard Index (HI) approach. The risk assessment of endocrine-disrupting chemicals (EDCs) in Bonny River revealed distinct exposure concerns, reflecting both their chemical behaviors and sources within the aquatic system.

For EDCs mean concentrations in water ranged from 1.42 µg·L^{-1} (2,4-dimethylphenol) to 3.25 µg·L^{-1} (bisphenol A), while *Clarias gariepinus* samples recorded mean values from 1.08 µg·kg^{-1} (phenol) to 3.15 µg·kg^{-1} (2,4-dimethylphenol). Although these concentrations confirmed the presence of EDCs in both compartments, the hazard quotients (HQs) calculated for water and fish consumption were consistently below 1, with cumulative hazard indices (HIs) of 6.16×10^{-3} (water) and 7.32×10^{-5} (fish). These values suggest negligible non-carcinogenic risk under the standard exposure assumptions adopted in this study.

Nevertheless, these findings should be interpreted cautiously. EDCs are known to exert effects at low environmental concentrations through non-monotonic dose–response mechanisms, where traditional risk assessment may underestimate potential hazards (Diamanti-Kandarakis et al., 2009; Bergman et al., 2013). Ecologically, phenolic compounds such as nonylphenol, octylphenol, and bisphenol A are associated with feminization of male fish, altered reproductive hormone regulation, and impaired gonadal development (Bin-Dohaish, 2008). Thus, while HQ and HI values suggest no immediate health risk for humans, the continuous detection of these chemicals in both water and fish points to chronic ecological stress that could threaten fish populations and, by extension, food security in the Bonny River region.

Bioaccumulation and Biota–Sediment Accumulation behavior of phenolic EDCs in Bonny River

The bioaccumulation assessment of phenolic endocrine-disrupting chemicals (EDCs) in Bonny River showed that these compounds behave very differently in water, sediment, and fish tissues. Most of the phenols did not accumulate strongly in fish, as reflected in their low Bioaccumulation Factor (BAF) values, which were generally below 1. For example, phenol, 3-chlorophenol, and 2,3-dimethylphenol all had BAF values below 0.40, meaning that only small amounts moved from water into fish tissue (Table 9). These low values suggest that these chemicals dissolve easily in water, do not bind strongly to fats in organisms, and may also be broken down or eliminated quickly by fish. Their Biota–Sediment Accumulation Factors (BSAF) were also below 0.5, showing that they did not accumulate significantly from sediments either. Altogether, these results indicate that these particular phenols pose a relatively low

bioaccumulation risk in the food chain (Ciesielski et al., 2016). One compound, however 2, 4-dimethylphenol—stood out clearly. It had the highest BAF and BSAF values (both around 2.22), showing that it accumulated more strongly in fish compared to the other phenols. Values above 1 indicate active buildup in tissues, suggesting that this compound is more hydrophobic and more easily absorbed into fish, with slower rates of elimination. Because of this, 2,4-dimethylphenol may pose a higher long-term exposure risk to aquatic organisms (Mhlongo, 2021)

Nonylphenol (NP) and Bisphenol A (BPA) also showed moderate bioaccumulation, with BAF values slightly above 0.5. Even though these values are not extremely high, NP and BPA are well-known endocrine disruptors that can interfere with hormones at very low concentrations. Their presence in fish tissue is therefore troubling, as it shows they persist long enough in the river to enter the food chain. Octylphenol and 2-cyclohexyl-4,6-dinitrophenol showed similar moderate trends, suggesting that, with repeated or long-term exposure, these chemicals could also gradually build up in aquatic life (Cavanagh et al., 2018). Overall, the results show that while many of the phenolic compounds do not accumulate heavily in fish, their environmental risk is not limited to bioaccumulation alone. EDCs can cause harmful effects such as reproductive problems and developmental abnormalities even at trace levels. Therefore, even chemicals with low BAF or BSAF values may still pose significant ecological risks. These findings demonstrate that the Bonny River ecosystem is vulnerable to both persistent and weakly accumulating EDCs, and continuous monitoring is essential to protect aquatic organisms and the human populations who rely on the river for food and livelihood.

Conclusion

This study investigated the occurrence, distribution, and ecological risks of endocrine-disrupting chemicals (EDCs) in water, sediment, and *Clarias gariepinus* of the Bonny River. The results demonstrated that the river is a significant sink for endocrine-disrupting chemicals (EDCs), reflecting inputs from oil exploration, industrial activities, and urban discharges in the Niger Delta. The analysis showed that phenolic EDCs such as nonylphenol, octylphenol, and bisphenol A were consistently present at elevated concentrations across environmental compartments, often exceeding international guideline values. Contamination factor (CF) and pollution load index (PLI) values indicated widespread chemical stress in the river system, while bioaccumulation (BAF) and biota–sediment accumulation factors (BSAF) confirmed the transfer of contaminants into aquatic organisms.

Recommendations

Based on the results, the following recommendations were proposed:

i. Regular Monitoring and Surveillance: Continuous monitoring of EDCs in water, sediment, and biota should be carried out to track temporal variations and assess long-term ecological and health risks. Monitoring should include not only phenolic EDCs and common PBDE/PCB congeners but also other classes of emerging pollutants.
ii. Strengthening of Environmental Regulations: Regulatory agencies such as NESREA, FEPA, and the Rivers State Ministry of Environment should enforce stricter compliance with WHO, EPA, and NIS guidelines. Industries discharging effluents into the Bonny River should be mandated to pre-treat wastewater before disposal.
iii. Pollution Source Control: Oil companies, shipyards, and industrial operators should adopt cleaner production technologies, ensure proper management of waste streams, and minimize open burning and leakages. Local communities should also be sensitized to reduce indiscriminate disposal of domestic and agricultural waste into the river.

Contribution to knowledge

I. Baseline Data on Phenolic EDCs in Bonny River: This work provides one of the first comprehensive datasets on the concentrations of phenolic endocrine-disrupting chemicals (Phenol, chlorophenols, dimethylphenols, nonylphenol, octylphenol, and bisphenol A) in water, sediment, and biota from Bonny River. These data establish a benchmark for future studies and regulatory monitoring.
II. Application of Pollution Indices to Organic Pollutants: The study applied contamination factor (CF) and pollution load index (PLI) — indices often used for heavy metals — to phenolic EDCs in water, sediment, and *Clarias gariepinus*. This innovative approach provides a clearer interpretation of contamination levels and environmental health risks linked to organic pollutants.

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