

Endocrine Disruption Potential of Pharmaceutical Residues and Parasitological Responses to Heavy Metal Pollution in Ikot Abasi Estuary, Akwa Ibom State, Nigeria.

Mahmoud Amina B¹., Farida G²., Okpoji, Awajjiroijana U^{3*}., Etesin Monday U⁴., Akpan Nsima A⁵., Nosike Elvis I⁶., Obi Justina N⁷., Ahmad Sani I⁸., Oji Nse N⁹., Okonkwo Princewill C⁹., and Godson Augustina¹⁰,

¹ Department of Chemistry, Nigeria Police Academy, Wudil, Kano, Nigeria

² Department of Biological Sciences, Nigeria Police Academy, Wudil, Kano, Nigeria

³ Department of Pure and Industrial Chemistry, University of Port Harcourt, Choba, Nigeria

^{4,10} Department of Chemistry, Akwa Ibom State University, Ikot Akpaden, Nigeria

⁵ Department of Chemical Sciences, Ritman University, Ikot Ekpene, Nigeria

⁶ Department of Chemistry, Federal Polytechnic Nekede, Nigeria.

⁷ Department of Chemistry, Federal University of Technology, Owerri, Nigeria.

⁸ Department of Chemistry, Maryam Abacha American University of Nigeria (MAAUN), Kano, Nigeria.

⁹ Department of Science Laboratory Technology (S.L.T), Federal Polytechnic Ugep, Nigeria.

Accepted 25, March, 2026

This study evaluated the occurrence of heavy metals, pharmaceutical residues, and endocrine-disrupting compounds in Ikot Abasi Estuary, Akwa Ibom State, Nigeria and assessed their ecological and public health implications. Water, sediment, and fish samples were collected from upstream, midstream, and downstream sections of the estuary. Heavy metals were determined using atomic absorption spectrophotometry, while pharmaceutical residues and endocrine-disrupting compounds were analysed using high-performance liquid chromatography. The fish samples were examined for endocrine and histopathological alterations, and parasitological responses, and human health risk was assessed to determine contaminant levels in the edible fish. The results showed that the concentration of Cd, Cr, Ni, Hg, estradiol, and ethinylestradiol increased significantly from upstream to downstream. The downstream water contained Pb and Hg concentrations of 0.056 and 0.006 mg/L, respectively, while sediment concentrations reached 48.9 mg/kg for Pb and 1.04 mg/kg for Hg. Estradiol and ethinylestradiol concentrations downstream were 0.041 and 0.026 µg/L, respectively, exceeding the recommended. Male fish exposed to the downstream showed marked endocrine disruption at 31%. Histopathological examination showed severe lesions in the gills, liver, and gonads. Parasite prevalence and diversity increased significantly with higher contaminant levels. There were strong positive correlations between estradiol and male vitellogenin ($r = 0.91$), heavy metals and parasite intensity ($r = 0.87$), and mercury and hepatic necrosis ($r = 0.84$). The assessment of human health risks indicated that the target hazard quotient for lead and mercury was above 1. The total hazard index was 4.46. Carcinogenic risk values for lead and cadmium exceeded acceptable limits. The study concludes that Ikot Abasi Estuary is under severe ecological stress due to combined contamination by heavy metals and endocrine-disrupting compounds, with potential consequences for aquatic life and human health.

Keywords: Ikot Abasi Estuary; heavy metals; pharmaceuticals; endocrine disruption; fish pathology; parasites; human health risk.

1.0 Introduction

Aquatic ecosystems are increasingly threatened by contamination arising from industrialisation, urbanisation, agriculture, and petroleum-related activities. Rivers, estuaries, lagoons, and coastal waters frequently receive large quantities of untreated or partially treated wastes containing heavy metals, pharmaceuticals, personal care products, and endocrine-disrupting chemicals (Akpór & Muchie, 2011; Patel et al., 2019). Because many of these pollutants are resistant to degradation and are continuously introduced through industrial discharge, hospital effluents, municipal wastewater, agricultural runoff, and petroleum exploration activities, they continue to exist in the environment (Kashif et al., 2021; Obinna et al., 2023). As a result, aquatic ecosystems are now significant sinks for both established and new pollutants, which have detrimental effects on the environment and human health (Li et al., 2024).

Because heavy metals are persistent, non-biodegradable, and able to build up in sediments and aquatic creatures, they rank among the most significant contaminants in aquatic systems. Lead, cadmium, chromium, nickel, mercury, copper, and zinc are among the metals that can find their way into rivers and estuaries through industrial discharge, petroleum operations, metal structure corrosion, atmospheric deposition, and urban runoff (Jaishankar et al., 2014). These metals can enter aquatic systems through the food chain or be directly absorbed by fish and other aquatic creatures from water and sediment (Zhao et al., 2012). Through bioaccumulation and biomagnification, their concentrations frequently rise gradually, exposing humans and higher trophic creatures to increased levels of pollution (Castro-Gonzalez & Mendez-Armenta, 2008).

There is ample evidence of the toxicological and ecological importance of heavy metals. Because they can induce brain

impairment, renal dysfunction, carcinogenicity, and reproductive abnormalities in both people and animals, lead and cadmium are especially dangerous (Jaishankar et al., 2014). Because mercury easily builds up in fish tissues and can harm exposed creatures' neurological and reproductive systems, it is also a serious problem (Castro-Gonzalez & Mendez-Armenta, 2008). Similarly, fish metabolism, development, enzyme activity, and reproductive function can all be affected by high quantities of copper and zinc (Eisler, 1993). According to Varanka et al. (2001), fish exposed to copper and other heavy metals undergo significant morphological and biochemical changes in their gills and liver.

Pharmaceuticals and endocrine-disrupting substances have recently become significant contaminants of aquatic habitats, in addition to heavy metals. Analgesics, antibiotics, anti-inflammatory medications, hormones, antidepressants, and personal care items are among the pharmaceuticals of environmental concern that find their way into water bodies.

through sewage effluents, hospital discharges, the pharmaceutical industry, aquaculture, and agricultural runoff (Patel et al., 2019). These substances frequently remain in aquatic systems for extended periods of time since conventional wastewater treatment facilities are unable to totally eliminate them (AL Falahi et al., 2022; Kashif et al., 2021). Pharmaceutical residues have been found in rivers and coastal habitats in South Africa, Brazil, Turkey, and Southeast Asia, according to recent investigations (Nibamureke & Barnhoorn, 2025; dos Santos et al., 2025; Deryal et al., 2025; Lee et al., 2025).

Endocrine-disrupting chemicals, such as steroid hormones, synthetic estrogens, bisphenol A, phthalates, and other substances that can interfere with hormone balance in living things, are particularly significant among these new pollutants (Gonsioroski et al., 2020). Endocrine disruptors can interfere with hormone synthesis and metabolism, imitate natural hormones, or block hormone receptors (Kar et al., 2021). Chronic exposure to endocrine-disrupting substances has been linked to feminisation, changed sex ratios, reproductive abnormalities, decreased fertility, and poor gonadal development in fish and other aquatic species (Okuthe et al., 2025). It has been demonstrated that high levels of ethinylestradiol and estradiol in water cause male fish to produce vitellogenin and result in intersex conditions, which are defined by the presence of both male and female reproductive tissues in one individual (Arcand-Hoy & Benson, 1998; Gonsioroski et al., 2020).

One of the most trustworthy indicators of exposure to estrogenic substances is the development of vitellogenin in male fish (Arcand-Hoy & Benson, 1998). Similarly, endocrine disruption in fish populations is frequently assessed using changes in the gonadosomatic index, hepatosomatic index, estrogen-to-testosterone ratio, and intersex incidence (Kar et al., 2021). In tilapia taken from a contaminated freshwater reservoir in Nigeria, Adeogun et al. (2016) found increased levels of male vitellogenin, gonadal abnormalities, and intersex. Fish exposed to endocrine-disrupting toxins in various aquatic habitats worldwide have shown similar results (Okuthe et al., 2025; Peivasteh-Roudsari et al., 2023).

Fish tissue histopathological analysis sheds more light on how contaminants affect aquatic life. Fish that are exposed to endocrine disruptors and heavy metals frequently have gill, liver, and gonad abnormalities. According to Varanka et al. (2001), liver vacuolation and hepatic necrosis signify extreme physiological stress and compromised detoxifying ability, whereas gill lamellar fusion and hyperplasia decrease respiratory efficiency. In contaminated environments, gonadal atrophy and oocyte degeneration are also significant markers of impaired reproduction (Adeogun et al., 2016).

Therefore, histopathological alterations serve as useful biomarkers for evaluating the health status of fish inhabiting polluted ecosystems. The present study was therefore undertaken to determine the concentrations of heavy metals, pharmaceutical residues, and endocrine-disrupting compounds in Ikot Abasi Estuary, to evaluate their effects on fish physiology and parasite burden, and to assess the potential health risks associated with consumption of contaminated fish from the estuary.

2.0 Literature Review

Parasites and their hosts are increasingly used as biological indicators of environmental contamination. Parasites may accumulate contaminants at concentrations higher than those observed in their hosts and are therefore sensitive indicators of environmental quality (Sures, 2005). Host-parasite systems have been widely applied in pollution studies because parasite prevalence, abundance, and diversity often increase in stressed or contaminated environments (Goater et al., 2013). Sures and Reimann (2003) demonstrated that fish parasites may contain much higher concentrations of trace metals than the tissues of their hosts. Likewise, Vidal-Martínez et al. (2010) reported that parasites of shrimp and fish could be used as bioindicators of chemical contamination in estuarine systems. Fish immunity may be weakened by the presence of heavy metals and endocrine-disrupting substances, making them more vulnerable to parasite infection and changing the dynamics of parasite diversity and transmission. In Nigeria's Akwa Ibom State, the Ikot Abasi Estuary is a significant estuarine environment. The local towns' livelihoods, transportation, pleasure, and fisheries are all supported by the estuary. Nonetheless, the region in which the area is located is marked by a high level of petroleum exploration, industrial activity, urbanisation, and an increase in the release of household and municipal trash. These actions make it easier for drugs, heavy metals, and substances that affect hormones to enter the estuary. Contamination of these resources could pose serious ecological and public health problems because local residents mostly depend on fish and other aquatic species that are taken from the estuary (Anarado et al., 2023; Okpoji et al., 2025).

The combined presence of heavy metals, pharmaceutical residues, endocrine-disrupting compounds, and parasitological responses in the Ikot Abasi Estuary is still poorly understood, despite the fact that numerous studies have examined heavy metal contamination or hydrocarbon pollution in Nigerian aquatic environments (Etesin et al. 2025; Ekwere et al., 2025). Most previous studies have focused on only one category of contaminant without considering the interactive effects of multiple pollutants and their consequences for fish health and human exposure. Thus, an integrated investigation that concurrently assesses the presence of contaminants, endocrine disruption, histopathological reactions, parasitological alterations, and dangers to human health in the estuary is required.

3.0 Materials and Methods

3.1 Study Area

The study was conducted in the Ikot Abasi Estuary located in Ikot Abasi Local Government Area of Akwa Ibom State,

Nigeria. The estuary forms part of the Qua Iboe River system and is influenced by tidal interactions from the Atlantic Ocean. Intensive anthropogenic activities, including oil and gas exploration, industrial discharges, artisanal fishing, urban settlements, and domestic wastewater inputs, characterise the area. Three sampling stations were established along the estuary based on pollution gradients: upstream (relatively less impacted), midstream (moderately impacted), and downstream (highly impacted, close to industrial and municipal discharge points).

3.2 Sampling Design and Sample Collection

To take seasonal variability into account, a cross-sectional environmental study was carried out throughout the dry and early wet seasons. To guarantee representativeness and analytical accuracy, water, sediment, and fish samples were taken in triplicate from each station. Tilapia (*Tilapia nilotica*), catfish (*Clarias gariepinus*), and croaker (*Pseudotolithus* sp.) were among the fish species chosen for the investigation.

3.2 Sampling Design and Sample Collection

A cross-sectional environmental survey was conducted during the dry and early rainy seasons to account for seasonal variability. Water, sediment, and fish samples were collected from each station in triplicate to ensure representativeness and analytical precision. Fish species selected for the study included tilapia (*Tilapia nilotica*), catfish (*Clarias gariepinus*), and croaker (*Pseudotolithus* sp.), based on their abundance and high consumption rates within the study area.

3.3 Collection and Preservation of Water Samples

Surface water samples were collected at a depth of 20–30 cm below the water surface using pre-cleaned sampling containers. Samples for pharmaceutical residue analysis were collected in 1 L amber glass bottles to minimise photodegradation, while samples for heavy metal determination were collected in acid-washed polyethylene bottles. Water samples designated for metal analysis were preserved immediately with concentrated nitric acid to achieve a pH less than 2. All samples were transported to the laboratory in ice chests and stored at 4 °C before analysis.

3.4 Collection and Preparation of Sediment Samples

Sediment samples were collected from the upper 0–10 cm layer of the estuarine bed using a stainless-steel grab sampler. Multiple subsamples were obtained at each station and combined to form representative composite samples. The samples were air-dried at room temperature, homogenised, and sieved through a 2 mm mesh to remove coarse materials before laboratory analysis.

3.5 Collection and Preparation of Fish Samples

Adult fish specimens were collected from local fishermen operating at each sampling station. As soon as possible, the samples were put on ice and brought to the lab. Body weight and length were among the morphometric measurements that were noted. The caudal vein was used to draw blood samples for the study of endocrine biomarkers. After the fish were dissected, organs such as the intestine, liver, gills, and gonads were removed for parasitological and histological analysis.

3.6 Determination of Pharmaceutical Residues in Water

Pharmaceutical residues were extracted using solid-phase extraction. A volume of 500 mL of each filtered water sample (0.45 µm) was passed through C18 extraction cartridges. The retained analytes were eluted with methanol, concentrated, and analysed using high-performance liquid chromatography. Diclofenac, ibuprofen, paracetamol, ciprofloxacin, sulfamethoxazole, oestradiol, and ethinylestradiol were among the target substances. Calibration curves created from approved analytical standards were used for quantification.

3.7 Heavy Metal Determination in Water and Sediment

While sediment samples were digested using a combination of nitric acid, perchloric acid, and hydrochloric acid, water samples were digested using pure nitric acid. Atomic absorption spectrophotometry was used to examine the digested samples for Pb, Cd, Cr, Ni, Cu, Zn, and Hg. In particular, cold vapour atomic absorption spectrophotometry was used to determine mercury. To guarantee analytical accuracy, quality control procedures included the use of certified reference materials, duplicate samples, and reagent blanks.

3.8 Analysis of Endocrine Biomarkers

Enzyme-linked immunosorbent assay methods were used to measure the amounts of male plasma vitellogenin. Commercial assay kits were used to assess the amounts of testosterone and oestrogen in plasma. The following formula was used to determine the hepatosomatic and gonadosomatic indices:

$$\text{GSI} = (\text{Gonad Weight} / \text{Body Weight}) \times 100$$

$$\text{HSI} = (\text{Liver Weight} / \text{Body Weight}) \times 100$$

For every sample, the ratio of oestrogen to testosterone was determined. In order to identify any intersex abnormalities, gonadal tissues were further investigated under a microscope.

3.9 Analysis of Histopathology

Gill, liver, and gonad tissue samples were embedded in paraffin wax after being dehydrated in graded ethanol, cleaned in xylene, and fixed in 10% buffered formalin for 48 hours. Using a microtome, sections around 5 µm thick were created, and they were then stained with haematoxylin and eosin. Pathological abnormalities include lamellar fusion, epithelial hyperplasia, hepatic vacuolation, necrosis, gonadal atrophy, and oocyte degeneration were detected under a microscope.

3.10 Examination of Parasites

Each fish's skin, gills, intestine, liver, and body cavity were checked for parasites. Standard taxonomic keys were used to identify the recovered parasites, which were stored in 70% ethanol. Prevalence, mean intensity, and mean abundance were among the parasitological indices that were computed. The Shannon diversity index was used to calculate parasite diversity.

3.11 Human Health Risk Assessment

The potential health risks associated with fish consumption were evaluated using estimated daily intake, target hazard quotient, hazard index, and carcinogenic risk. The equations used were:

$$EDI = (C \times IR) / BW$$

$$THQ = EDI / RfD$$

$$HI = \sum THQ$$

$$CR = EDI \times CSF$$

Where C represents contaminant concentration in fish tissue (mg/kg), IR is ingestion rate (0.031 kg/day), BW is average body weight (70 kg), RfD is the oral reference dose, and CSF is the cancer slope factor. Reference dose values (mg/kg/day) included Pb (0.0035), Cd (0.001), Cr (0.003), Ni (0.02), Cu (0.04), Zn (0.3), and Hg (0.0003). Cancer slope factors ((mg/kg/day)⁻¹) included Pb (0.0085), Cd (6.1), Cr (0.5), and Ni (0.91). Risk interpretation followed standard criteria, where THQ values less than 1 indicate no significant risk, while values greater than 1 indicate potential health risk. Acceptable carcinogenic risk ranges from 10⁻⁶ to 10⁻⁴.

3.12 Statistical Analysis

All data were expressed as mean ± standard deviation. Differences among sampling stations were analysed using one-way analysis of variance followed by Tukey's post hoc test. Pearson correlation analysis was used to evaluate relationships between contaminant concentrations and biological responses. Statistical significance was set at p < 0.05. All statistical analyses were performed using SPSS version 25.

4.0 Results

At every sampling location, pharmaceutical residues were found, and their amounts steadily increased from upstream to downstream. Diclofenac concentrations were more than an order of magnitude higher than the recommended value of 0.10 µg/L at all locations, ranging from 0.82 ± 0.06 µg/L upstream to 1.67 ± 0.12 µg/L downstream. At midstream and downstream locations, ciprofloxacin levels were also elevated, rising from 0.48 ± 0.04 µg/L upstream to 0.95 ± 0.07 µg/L downstream, exceeding the recommended threshold of 0.50 µg/L. Particularly notable exceedances were seen in oestrogenic substances. The range of oestradiol concentrations was 0.019 ± 0.002 to 0.041 ± 0.004 µg/L, which was around 19–41 times higher than the recommended level of 0.001 µg/L. Similarly, ethinylestradiol exceeded the limit (0.0005 µg/L) by more than 20–50 times, ranging from 0.011 ± 0.001 to 0.026 ± 0.003 µg/L. Ibuprofen, paracetamol, and sulfamethoxazole, although without specified guideline limits, exhibited relatively high concentrations, with paracetamol showing the highest values (2.14–3.52 µg/L) as shown in Table 1.

Table 1. Concentration of Pharmaceutical Residues in Surface Water of Ikot Abasi Estuary

Pharmaceutical Residue	Upstream (µg/L)	Midstream (µg/L)	Downstream (µg/L)	WHO Guideline
Diclofenac	0.82 ± 0.06	1.24 ± 0.09	1.67 ± 0.12	0.10
Ibuprofen	1.35 ± 0.10	1.91 ± 0.14	2.43 ± 0.18	ND
Paracetamol	2.14 ± 0.15	2.86 ± 0.21	3.52 ± 0.25	ND
Ciprofloxacin	0.48 ± 0.04	0.72 ± 0.05	0.95 ± 0.07	0.50
Sulfamethoxazole	0.31 ± 0.03	0.45 ± 0.04	0.63 ± 0.05	ND
Estradiol	0.019 ± 0.002	0.028 ± 0.003	0.041 ± 0.004	0.001
Ethinylestradiol	0.011 ± 0.001	0.017 ± 0.002	0.026 ± 0.003	0.0005

Heavy metal concentrations in surface water increased progressively along the estuarine gradient. Lead (Pb) exceeded the WHO standard (0.010 mg/L) by around two to five times, ranging from 0.021 ± 0.003 mg/L upstream to 0.056 ± 0.005 mg/L downstream. At every location, cadmium (Cd) concentrations (0.004–0.014 mg/L) were higher than the allowable limit (0.003 mg/L). At midstream and downstream locations, chromium (Cr) levels were higher than the recommended level of 0.050 mg/L, reaching 0.074 ± 0.006 mg/L downstream. At midstream and downstream sites, nickel (Ni) concentrations also surpassed the limit (0.020 mg/L). Mercury (Hg) exhibited critical exceedance, rising six times above the recommended level from 0.001 ± 0.0001 mg/L upstream (at the limit) to 0.006 ± 0.0004 mg/L downstream. In contrast, copper (Cu) and zinc (Zn) remained well below their respective limits across all stations. As Table 2 illustrates, the overall pattern suggests substantial toxic metal contamination, especially in downstream areas.

Table 2. Heavy Metal Concentrations in Surface Water of Ikot Abasi Estuary

Heavy Metal	Upstream (mg/L)	Midstream (mg/L)	Downstream (mg/L)	WHO Limit (mg/L)
Pb	0.021 ± 0.003	0.038 ± 0.004	0.056 ± 0.005	0.010
Cd	0.004 ± 0.001	0.009 ± 0.001	0.014 ± 0.002	0.003
Cr	0.031 ± 0.003	0.052 ± 0.005	0.074 ± 0.006	0.050
Ni	0.018 ± 0.002	0.027 ± 0.003	0.041 ± 0.004	0.020
Cu	0.026 ± 0.003	0.044 ± 0.004	0.062 ± 0.005	2.000
Zn	0.071 ± 0.005	0.094 ± 0.007	0.126 ± 0.009	3.000
Hg	0.001 ± 0.0001	0.003 ± 0.0002	0.006 ± 0.0004	0.001

Heavy metals were found to have accumulated significantly in the sediment, with concentrations rising noticeably from upstream to downstream. At the downstream site, lead (Pb) exceeded the sediment guideline of 35.0 mg/kg, rising from 18.4 ± 1.5 mg/kg upstream to 48.9 ± 3.5 mg/kg downstream. At every location, cadmium (Cd) concentrations (0.92–3.06 mg/kg) were greater than the recommended range (0.60 mg/kg), with downstream values around five times higher. Additionally, all stations had levels of nickel (Ni) and chromium (Cr) above their respective limits, indicating widespread pollution. Zinc (Zn) surpassed the limit (123.0 mg/kg) at the downstream station, whereas copper (Cu) exceeded the guideline (35.7 mg/kg) at both midstream and downstream. The most noticeable contamination was found in mercury (Hg), with values ranging from 0.38 ± 0.03 to 1.04 ± 0.08 mg/kg, up to six times higher than the recommended level of 0.17 mg/kg. These results confirm that sediments act as major reservoirs of heavy metals within the estuary, as shown in Table 3.

Table 3. Heavy Metal Concentrations in Sediment Samples from Ikot Abasi Estuary

Heavy Metal	Upstream (mg/kg)	Midstream (mg/kg)	Downstream (mg/kg)	Sediment Quality Guideline (mg/kg)
Pb	18.4 ± 1.5	31.7 ± 2.3	48.9 ± 3.5	35.0
Cd	0.92 ± 0.08	1.84 ± 0.12	3.06 ± 0.21	0.60
Cr	41.5 ± 3.0	65.8 ± 4.6	88.3 ± 5.9	37.3
Ni	24.2 ± 1.8	39.1 ± 2.8	57.6 ± 4.1	18.0
Cu	28.5 ± 2.0	44.6 ± 3.1	63.2 ± 4.5	35.7
Zn	74.3 ± 5.2	102.7 ± 7.1	146.5 ± 10.3	123.0
Hg	0.38 ± 0.03	0.62 ± 0.05	1.04 ± 0.08	0.17

Tilapia nilotica's endocrine indicators displayed noticeable changes along the pollution gradient. Male plasma vitellogenin concentrations increased by about eight times, from 0.9 ± 0.1 µg/mL at the reference site to 7.2 ± 0.5 µg/mL downstream. In contrast, poor gonadal development was indicated by the gonadosomatic index, which dropped from $2.9 \pm 0.2\%$ at the reference site to $1.4 \pm 0.1\%$ downstream. The hepatosomatic index rose from $1.7 \pm 0.1\%$ to $3.0 \pm 0.2\%$, indicating either metabolic stress or liver hypertrophy. A hormonal imbalance was shown by the estrogen/testosterone ratio, which gradually rose from 0.42 ± 0.03 to 1.27 ± 0.09 . From 0% at the reference site to 31% downstream, intersex occurrence increased dramatically, as shown in Table 4.

Table 4. Endocrine Disruption Biomarkers in Fish Species (*Tilapia nilotica*)

Biomarker	Reference Site	Upstream	Midstream	Downstream
Plasma Vitellogenin in Males (µg/mL)	0.9 ± 0.1	2.8 ± 0.2	4.6 ± 0.3	7.2 ± 0.5
Gonadosomatic Index (%)	2.9 ± 0.2	2.4 ± 0.2	1.9 ± 0.1	1.4 ± 0.1
Hepatosomatic Index (%)	1.7 ± 0.1	2.1 ± 0.1	2.5 ± 0.2	3.0 ± 0.2
Estrogen/Testosterone Ratio	0.42 ± 0.03	0.68 ± 0.05	0.91 ± 0.07	1.27 ± 0.09
Intersex Occurrence (%)	0	8	18	31

From upstream to downstream locations, the frequency of histopathological abnormalities rose significantly. Gill hyperplasia grew from 12% to 57%, indicating growing respiratory impairment, while gill lamellar fusion increased from 8% to 41%, and vacuolation increased from 21% to 73%, indicating significant cellular damage and poor detoxification. Oocyte degeneration and gonadal atrophy both increased from 5% to 33% and 7% to 38%, respectively. As Table 5 illustrates, these results reveal that tissue damage increases as pollution levels rise.

Table 5. Histopathological Alterations in Fish Collected from Ikot Abasi Estuary

Lesion Type	Upstream (%)	Midstream (%)	Downstream (%)
Gill Lamellar Fusion	16	37	62
Gill Hyperplasia	12	34	57
Liver Vacuolation	21	48	73
Hepatic Necrosis	8	19	41
Gonadal Atrophy	5	16	33
Oocyte Degeneration	7	22	38

Parasite prevalence increased consistently across all species and sampling stations. *Clinostomum complanatum* infection in tilapia increased from 12% upstream to 39% downstream, while *Procamallanus laevisconchus* in catfish increased from 18% to 47%. Similarly, *Contracaecum* sp. in croaker increased from 10% to 34%, *Diplostomum* sp. in tilapia from 8% to 29%, and *Capillaria* sp. in catfish from 6% to 28%. The consistent increase across all parasite taxa suggests enhanced susceptibility and transmission in polluted environments, as shown in Table 6.

Table 6. Parasitological Profile of Fish from Ikot Abasi Estuary

Parasite Species	Host Fish	Upstream Prevalence (%)	Midstream Prevalence (%)	Downstream Prevalence (%)
<i>Clinostomum complanatum</i>	Tilapia	12	24	39
<i>Procamallanus laevisconchus</i>	Catfish	18	31	47
<i>Contracaecum</i> sp.	Croaker	10	19	34
<i>Diplostomum</i> sp.	Tilapia	8	17	29
<i>Capillaria</i> sp.	Catfish	6	15	28

Along the estuarine gradient, the parasite burden dramatically rose. While mean abundance increased from 0.9 ± 0.2 to 3.5 ± 0.4 , mean parasite intensity increased from 2.3 ± 0.4 upstream to 7.1 ± 0.8 downstream. Greater parasite diversity in more contaminated areas is indicated by the Shannon diversity index, which rose from 1.14 upstream to 2.06 downstream. According to Table 7, these findings imply that pollution affects host susceptibility and parasite ecology.

Table 7. Parasite Burden and Diversity Indices in Fish Samples

Station	Mean Parasite Intensity	Mean Abundance	Shannon Diversity Index
Upstream	2.3 ± 0.4	0.9 ± 0.2	1.14
Midstream	4.8 ± 0.6	2.1 ± 0.3	1.72
Downstream	7.1 ± 0.8	3.5 ± 0.4	2.06

Contaminants and biological responses were shown to have strong and statistically significant positive associations. While ethinylestradiol had a substantial link with intersex occurrence ($r = 0.88$, $p < 0.001$), oestradiol had a very strong correlation with male vitellogenin ($r = 0.91$, $p < 0.001$). Additionally, there were significant correlations between heavy metals and parasitological and pathogenic effects. There was a high correlation between mercury and hepatic necrosis ($r = 0.84$, $p = 0.001$) and between cadmium and gonadal atrophy ($r = 0.81$, $p = 0.002$). As indicated in Table 8, total heavy metals demonstrated a substantial connection with parasite intensity ($r = 0.87$, $p < 0.001$), suggesting combined harmful effects.

Table 8. Correlation Between Contaminants and Biological Responses

Variable Pair	Correlation Coefficient (r)	p-value
Estradiol vs Male Vitellogenin	0.91	<0.001
Ethinylestradiol vs Intersex Occurrence	0.88	<0.001
Pb vs Parasite Prevalence	0.76	0.004
Cd vs Gonadal Atrophy	0.81	0.002
Hg vs Hepatic Necrosis	0.84	0.001
Total Heavy Metals vs Parasite Intensity	0.87	<0.001

Although risk indices suggested possible health issues, the estimated daily intake amounts for heavy metals were generally low. The safety threshold of 1 was exceeded by lead (THQ = 1.18) and mercury (THQ = 1.06), suggesting a possible non-carcinogenic risk. Although they were below the threshold, cadmium (0.94), chromium (0.72), and nickel (0.56) increased cumulative risk. Significant combined danger from various metals was indicated by the overall hazard index (4.46), which was significantly higher than 1. According to Table 9, the carcinogenic risk values for Pb (3.4×10^{-4}), Cd (2.1×10^{-4}), and Cr (1.8×10^{-4}) were higher than the tolerable risk range (10^{-6} – 10^{-1}), indicating a possible long-term cancer risk linked to eating fish from the estuary.

Table 9. Human Health Risk Assessment of Heavy Metals Through Fish Consumption

Heavy Metal	Estimated Daily Intake (mg/kg/day)	Target Hazard Quotient (THQ)	Carcinogenic Risk
Pb	0.00042	1.18	3.4×10^{-4}
Cd	0.00013	0.94	2.1×10^{-4}
Cr	0.00058	0.72	1.8×10^{-4}
Ni	0.00031	0.56	7.4×10^{-5}
Hg	0.00007	1.06	—
Total Hazard Index		4.46	—

5.0 Discussion

The present study demonstrated a progressive increase in contaminant concentrations from the upstream section of Ikot Abasi Estuary to the downstream section, indicating that the estuary receives cumulative inputs from industrial, municipal, and petroleum-related activities. This part of the estuary appears to be a significant sink for pollutants, according to the greater quantities of heavy metals and pharmaceutical residues found downstream (Okpoji *et al.*, 2025). Similar spatial patterns have been documented in estuarine systems where pollutants build up downstream as a result of sedimentation, hydrodynamic transport, and ongoing human discharge (Patel *et al.*, 2019; Li *et al.*, 2024). The current study's findings of diclofenac, ibuprofen, paracetamol, ciprofloxacin, sulfamethoxazole, oestradiol, and ethinylestradiol attest to the estuary's contamination by endocrine-disrupting substances as well as traditional medications.

Because both oestradiol and ethinylestradiol concentrations were higher than suggested environmental guideline values, they were very concerning. Their existence is probably a result of hospital effluents, pharmaceutical waste, and untreated household sewage being dumped into the estuary. According to numerous studies (AL Falahi *et al.*, 2022; Obinna *et al.*, 2023; Kashif *et al.*, 2021), traditional wastewater treatment systems frequently fail to remove steroid hormones and associated pharmaceutical substances, allowing them to remain in aquatic systems. The Istanbul Strait, South African rivers, Brazilian urban rivers, and Southeast Asian coastal waters have all been found to have similar amounts of oestrogenic chemicals (Nibamureke & Barnhoorn, 2025; dos Santos *et al.*, 2025; Deryal *et al.*, 2025; Lee *et al.*, 2025). Lead, cadmium, chromium, nickel, and mercury contents in the water column also rose downstream, above recommended limits at certain sites. Mercury concentrations were around six times higher than the suggested threshold, while lead concentrations were more than five times the WHO guideline downstream. According to Okpoji *et al.* (2025a), these elevated amounts are indicative of significant anthropogenic contamination, most likely from petroleum exploration, boat traffic, industrial discharge, corroded infrastructure, and urban runoff. Heavy metals are persistent, non-biodegradable contaminants that can linger in aquatic systems for extended periods of time, according to Jaishankar *et al.* (2014). Similar results of high levels of heavy metals in estuarine fish and water have been documented in Nigeria and other places.

While Al-Busaidi *et al.* (2011) and Alturiqi and Albedair (2012) reported heavy metal contamination in marine fish from Oman and Saudi Arabia, Ezemonye *et al.* (2019) found increased levels of lead and cadmium in water, fish, and prawns from the Benin River in Nigeria. The quantities of heavy metals found in the sediment were significantly higher than those found in the water column. Because sediments serve as long-term storage facilities for pollutants, this result is anticipated. Heavy metals are eventually deposited in the bottom sediments after being injected into the estuary and adsorbed onto suspended particles. According to Zhao *et al.* (2012), the degree of industrialisation and the surrounding environment have a significant impact on the accumulation of metals in estuary sediments. Similar findings were documented by Farkas *et al.* (2003), who discovered that heavy metals gradually build up in aquatic habitats before entering fish tissues through interactions between sediment and water (Okpoji *et al.*, 2025).

Because many fish and invertebrates either directly consume the sediment or coexist closely with it, the buildup of heavy metals in sediment has significant ecological ramifications. Therefore, benthic species may carry sediment-bound metals into aquatic food webs, where they may then biomagnify in larger fish. Heavy metal bioaccumulation and biomagnification in fish can pose major health risks to humans who eat contaminated seafood, according to Castro-Gonzalez and Mendez-Armenta (2008). Additionally, metal concentrations in fish tissues are frequently directly correlated with environmental contamination levels, according to Yilmaz *et al.* (2007). The endocrine biomarker data unequivocally demonstrated that the reproductive physiology of fish in the estuary was changed by exposure to pharmaceutical residues and endocrine-disrupting substances. The estrogen-to-testosterone ratio, the incidence of intersex, and male plasma vitellogenin all significantly increased downstream (Ebikienmo *et al.*, 2026). Male fish typically lack vitellogenin, a female-specific egg yolk precursor protein, or have extremely small amounts of it. As a result, the higher levels seen in male fish offer compelling proof of exposure to oestrogenic pollutants. According to Arcand-Hoy and Benson (1998), one of the most accurate markers of endocrine disturbance in aquatic environments is the induction of vitellogenin in male fish. In a similar vein, Kar *et al.* (2021) observed that exposure to endocrine-disrupting substances is characterised by enhanced vitellogenin and increased estrogen-to-testosterone ratios.

The discovered pollutants' endocrine-disrupting effect is further supported by the reported intersex incidence of up to 31% downstream. Intersex fish are frequently found in habitats contaminated by oestrogens and estrogen-like substances, and they have both male and female reproductive tissues. While Gonsioroski *et al.* (2020) highlighted that steroid hormones like oestradiol and ethinylestradiol may interfere with sex differentiation and reproductive development, Adeogun *et al.* (2016) reported intersex occurrence and gonadal abnormalities in tilapia collected from a contaminated freshwater reservoir in Nigeria. In a similar vein, Okuthe *et al.* (2025) found that endocrine disruptors and medicines affect reproductive biology and cause feminisation in aquatic creatures. Fish reproductive potential was negatively impacted, as seen by the decrease in gonadosomatic index seen downstream. Reduced reproductive fitness is suggested by decreased values of the gonadosomatic index, a crucial indicator of gonad growth in relation to body weight (Okpoji *et al.*, 2025). Simultaneously, the hepatosomatic index rose downstream, signifying liver hypertrophy. This rise could be linked to increased detoxifying activities and metabolic stress brought on by pollution exposure. According to Kar *et al.* (2021), fish exposed to endocrine-disrupting substances frequently experience increases in the hepatosomatic index and decreases in the gonadosomatic index.

Fish from the contaminated estuary portions had significant tissue damage, according to histopathological analysis. Downstream, gill lamellar fusion and hyperplasia were very prevalent. These lesions may hinder the gills' ability to absorb oxygen and decrease their effective respiratory surface area. Fish exposed to heavy metals and other toxicants in contaminated waterways have been shown to develop similar gill ulcers. According to Varanka *et al.* (2001), fish tissues exposed to copper sulphate suffered significant structural damage, including changes to the liver and gills.

The liver is a main target organ for contaminant poisoning, according to the liver lesions found in this study, such as vacuolation and hepatic necrosis (Izuchukwu *et al.*, 2026). The liver is especially vulnerable to damage after extended exposure to pollutants since it is in charge of metabolism and detoxification (Obunadike *et al.*, 2026). Fish may be less able to detoxify other pollutants if they have severe vacuolation and necrosis, which are signs of abnormal liver function.

Varanka *et al.* (2001) found similar results, noting morphological and biochemical damage in fish liver after heavy metal

exposure.

Fish reproduction was adversely affected by pollutant exposure, as evidenced by the incidence of gonadal atrophy and oocyte degeneration (Ohaturuonye et al., 2025). The severity of these lesions downstream raises the possibility that gamete formation and fertility are being hampered by the combined impacts of heavy metals and endocrine-disrupting substances. Similar reports of gonadal degeneration and reproductive anomalies in fish living in Nigerian contaminated waters were made by Adeogun et al. (2016) (Onoja et al., 2025). Parasite intensity and prevalence both rose from upstream to downstream, according to parasitological analysis. *Clinostomum*, *Procamallanus*, *Contracaecum*, *Diplostomum*, and *Capillaria* were more common in the contaminated stations, which may indicate that pollution compromised fish immunity and increased their susceptibility to infection. According to Goater et al. (2013), pollutants change host physiology and inhibit immune function, making stressed fish more vulnerable to parasites. According to Okpoji et al. (2026), polluted habitats may encourage the survival of intermediary hosts and facilitate parasite transmission, as seen by the rise in parasite diversity downstream.

The substantial positive correlation between the content of heavy metals and the severity of parasites is consistent with earlier research showing a close association between pollutants and parasitism in aquatic environments. Because they accumulate contaminants and react strongly to environmental stress, parasites are good bioindicators, according to Sures (2005). According to Sures and Reimann (2003), parasites frequently have trace metal concentrations that are higher than those of their fish hosts. Similarly, prawn parasites can act as markers of chemical pollution in estuarine environments, according to Vidal-Martinez et al. (2010). Therefore, additional proof of serious environmental degradation is provided by the greater parasite intensity found in the downstream portion of the Ikot Abasi Estuary (Ekesiobi et al., 2026). The inference that pollutants were the cause of the observed biological reactions is further supported by the study's considerable positive correlations. Ethinylestradiol was strongly linked to the occurrence of intersex, whereas oestradiol was strongly tied with male vitellogenin (Umuenui et al., 2025). These results validate that the fish's reproductive problems were mostly caused by endocrine-disrupting chemicals (Etesin et al., 2025). Furthermore, cadmium was linked to gonadal atrophy, mercury was strongly correlated with hepatic necrosis, and overall heavy metal content was strongly correlated with parasite intensity. These connections show that the biological consequences noted in the study were directly related to the estuary's pollution burden rather than occurring at random (Ogbaji et al., 2025).

According to the human health risk assessment, the total hazard index was significantly higher than 1, and the target hazard quotient values for lead and mercury were greater than unity. These findings suggest that eating fish from the estuary could have a negative impact on locals' health (Aghanwa et al., 2025). Mercury is extremely harmful to the reproductive and neurological systems, whereas lead is known to impact the kidney, blood-forming organs, and nervous system (Jaishankar et al., 2014). Long-term exposure to heavy metals through fish diet can result in cumulative health impacts, according to Castro-Gonzalez and Mendez-Armenta (2008). In a similar vein, Ezemonye et al. (2019) noted that eating fish from polluted Nigerian rivers could put consumers at grave risk (Olotu et al., 2025).

Conclusion

The study demonstrated that the Ikot Abasi Estuary is increasingly affected by contamination from heavy metals, pharmaceutical residues, and endocrine-disrupting compounds. Lead, cadmium, chromium, nickel, mercury, oestradiol, and ethinylestradiol concentrations rose dramatically from the estuary's upstream to downstream sections, suggesting that residential, industrial, and petroleum activities had a greater impact on the latter. The estuary bed is a long-term sink for pollutants, as evidenced by the significantly higher quantities of toxins found in sediments compared to water.

Fish with high amounts of oestrogenic chemicals and pharmaceutical residues showed obvious signs of endocrine disturbance. Increased plasma vitellogenin, higher estrogen-to-testosterone ratios, a lower gonadosomatic index, and a higher incidence of intersex occurrence were all seen in male fish taken from the more contaminated areas of the estuary.

Extensive gill, liver, and gonadal damage, including lamellar fusion, hepatic necrosis, gonadal atrophy, and oocyte degeneration, was also revealed by histopathological testing. Furthermore, the prevalence and intensity of parasites rose dramatically with the quantity of contaminants, indicating that pollution reduced fish immunity and changed host-parasite interactions.

According to a human health risk assessment, eating fish from the estuary's downstream section could put locals at unacceptable risk for health problems. Lead and cadmium carcinogenic risk values were above allowable limits, and the hazard index was higher than the suggested safety threshold. According to these results, eating tainted fish from the estuary for an extended period of time may have negative non-carcinogenic and carcinogenic impacts.

The findings show that the downstream area of the Ikot Abasi Estuary is the most susceptible and that the estuary is under extreme ecological stress. Stricter regulation of household and industrial discharges, better wastewater treatment, and routine monitoring of heavy metals, medications, and endocrine-disrupting substances in the estuary are therefore desperately needed. To preserve aquatic biodiversity and lower health hazards for populations that rely on the estuary for food and livelihood, ongoing monitoring of fish health and seafood quality is also advised.

References

- Adeogun, A. O., Ibor, O. R., Chukwuka, A. V., & Arukwe, A. (2016). Endocrine-disruptor molecular responses, occurrence of intersex and gonado-histopathological changes in tilapia species from a tropical freshwater dam in Nigeria. *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology*, 178, 10–19. <https://doi.org/10.1016/j.cbpc.2015.09.001>
- Aghanwa, C. I., Umuenui, U. E., Etukudo, N. J., Amachree, J. B., Okpoji, A. U., Ejeka, C. J., & Ekwere, I. O. (2025). Atmospheric deposition of soot and heavy metals from gas flaring into surface waters of Ebocha, Rivers State, Nigeria. *Asian Journal of Environment & Ecology*, 24(11), 137–147.
- Akpor, O. B., & Muchie, M. (2011). Environmental and public health implications of wastewater quality. *African Journal of Biotechnology*, 10(13), 2379–2387.
- AL Falahi, O. A., Abdullah, S. R. S., Hasan, H. A., Othman, A. R., Ewadh, H. M., Kurniawan, S. B., & Imron, M. F. (2022). Occurrence of pharmaceuticals and personal care products in domestic wastewater, available treatment technologies, and potential treatment

- using constructed wetland: A review. *Process Safety and Environmental Protection*, 168, 1067–1088. <https://doi.org/10.1016/j.psep.2022.10.082>
- Al-Busaidi, M., Yesudhasan, P., Al-Mughairi, S., Al-Rahbi, W. A. K., Al-Harthy, K. S., Al-Mazrooei, N. A., & Al-Habsi, S. H. (2011). Toxic metals in commercial marine fish in Oman with reference to national and international standards. *Chemosphere*, 85(1), 67–73. <https://doi.org/10.1016/j.chemosphere.2011.06.038>
- Alturqi, A. S., & Albedair, L. A. (2012). Evaluation of some heavy metals in certain fish, meat and some meat products in Saudi Arabian markets. *Egyptian Journal of Aquatic Research*, 38(1), 45–49. <https://doi.org/10.1016/j.ejar.2012.08.003>
- Anarado, C. J. O., Okpoji, A. U., & Anarado, C. E. (2023). Bioaccumulation and health risk assessment of lead, cadmium, arsenic, and mercury in blue crabs found in creeks in Bayelsa State of the Niger Delta region of Nigeria. *Asian Journal of Environmental & Ecology*, 21(4), 46–59.
- Arcand-Hoy, L. D., & Benson, W. H. (1998). Fish reproduction: An ecologically relevant indicator of endocrine disruption. *Environmental Toxicology and Chemistry*, 17(1), 49–57. <https://doi.org/10.1002/etc.5620170108>
- Castro-González, M. I., & Méndez-Armenta, M. (2008). Heavy metals: Implications associated with fish consumption. *Environmental Toxicology and Pharmacology*, 26(3), 263–271. <https://doi.org/10.1016/j.etap.2008.06.001>
- Deryal, G., Korkmaz, N. E., Aksu, A., Kapudan, T., Gazioğlu, C., & Balkis, N. Ç. (2025). Presence and environmental risk assessment of fluoxetine and serotonin hormone in the Istanbul Strait, Türkiye. *International Journal of Environment Research*, 19, 86. <https://doi.org/10.1007/s41742-025-00760-4>
- dos Santos, M. S. R., Vidal, C., Santos, V. S., Domingues, R., & Montagner, C. C. (2025). Seasonal variation and risk assessment for the presence of pharmaceuticals in Brazilian urban rivers. *Environmental Science: Water Research & Technology*, 11(3), 681–690. <https://doi.org/10.1039/D4EW00828F>
- Ebikienmo, P. J., Ekesiobi, S. U., Okpoji, A. U., Dare, B. E., Ayodeji, O. T., & Okpanachi, C. B. (2026). Assessment of groundwater quality and potential non-carcinogenic health risk around Epie Creek, Yenagoa, Nigeria. *Asian Journal of Physical and Chemical Sciences*, 14(1), 26–39. <https://doi.org/10.9734/ajopacs/2026/v14i1279>
- Eisler, R. (1993). Zinc hazards to fish, wildlife, and invertebrates: A synoptic review (Biological Report 10). U.S. Fish and Wildlife Service.
- Ekesiobi, S. U., Ekpe, J. E., Okpoji, A. U., Hassan, D. H., Ekwere, I. O., Awortu, R. C., Etesin, M. U., Nwofia, U., Okeke, C. F., & Nwankwo, A. O. (2025). Hydrochemical characterisation and health-risk assessment of drinking water sources in Brass Island, Bayelsa State, Nigeria. *Asian Journal of Chemical Sciences*, 15(6), 64–76. <https://doi.org/10.9734/ajocscs/2025/v15i6406>
- Ekesiobi, S. U., Thompson, N. I., Akpan, N. A., Okeke, N. P., Ohatuonye, S. O., Okabekwe, V. C., Dare, B. E., & Okpoji, A. U. (2026). Integrated water quality and human health risk assessment in Diobu, Port Harcourt, Rivers State, Nigeria. *Asian Journal of Chemical Sciences*, 16(1), 90–99. <https://doi.org/10.9734/ajocscs/2026/v16i1423>
- Ekwere, I. O., Okpoji, A. U., Igwegbe, K. C., Okonkwo, C. O., Yekeen, A. A., Obunezi, O. C., Okpanachi, C. B., Garuba, M. H., Ogini, O. R., & Odibo, U. E. (2025). Nutritional–Toxicological Trade-Off: Comparative Study of Polycyclic Aromatic Hydrocarbons in Smoked and Oven-Dried Nile Tilapia (*Oreochromis niloticus*). *Journal of Environment, Climate, and Ecology*, 2(2), 90–97. <https://doi.org/10.69739/jece.v2i2.952>
- Ekwere, I. O., Okpoji, A. U., Ufuoma, V. O., Akinola, A. E., Raymond, C. A., Clement, R. O., Alaekwe, I. O., Etesin, M. O., & Edodi, I. O. (2025). Nutritional evaluation of Nile tilapia (*Oreochromis niloticus*) processed by different drying methods in Akwa Ibom State, Nigeria. *Journal of Sustainable Research and Development*, 1(2), 11–17. <https://doi.org/10.69739/jsrd.v1i2.1033>
- Etesin, M. U., Ezeabsili, P. I., Agu, M. O., Okeke, C. F., Olotu, O. N., Aligwo, M. C., Eze, V. C., Nwankwo, A. O., Okpoji, A. U., & Ekong, I. U. (2025). Determination of polychlorinated biphenyls in soils and industrial effluents and health risks assessment in Uyo, Akwa Ibom State, Nigeria. *Journal of Medical Science, Biology, and Chemistry*, 2(2), 285–292. <https://doi.org/10.69739/jmsbc.v2i2.1258>
- Ezemonye, L. I., Adebayo, P. O., Enuneku, A. A., Tongo, I., & Ogbomida, E. (2019). Potential health risk consequences of heavy metal concentrations in surface water, shrimp (*Macrobrachium macrobrachion*), and fish (*Brycinus longipinnis*) from Benin River, Nigeria. *Toxicology Reports*, 6, 1–9. <https://doi.org/10.1016/j.toxrep.2018.11.010>
- Farkas, J., Salánki, J., & Specziár, A. (2003). Age- and size-specific patterns of heavy metals in the organs of freshwater fish *Abramis brama* L. populating a low-contaminated site. *Water Research*, 37(4), 959–964. [https://doi.org/10.1016/S0043-1354\(02\)00447-5](https://doi.org/10.1016/S0043-1354(02)00447-5)
- Gabriel, L., Barboza, A., Cunha, S. C., Monteiro, C., Fernandes, J. O., & Guilhermino, L. (2020). Bisphenol A and its analogues in muscle and liver of fish from the North East Atlantic Ocean in relation to microplastic contamination: Exposure and risk to human consumers. *Journal of Hazardous Materials*, 393, 122419. <https://doi.org/10.1016/j.jhazmat.2020.122419>
- Goater, T. M., Goater, C. P., & Esch, G. W. (2013). *Parasitism: The diversity and ecology of animal parasites* (2nd ed.). Cambridge University Press.
- Gonsioroski, A., Mourikes, V. E., & Flaws, J. A. (2020). Endocrine disruptors in water and their effects on the reproductive system. *International Journal of Molecular Sciences*, 21(6), 1929. <https://doi.org/10.3390/ijms21061929>
- Izuchukwu, E. C., Akpan, N. A., Igwegbe, K. C., Okpoji, A. U., Ezeabasili, P. I., Obi, J. N., & Anarah, S. E. (2026). Environmental and toxicological risk assessment of heavy metals in Eleme agricultural soils. *Asian Journal of Agricultural and Horticultural Research*, 13(1), 67–81. <https://doi.org/10.9734/ajahr/2026/v13i1436>
- Izuchukwu, E. C., Etukudo, N. J., Akpan, N. A., Igwegbe, K. C., Edodi, I. T., Okpoji, A. U., & Etesin, M. U. (2026). Physicochemical, microbiological and toxicological assessment of borehole water in Rumuokoro, Port Harcourt, Nigeria. *Asian Journal of Geographical Research*, 9(1), 99–112. <https://doi.org/10.9734/ajgr/2026/v9i1359>
- Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., & Beeregowda, K. N. (2014). Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology*, 7(2), 60–72. <https://doi.org/10.2478/intox-2014-0009>
- Kar, S., Sangem, P., Anusha, N., & Senthilkumaran, B. (2021). Endocrine disruptors in teleosts: Evaluating environmental risks and biomarkers. *Aquaculture and Fisheries*, 6(1), 1–26. <https://doi.org/10.1016/j.aaf.2020.07.013>
- Kashif, M., Kashif, A., Fuwad, A., & Choi, Y. (2021). Current advances in treatment technologies for removal of emerging contaminants from water—A critical review. *Coordination Chemistry Reviews*, 442, 213993. <https://doi.org/10.1016/j.ccr.2021.213993>
- Kayode-Afolayan, S. D., Ahuekwe, E. F., & Nwinyi, O. C. (2022). Impacts of pharmaceutical effluents on aquatic ecosystems. *Scientific African*, 17, e01288. <https://doi.org/10.1016/j.sciaf.2022.e01288>
- Lee, T. H. Y., Duangnamon, D., Boontha, T., Webster, R. D., & Ziegler, A. D. (2025). Emerging and persistent contaminants in a remote coastal stream system: Five priority compounds in Southeast Asia. *Sustainability*, 17(2), 581. <https://doi.org/10.3390/su17020581>
- Li, X., Shen, X., Jiang, W., Xi, Y., & Li, S. (2024). Comprehensive review of emerging contaminants: Detection technologies, environmental impact, and management strategies. *Ecotoxicology and Environmental Safety*, 278, 116420. <https://doi.org/10.1016/j.ecoenv.2024.116420>
- Nibamureke, U. M. C., & Barnhoorn, I. E. J. (2025). Screening of pharmaceuticals in surface waters from Vhembe District, Limpopo Province, South Africa. *Water*, 17(3), 379. <https://doi.org/10.3390/w17030379>
- Obinna, J., Onyinyechi, B., & Ejileugha, C. (2023). Pharmaceuticals and personal care products as emerging contaminants: Need for a combined treatment strategy. *Journal of Hazardous Materials Advances*, 9, 100206. <https://doi.org/10.1016/j.hazadv.2022.100206>
- Obunadike, J. C., Okpoji, A. U., Dare, B. E., Obi, J. N., Udo, J. J., Akpan, M. P., & Garuba, M. H. (2025). Domestic wastewater discharge effects on water quality and public health in Choba River, Rivers State, Nigeria. *Journal of Applied Physical Science International*, 17(2), 37–49. <https://doi.org/10.56557/japsi/2025/v17i210117>

- Ogbaji, H. O., Akpan, N. A., Ijioma, C. C., Okpoji, A. U., Eze, V. C., Obi, J. N., Martins, N. P., & Etesin, M. U. (2025). Seasonal variation in hydrocarbon contamination of sediments and biota in Bonny Estuary, Rivers State, Nigeria. *Asian Journal of Geographical Research*, 8(4), 330–338. <https://doi.org/10.9734/ajgr/2025/v8i4341>
- Ohaturuonye, S. O., Okpoji, A. U., Akpan, N. A., Njoku, C. A., Isaac, S. C., Etesin, M. U., & Ekwere, I. O. (2025). Biomarker responses in fish and crustaceans exposed to heavy metals and petroleum hydrocarbons in the Qua Iboe Estuary, Niger Delta. *Asian Journal of Research in Zoology*, 8(4), 234–244. <https://doi.org/10.9734/ajriz/2025/v8i4233>
- Okpoji, A. U., Akpan, N. A., Eze, V. C., Ijioma, C. C., Hassan, D. H., Kareem, M. M., Obi, A. I., Aningo, G. N., Okoye, P. I., Ogbonnaya, C. N., Ekwere, I. O., Okeke, C. F., & Aligwo, M. C. (2025). Toxicity and bioaccumulation of heavy metals and polycyclic aromatic hydrocarbons in estuarine fish from the Andoni Estuary, Niger Delta, Nigeria. *Journal of Applied Physical Science International*, 17(2), 10–22. <https://doi.org/10.56557/japsi/2025/v17i210026>
- Okpoji, A. U., Anarado, C. O., Mmuta, E. C., Ekwere, I. O., Alaekwe, I. O., Odibo, U. E., Igwegbe, K. C., Eboj-Ajoku, I. O., & Obunezi, O. C. (2025). Toxicological evaluation of Pb, Cd, As, and Hg in blue crab from oil-polluted creeks in the Niger Delta. *Journal of Life Science and Public Health*, 1(1), 24–31. <https://doi.org/10.69739/jlsp.v1i1.879>
- Okpoji, A. U., Chinyere, U. E., Nwokoye, J. N., Ezekwuemen, O. I., Alaekwe, I. O., Odidika, C. C., Owughara, C. N., Enyi, C. M., & Kolawole, O. O. (2025). Environmental Assessment of Heavy Metals and Hydrocarbon Pollution in Surface Waters of Oil-Bearing Communities in Andoni, Rivers State, Nigeria. *International Journal of Modern Science and Research Technology*, 3(8), 22–30. <http://www.ijmsrt.com>
- Okpoji, A. U., Eboh-Ajoku, I. O., Mmuta, E. C., Ndubuisi, J. O., Alaekwe, I. O., Odibo, U. E., Nwoka, N. G., Okafor, C. A., & Obunezi, O. C. (2025). Integrated environmental risk assessment of BTEX and PAHs in water and sediment samples from the Bonny River, Nigeria. *ISA Journal of Multidisciplinary (ISAJM)*, 2(4), 14–21.
- Okpoji, A. U., Ekwere, I. O., Igwegbe, K. C., Anarado, C. J. O., Ogbonna, C., Ewuola, A. A., Odibo, U. E., & Garuba, M. H. (2025). Volatile organic compounds from gas flaring and their atmospheric implications in the Niger Delta. *Journal of Life Science and Public Health*, 1(1), 32–39. <https://doi.org/10.69739/jlsp.v1i1.962>
- Okpoji, A. U., Ekwere, I. O., Igwegbe, K. C., Etesin, U. M., Ugwuanyi, G. C., Okpanachi, C. B., Ewuola, A. A., Mojisola, K. M., & Ezekwueme, O. I. (2025). Solar-enhanced photocatalytic degradation of pharmaceutical residues in wastewater using Fe-, Cu-, and Zn-doped TiO₂ nanomaterials. *Journal of Environment, Climate, and Ecology*, 2(2), 56–62. <https://doi.org/10.69739/jece.v2i2.961>
- Okpoji, A. U., Emem, J. A., Ekwere, I. O., Odibo, U. E., Alaekwe, I. O., Warder, A. B., & Eboj-Ajoku, O. I. (2025). Bioaccumulation of nickel, lead, and cadmium in tissues of *Callinectes sapidus* from the Iko River, Nigeria: Implications for human health risk and environmental safety. *Journal of Environment, Climate, and Ecology*, 2(2), 29–37. <https://doi.org/10.69739/jece.v2i2.844>
- Okpoji, A. U., Etesin, M. U., Ekwere, I. O., Martins, N. P., Okpanachi, C. B., Adisa, O. J., & Okonkwo, C. C. (2025). Geochemical speciation and ecological risk of heavy metals in estuarine sediments of the Qua Iboe River, Nigeria. *Asian Journal of Chemical Sciences*, 15(6), 20–31. <https://doi.org/10.9734/ajocs/2025/v15i6402>
- Okpoji, A. U., Ndubuisi, J. O., Eboh-Ajoku, I. O., Emem, J. A., Ekwere, I. O., Alaekwe, I. O., Odibo, U. E., Igwegbe, K. C., Onoja, C. R., Warder, A. B., & InyangAbia, A. J. (2025). Trematode infections and histopathological effects in *Chrysichthys nigrodigitatus* from the polluted Andoni River, Niger Delta, Nigeria. *Journal of Agriculture, Aquaculture, and Animal Science*, 2(2), 66–72. <https://doi.org/10.69739/jaaas.v2i2.882>
- Okpoji, A. U., Nwoka, N. G., Odibo, U. E., Alaekwe, I. O., Okafor, C. A., Ogwu, N. G., & Akatakpo, C. U. (2025). Seasonal variation in hydrochemical characteristics and heavy metal risk assessment of groundwater in Andoni-Isiokwan District, Niger Delta, Nigeria. *International Journal of Modern Science and Research Technology*, 3(8), 44–51. <http://www.ijmsrt.com>
- Okpoji, A. U., Ogbaji, H. O., Hassan, D. H., Orji-Azuka, L. N., Rasheed, H. O., Ohaturuonye, S. O., Ejeka, J. C., Okpanachi, C. B., & Ekwere, I. O. (2025). Physico-chemical transport of volatile organic compounds (VOCs) from gas flaring into surface waters of Ogoniland, Rivers State, Nigeria. *Asian Journal of Physical and Chemical Sciences*, 13(4), 151–159. <https://doi.org/10.9734/ajopacs/2025/v13i4271>
- Okpoji, A. U., Ogbaji, H. O., Hassan, D. H., Orji-Azuka, L. N., Rasheed, H. O., Ohaturuonye, S. O., Ejeka, J. C., Okpanachi, C. B., & Ekwere, I. O. (2025). Physico-chemical transport of volatile organic compounds (VOCs) from gas flaring into surface waters of Ogoniland, Rivers State, Nigeria. *Asian Journal of Physical and Chemical Sciences*, 13(4), 151–159. <https://doi.org/10.9734/ajopacs/2025/v13i4271>
- Okpoji, A. U., Orji-Azuka, L. N., Igwegbe, K. C., Ekwere, I. O., Ewuola, A. A., Garuba, M. H., & Etukudo, E. W. (2025). Water quality and ecotoxicological impacts of surfactants and heavy metals in urban rivers of Benin City, Niger Delta, Nigeria. *Asian Journal of Geographical Research*, 8(3), 697–707. <https://doi.org/10.9734/ajoger/2025/v8i3223>
- Okuthe, G. E., Dube, E., & Mafunda, P. S. (2025). Effects of pharmaceuticals and endocrine-disrupting chemicals on reproductive biology of aquatic fauna: Penguins as sentinel species. *Journal of Xenobiotics*, 15(4), 110. <https://doi.org/10.3390/jox15040110>
- Olotu, O. N., Okagbare, U. V., Okpoji, A. U., Orji-Azuka, L. N., Etesin, M. U., & Ekwere, I. O. (2025). Spatio-seasonal assessment of water and sediment quality of the Imiringi River and implications for fisheries and aquatic resources in the Niger Delta. *Journal of Agriculture, Aquaculture, and Animal Science*, 2(2), 174–184. <https://doi.org/10.69739/jaaas.v2i2.1309>
- Onoja, C. R., Ogbaji, H. O., Edodi, I. O., Mmuta, E. C., Igwegbe, K. C., Oguni, O. R., Odibo, U. E., Ewuola, A. A., Mahmoud, A. B., & Okpoji, A. U. (2025). Heavy Metal Contamination and Health Risk Assessment of Smoked-Dried Fish Sold in Eke-Awka Market, Anambra State, Nigeria. *Journal of Sustainable Research and Development*, 1(2), 18–25. <https://doi.org/10.69739/jsrd.v1i2.1044>
- Patel, M., Kumar, R., Kishor, K., Mlsna, T., Pittman, C. U., Jr., & Mohan, D. (2019). Pharmaceuticals of emerging concern in aquatic systems: Chemistry, occurrence, effects, and removal methods. *Chemical Reviews*, 119(6), 3510–3673. <https://doi.org/10.1021/acs.chemrev.8b00299>
- Peivasteh-Roudsari, L., Barzegar-Bafrouei, R., Sharifi, K. A., Azimialim, S., Karami, M., Abedinzadeh, S., Asadinezhad, S., Tajdar-Oranj, B., Mahdavi, V., Alizadeh, A. M., et al. (2023). Origin, dietary exposure, and toxicity of endocrine-disrupting food chemical contaminants: A comprehensive review. *Heliyon*, 9(7), e18140. <https://doi.org/10.1016/j.heliyon.2023.e18140>
- Sures, B. (2005). Effects of pollution on parasites and use of parasites in pollution monitoring. In K. Rohde (Ed.), *Marine parasitology* (pp. 421–425). CSIRO Publishing.
- Sures, B., & Reimann, N. (2003). Analysis of trace metals in the Antarctic host–parasite system *Notothenia coriiceps* and *Aspersentis megarhynchus* (Acanthocephala) caught at King George Island, South Shetland Islands. *Polar Biology*, 26(10), 680–686. <https://doi.org/10.1007/s00300-003-0536-9>
- Umuenu, U. E., Rasheed, H. O., Edodi, I. O., Aningo, G. N., Okpoji, A. U., Etesin, M. U., Okonkwo, C. C., Ekwere, I. O., Okeke, C. F., & Anarah, S. E. (2025). Nutrient enrichment and eutrophication potential of agricultural runoff in Otuoke, Bayelsa State, Nigeria. *Asian Journal of Agricultural and Horticultural Research*, 12(4), 154–163. <https://doi.org/10.9734/ajahr/2025/v12i4424>
- Varanka, Z., Rojik, I., Varanka, I., Nemcsok, J., & Ábrahám, M. (2001). Biochemical and morphological changes in carp (*Cyprinus carpio* L.) liver following exposure to copper sulphate and tannic acid. *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology*, 128(4), 467–478. [https://doi.org/10.1016/S1532-0456\(01\)00186-2](https://doi.org/10.1016/S1532-0456(01)00186-2)
- Vidal-Martínez, V. M., Aguirre-Macedo, M. L., Del Río-Rodríguez, R., Gold-Bouchot, G., Rendón-von Osten, J., & Miranda-Rosas, G. A. (2006). The pink shrimp *Farfantepenaeus duorarum*, its symbionts and helminths as bioindicators of chemical pollution in Campeche Sound, Mexico. *Journal of Helminthology*, 80(2), 159–174. <https://doi.org/10.1079/JOH2006345>

- Yilmaz, F., Özdemir, N., Demirak, A., & Tuna, A. L. (2007). Heavy metal levels in two fish species, *Leuciscus cephalus* and *Lepomis gibbosus*. *Food Chemistry*, 100(2), 830–835. <https://doi.org/10.1016/j.foodchem.2005.09.020>
- Zhao, S., Feng, C., Quan, W., Chen, X., Niu, J., & Shen, Z. (2012). Role of living environments in the accumulation characteristics of heavy metals in fishes and crabs in the Yangtze River Estuary, China. *Marine Pollution Bulletin*, 64(6), 1163–1171. <https://doi.org/10.1016/j.marpolbul.2012.03.023>