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Health Risk Analysis and Source Apportionment of Polyaromatic Hydrocarbons in Water and Sediment in Aluu River

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Abstract: This study focuses on the health risk analysis and source apportionment of polyaromatic hydrocarbons in water and sediment in Aluu River. The objectives were to quantify and characterize PAH concentrations, determine the sources of these contaminants and the health risks associated with exposure to polycyclic aromatic hydrocarbons. Surface water and sediment samples were collected from multiple locations along the Aluu River using standard sampling protocols. PAHs were extracted and quantified using Gas Chromatography-Mass Spectrometry (GC-MS) methods. Source apportionment was conducted using principal component analysis (PCA), while ecological and human health risk assessments were performed using hazard quotient (HQ) and cancer risk (CR) models. PAHs were detected in both water and sediment, with total concentrations ranging from 3.33 to 6.41 µg/L in water and 22.33 to 31.00 µg/kg in sediments. High molecular weight PAHs (HPAHs) predominated, suggesting pyrogenic sources. Health risk assessments indicated elevated HQs for several carcinogenic PAHs such as chrysene, benzo[a]pyrene, and benzo[ghi]perylene. The total cancer risk from PAHs in surface water ranged from 0.039 to 0.090, significantly above the acceptable threshold (1.0×10^{-6}), indicating potential long-term health concerns. Principal component analysis (PCA) identified distinct pollution sources for PAHs, including industrial discharge, combustion activities, and urban runoff. The findings demonstrate significant contamination of the Aluu River by PAHs, with sediment acting as a major sink for these pollutants. The dominance of high-risk carcinogenic PAHs, coupled with elevated health risk indices, indicates potential long-term ecological degradation and serious public health concerns for populations dependent on the river. Establishment of a long-term environmental monitoring program to track PAHs trends and evaluate effectiveness of mitigation strategies is recommended

Keywords: Polycyclic Aromatic Hydrocarbons (PAHs), Health Risk Assessment, Source Apportionment, River Sediment, Aluu River.

Introduction

Freshwater systems are vital to human survival, ecosystem stability, and economic development, yet they are increasingly burdened by chemical pollution arising from rapid urbanization and industrial growth. Rivers act as natural receivers of municipal waste, agricultural runoff, atmospheric deposition, and industrial discharges, making them particularly vulnerable to contamination by persistent organic pollutants. Among these contaminants, polycyclic aromatic hydrocarbons (PAHs) have gained global attention due to their environmental persistence, toxicity, and widespread occurrence in aquatic environments [1].

Polycyclic aromatic hydrocarbons are a class of organic compounds composed of fused aromatic rings formed primarily during incomplete combustion of organic materials such as fossil fuels, biomass, petroleum products, and waste. PAHs enter aquatic systems through multiple pathways, including oil spills, vehicular emissions, industrial effluents, urban runoff, domestic waste disposal, and atmospheric deposition. Once introduced into river systems, PAHs tend to associate strongly with suspended particles and sediments because of their hydrophobic nature. Sediments therefore act as long-term reservoirs of PAHs, capable of releasing these compounds back into the water column under changing environmental conditions, thereby prolonging ecological exposure [2].

The presence of PAHs in water and sediment poses significant ecological and human health risks. Many PAH compounds are known to be mutagenic, carcinogenic, and teratogenic. Aquatic organisms exposed to PAHs may experience impaired growth, reproductive toxicity, and bioaccumulation within the food chain. Humans can be exposed through the consumption of contaminated water and aquatic food sources, dermal contact, or inhalation of volatilized compounds. Long-term exposure has been associated with increased risks of cancer, respiratory disorders, and organ damage. Consequently, monitoring PAH levels in freshwater systems is essential for protecting ecosystem integrity and safeguarding public health [3].

Source apportionment plays a crucial role in understanding the origins of PAHs and developing effective pollution control strategies. PAHs generally originate from two broad categories: pyrogenic sources, resulting from high-temperature combustion processes, and petrogenic sources, derived from crude oil and petroleum products. Distinguishing between these sources provides insight into dominant human activities contributing to contamination and supports evidence-based environmental management. In developing countries such as Nigeria, inadequate waste management systems, increasing vehicular emissions, artisanal petroleum activities, and rapid population growth intensify the release of PAHs into rivers and other water bodies. Despite the growing recognition of PAH pollution globally, localized assessments combining both source identification and health risk evaluation remain limited in many Nigerian freshwater systems [4].

Aluu River is an important freshwater resource supporting domestic, agricultural, and fishing activities for surrounding communities. However, the river is exposed to increasing anthropogenic pressures associated with settlement expansion, transportation activities, waste discharge, and land-use changes within its catchment. These activities create conditions conducive to the introduction and accumulation of PAHs in both water and sediment [5]. The lack of comprehensive scientific data on PAH contamination in Aluu River represents a significant knowledge gap that hinders effective environmental protection and public health planning.

This study therefore investigates the health risk analysis and source apportionment of polycyclic aromatic hydrocarbons in water and sediment in Aluu River. By determining the concentration, distribution, and likely origins of PAHs, and by evaluating their potential risks to human health, the research aims to generate baseline data necessary for environmental monitoring and sustainable river management. The outcomes of this work will contribute to the broader understanding of PAH pollution in freshwater systems in Nigeria and support strategies aimed at reducing contaminant exposure and protecting community well-being.

Materials and Methods

Study area

This study area for this study is Aluu in Ikwerre Local Government Area of Rivers State. Aluu is located in Rivers State, South-south, Nigeria. Aluu is located at latitude 04o 55' 14.8" North and longitude 06o 55' 07.7" East with an elevation of 15.2 m in Ikwere Local Government Area of Rivers State, Nigeria. Aluu is characterized by alternate seasons of wet and dry with total annual rainfall of about 240 cm, relative humidity of over 90% and average annual temperature of 27 oC. The occupation of the people in Aluu are mainly trading, hunting, fishing and farming. The vegetation of this study area is made up of red and white mangrove (Rhizophora mangle and Avicenia spp., respectively), Nypa palm (Nypa fruticans), Ipomoea aquatica, Nymphea lotus, Mimosa pigra, Eichhornianatans, water lily, aquatic fern etc. There are a number of human and economic activities taking place within the study area; for instance, agricultural product transportation, dredging, etc. They produce crops such as cassava, maize, vegetables, and yam, among others.

Methods

Water sample collection

1L plastic bottle with a screw cap, previously cleaned with detergent, immersed overnight in 10% (v/v) HNO_3, and rinsed with deionised water, was utilised for collecting water samples. Ten water samples were obtained at a depth of 30 cm below the surface at various points within specified sampling sites along the Aluu River. The water samples were promptly placed in ice-pack containers and conveyed to Integrated Science and Engineering Laboratory, Elekahia, Rivers State.

Sediment sample collection

At the same location as the water samples, ten sediment samples were taken from the Aluu River; these samples were placed in polythene bags. The water samples were immediately placed into ice-pack containers and sent to Integrated Science and Engineering Laboratory, Elekahia, Rivers State. Table 3.1 shows the locations of the samples and their spatial coordinates.

Table 1.1: Coordinates of Sample Area

Location	Latitude	Longitude
Omouko River (L1)	4°16’66.0°N	6°34’57.5°E
	4°17’56.0°N	6°35’56.5°E
	4°17’19.0°N	6°35’53.5°E
Omuihuechi River (L2)	4°18’57.5°N	6°35’20.3°E
	4°17’54.8°N	6°37’20.8°E

Omuchiolu River (L3)	4°15’59.6°N	6°36’21.5°E
	4°14’41.0°N	6°33’19.5°E
	4°15’42.0°N	6°35’18.4°E
	4°16’41.1°N	6°36’17.3°E
	4°13’45.0°N	6°35’22.6°E

Determination of PAHs

Determination of PAHs in water

The surface water sample was filtered with filter paper to remove debris and suspended materials and then poured into a 2 litre separatory funnel. Liquid-liquid extraction (LLE) as described in APHA was used. For the first LLE, the mixture of 100 ml n-hexane and dichloromethane (1:1 v/v) was added and shaken vigorously for 2 min before two phase separation. The water-phase was drained from the separatory funnel into a 1000 ml beaker. The organic-phase was carefully poured into a glass funnel containing 20 g of anhydrous sodium sulphate. Following the second and third LLE, the water-phase was poured back into the separatory funnel to re-extract with 50 ml of the same solvent mixture. The extract was concentrated to the volume of 2 ml under a gentle stream of nitrogen using rotary evaporator and then analyzed with Gas Chromatograph.GC analysis was conducted to detect 16 PAH components. The 16 priority PAHs were used for quantitation: naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, chrysene, benzo [a] anthracene, benzo [b] fluoranthene, benzo [k] fluoranthene, benzo [a] pyrene, dibenzo [a,h] anthracene, benzo [g,h,i] perylen, Indeno [1,2,3-cd] pyrene.

Determination of PAHs in Sediment

100 g of freeze dried sediment samples were placed in cellulose thimble and soxhlet extractor, which contains hexane and toluene. After the first extraction, tetrachloromethane was used to elute only PAHs (Ekpete et al., 2019). The concentrations of the PAHs was achieved by the use of gas chromatographic (GC) technique coupled with a flame ionization detector (FID).

Table 1.2 shows the different parameters programmed for the analysis of the polycyclic aromatic hydrocarbons in the water samples.

Item	Description
Model of GC	Agilent/ HP 6890 GC PLUS
Flame Ionization Detector	Agilent 5973 FID

Conditions of GC	Inlet Temperature: 270°C Transfer Line Temperature: 280°C Column Oven Temperature programmed from 35 to 280°C with initial temperature maintained for 5 min then 10°C/min to 280°C for 10.5 min and the final one for 29.9 min 50°C/min to 285°C.
Capillary Column	GC was fitted with a HP-5 FID low bleed capillary Column (30m x 0.25 mm i.d, 0.25µm film thickness) Agilent technologies USA.
Carrier Gas	Helium at a flow rate of 1.25mL/min.
Temperature of Mass Selector Detector	Ion source temperature of 350°C and a quadruple temperature of 180°C. 230°C was set as the MS ion source temperature.
Electron Impact (EI)	EI mass spectra were obtained at acceleration energy of 70 eV.
Injection	1.0 µL aliquot of extract was automatically injected in the split/splitless mode using an auto sampler 7683 (Agilent Technologies, Inc., USA).
Filament Delay Time	3.3 min
Spectra Library	Library – MS searches were done using NIST/EPA/NIH Mass Spectra Library (NIST 05) and NIST Mass Spectral Search Program Version 2.0d, CHEMCO and ADAMS data base performed characterization purposes in the GC – MS data system.

Health risk assessment

Non-carcinogenic risk assessment

The probability of non-carcinogenic risk is assessed by the hazard quotient (HQ) factor. This factor is non-carcinogenic CDI based on the oral reference dose (RFD) calculated according to the following equation:

$$HQ = CDI/RFD \quad 1$$

where HQ: the non-cancer hazard quotient, CDI: non-carcinogenic chronic daily intake (mg/kg/day), RFD: RFD is an estimation of the daily human contact surface of a population and includes a sensitive population that does not have a harmful effect on their health throughout their lifetime (Bamuwamye et al. 2015)

Non-carcinogenic potential risk to human health was assessed by hazard index (HI) index, which is the sum of all HQ calculated for individual pollutants. The HI is used to estimate the total non-carcinogenic risk effects of the exposures to a multiple of pollutants in the drinking water and calculated as follows: (Bamuwamye et al. 2015):

$$HI = \sum HQ = HQPb + HQCd + HQCu. \quad 2$$

Therefore, if the value of HQ or HI>1, there is a possibility of adverse effects on human health so that the closer to 1, the greater the non-carcinogenic risk.

Carcinogenic risk assessment of MP PAHs

The carcinogenic risk potential through the surface water and sediment is estimated using incremental lifetime cancer risk (ILCR).

CDI in the following equation is the chronic daily intake of carcinogenic chemical materials (mg/kg/day). This index shows the mean daily dose of exposure to the carcinogenic materials in a lifetime:

$$ILCR = CDI \times CSF. \quad 3$$

The cumulative cancer risk as a result of exposure to multiple carcinogenic pollutants due to the consumption of water was assumed to be the sum of the individual pollutant increment risk and calculated using the following equation:

$$\sum ILCR = ILCR1 + ILCR2 + ILCR3 + \ldots ILCRn. \quad 4$$

In this equation, n is the individual carcinogenic of each pollutant in the bottled water or tap water. The level of acceptable cancer risk (ILCR) or for regulatory purposes is considered between $10{-}4$ and $10{-}6$.

Table 3: Parameters for estimating human cancer risk.

Parameters	Units	Values	
		Ingestion	**Dermal absorption**
Pollutant concentration (C)	µg/L		
Daily average intake (DI)	L/day	2.2	
Skin surface area (SA)	cm^2		18000

Permeability coefficient (KP)	cm/hour		
Exposure Time (ET)	Hour/event		0.58
Exposure frequency (EF)	Day/years	365	350
Exposure duration (EP)	Year	70	30
Conversion factor (CF)	L/cm^3		0.001
Body weight (BW)	Kg	70	70
ABS	All	0.001	0.001
Average time (AT)	Days	25550	25550

Carcinogenic human health risk of PAHs

In estimating the level of exposure due to oral consumption of PAHs in the water the equation for estimated daily intake (EDI) for carcinogenic chemicals was calculated as follows;

$$\text{ADD mg/kg/day} = \frac{Cp \times IR \times EF \times ED}{BW \times AT}$$

where: Cp is the concentration of MP and PAHs water and sediment (mg/kg), IR is the ingestion rate (0.0312 for normal consumption in adult and 0.1424 kg/day for habitual consumers of water), EF is the exposure frequency (365 days/year), ED is the exposure duration over a lifetime; assumed as 70 years for both children and adult, BW body weight (70 kg for adults), and AT average lifetime (70 years × 365 days/year). EDI was calculated for 70 years exposure for adult as follows

$$ILCR = CDI \times CSF.$$

where: CSF is cancer slope factor, also known as potency factor; 2.0 mg/kg/day. The carcinogenic HQ was evaluated as follows:

$$HQ = \frac{EDI}{RfD}$$

Oral RfD = Oral RfD for chronic acceptable daily intake and is 0.00002 mg/kg/day. HQ greater than 1 is considered a health risk (Ibeto et al., 2019).

Table 4: Reference Dose (RfD) values (mg/kg-day):

Compound	RfD
Naphthalene	2.00e-02
Acenaphthene	6.00e-02
Acenaphthylene	3.00e-02
Anthracene	3.00e-02
Fluorene	4.00e-02
Phenanthrene	4.00e-02

Pyrene	3.00e-02
Fluoranthene	4.00e-02
Chrysene	1.00e-03
Benzo[a]anthracene	1.00e-04
Benzo[a]pyrene	3.00e-04
Benzo[k]fluoranthrene	3.00e-04
Dibenz[a,h]anthracene	7.00e-04
Benzo[ghi]perylene	3.00e-04
Indeno(1,2,3-cd)pyrene	5.00e-04

RESULTS

Table 1: PAHs in surface water from Aluu River

Sample Description	L1	L2	L3
Naphthalene	0.46±0.002	0.067±0.01	0.031±0.021
Acenaphthene	0.029±0.01	0.25±0.010	0.022±0.011
Acenaphthylene	0.043±0.02	0.082±0.04	0.031±0.012
Anthracene	0.078±0.01	1.12±0.02	0.302±0.027
Fluorene	0.17±0.03	0.45±0.05	0.012±0.014
Phenanthrene	0.016±0.001	0.018±0.02	0.291±0.011
Total LPAHs	**0.796±0.081**	**1.987±0.012**	**0.689±0.095**
Pyrene	0.97±0.04	0.15±0.012	0.063±0.02
Fluoranthene	0.04±0.001	0.47±0.02	0.027±0.01
Chrysene	0.54±9.03	0.46±0.01	0.622±0.01
Benzo[a]anthracene	0.20±0.03	1.27±0.051	0.01±0.01
Benzo[a]pyrene	0.23±0.021	0.56±0.07	0.680±0.08
Benzo[k]fluoranthrene	0.26±0.08	1.006±0.02	0.03±0.001
Benzo(b)fluoranthene	0.01±0.02	0.005±0.02	0.006±0.02
Dibenz[a,h]anthracene	0.011±0.03	0.150±0.001	0.14±0.002
Benzo[ghi] perylene	1.73±0.02	0.37±0.002	1.056±0.001
Indeno(1,2,3-cd)pyrene	0.88±0.07	0.015±0.001	0.012±0.001
Total HPAHs	**4.861±9.322**	**4.551±0.187**	**2.64±0.135**
Total PAHs	**5.657±0.178**	**6.408±0143**	**3.329±0.044**

Table 2: PAHs in Sediment from Aluu River

Sample Description	L1	L2	L3
Naphthalene	0.018±0.101	2.12±0.83	1.70±0.29
Acenaphthene	2.955±1.140	1.6±0.136	1.810±0.264
Acenaphthylene	2.128±0.20	3.10±0.70	3.150±0.42
Anthracene	2.70±0.31	3.6±0.14	1.308±0.310
Fluorene	1.453±0.770	1.9±0.170	2.730±0.243
Phenanthrene	8.15±1.15	1.3±0.119	2.525±1.192
Total LPAHs	**16.404±2.671**	**13.67±3.095**	**11.915±2.719**
Pyrene	1.10±0.15.9	0.5±0.84	1.02±0.03
Fluoranthene	2.17±0.513	1.02±0.19	1.00±0.78
Chrysene	3.32±0.5 23	0.15±0.01	1.88±0.70
Benzo[a]anthracene	0.03±0.14	2.50±1.7	1.03±0.38
Benzo[a]pyrene	1.5±0.10	1.31±0.22	1.10±0.80
Benzo(b)fluoranthene	0.01±0.01	0.02±0.01	0.01±0.10
Benzo[k]fluoranthrene	2.51±0.55	1.51±0.17	0.90±0.34
Dibenz[a,h]anthracene	1.70±0.131	2.6±0.114	0.38±0.210
Benzo[ghi] perylene	3.07±0.503	1.11±0.19	2.00±0.718
Indeno(1,2,3-cd)pyrene	1.8±0.110	0.31±0.12	1.10±0.180
Total HPAHs	**14.6±2.047**	**11.01±2.854**	**10.41±4.138**
Total PAHs	**31.004±4.718**	**24.68±5.950**	**22.325±6.857**

Table 3: Estimated Daily Intake of PAHs in Surface water

Compound	L1 **mg/kg/day**	L2 **mg/kg/day**	L3 **mg/kg/day**
Naphthalene	0.0131	0.00191	0.00089
Acenaphthene	0.00083	0.00714	0.00063
Acenaphthylene	0.00123	0.00234	0.00089
Anthracene	0.00223	0.0320	0.00863
Fluorene	0.00486	0.01286	0.00034
Phenanthrene	0.00046	0.00051	0.00831
Pyrene	0.0277	0.00429	0.00180
Fluoranthene	0.00114	0.01343	0.00077

Chrysene	0.01543	0.01314	0.01777
Benzo[a]anthracene	0.00571	0.03629	0.00029
Benzo[a]pyrene	0.00657	0.01600	0.01943
Benzo(b)fluoranthene	0.00013	0.00010	0.00011
Benzo[k]fluoranthrene	0.00743	0.02874	0.00086
Dibenz[a,h]anthracene	0.00031	0.00429	0.00400
Benzo[ghi]perylene	0.04943	0.01057	0.03017
Indeno(1,2,3-cd)pyrene	0.02514	0.00043	0.00034

Table 4: Non-Cancer Risk (HQ) for of PAHs in surface water from the Aluu River

Compound	L1 **mg/kg/day**	L2 **mg/kg/day**	L3 **mg/kg/day**
Naphthalene	0.657	0.096	0.044
Acenaphthene	0.0138	0.119	0.0105
Acenaphthylene	0.041	0.078	0.030
Anthracene	0.074	1.067	0.288
Fluorene	0.121	0.321	0.0086
Phenanthrene	0.015	0.017	0.277
Pyrene	0.924	0.143	0.060
Fluoranthene	0.0286	0.336	0.0193
Chrysene	15.429	13.143	17.771
Benzo[a]anthracene	57.143	362.857	2.857
Benzo[a]pyrene	21.905	53.333	64.762
Benzo(b)fluoranthene	0.0107	0.0105	0.0125
Benzo[k]fluoranthrene	24.762	95.810	2.857
Dibenz[a,h]anthracene	1.048	14.286	13.333
Benzo[ghi]perylene	164.762	35.238	100.571
Indeno(1,2,3-cd)pyrene	83.810	1.429	1.143

Table 5: Cancer Risk (CR) of PAHs in surface water from the Aluu River

Compound	CSF	L1	L2	L3
Naphthalene	0.12	6.76×10^{-4}	9.84×10^{-5}	4.56×10^{-5}
Fluoranthene	0.04	4.90×10^{-7}	5.76×10^{-6}	3.31×10^{-7}
Chrysene	0.017	0.00132	0.00113	0.00152
Benzo[a]anthracene	0.1	0.00269	0.01711	1.35×10^{-4}
Benzo[a]pyrene	7.3	0.02056	0.05006	0.06078
Benzo[k]fluoranthene	0.7	0.00287	0.01109	3.31×10^{-4}
Dibenz[a,h]anthracene	7.3	0.00081	0.01102	0.01029
Indeno(1,2,3-cd)pyrene	0.042	0.01078	1.84×10^{-4}	1.47×10^{-4}
Total Cancer Risk		0.03903	0.09041	0.07259

Table 6: Estimated Daily Intake (EDI) for PAHs in sediment from Aluu River

Compound	L1(mg/kg/day)	L2(mg/kg/day)	L3(mg/kg/day)
Naphthalene	2.00e-08	2.90e-06	2.33e-06
Acenaphthene	4.05e-06	2.19e-06	2.48e-06
Acenaphthylene	2.92e-06	4.25e-06	4.32e-06
Anthracene	3.70e-06	4.93e-06	1.79e-06
Fluorene	1.99e-06	2.60e-06	3.74e-06
Phenanthrene	1.12e-05	1.78e-06	3.46e-06
Pyrene	1.51e-06	6.80e-07	1.40e-06
Fluoranthene	2.97e-06	1.40e-06	1.37e-06
Chrysene	4.55e-06	2.10e-07	2.58e-06
Benzo[a]anthracene	4.00e-08	3.42e-06	1.41e-06
Benzo[a]pyrene	2.05e-06	1.79e-06	1.51e-06
Benzo(b)fluoranthene	1.05e-06	1.02e-06	1.01e-06
Benzo[k]fluoranthrene	3.44e-06	2.07e-06	1.23e-06
Dibenz[a,h]anthracene	2.33e-06	3.56e-06	5.20e-07
Benzo[ghi]perylene	4.21e-06	1.52e-06	2.74e-06
Indeno(1,2,3-cd)pyrene	2.47e-06	4.20e-07	1.51e-06

Table 7: Non-Cancer Risk for PAHs in sediment from Aluu River

Compound	L1	L2	L3
Naphthalene	6.67×10^{-7}	9.70×10^{-5}	7.80×10^{-5}
Acenaphthene	6.75×10^{-5}	3.70×10^{-5}	4.10×10^{-5}
Acenaphthylene	9.73×10^{-5}	1.42×10^{-4}	1.44×10^{-4}
Anthracene	1.23×10^{-5}	1.64×10^{-5}	5.97×10^{-6}
Fluorene	4.98×10^{-5}	6.50×10^{-5}	9.35×10^{-5}
Phenanthrene	3.73×10^{-4}	5.93×10^{-5}	1.15×10^{-4}
Pyrene	5.03×10^{-5}	2.27×10^{-5}	4.67×10^{-5}
Fluoranthene	7.43×10^{-5}	3.50×10^{-5}	3.43×10^{-5}
Chrysene	4.55×10^{-3}	2.10×10^{-4}	2.58×10^{-3}
Benzo[a]anthracene	4.00×10^{-4}	3.42×10^{-2}	1.41×10^{-2}
Benzo[a]pyrene	6.83×10^{-3}	5.97×10^{-3}	5.03×10^{-3}
Benzo(b)fluoranthene	1.23×10^{-3}	1.11×10^{-3}	1.12×10^{-3}
Benzo[k]fluoranthrene	1.15×10^{-2}	6.90×10^{-3}	4.10×10^{-3}
Dibenz[a,h]anthracene	7.77×10^{-3}	1.19×10^{-2}	1.73×10^{-3}
Benzo[ghi]perylene	1.40×10^{-2}	5.07×10^{-3}	9.13×10^{-3}
Indeno(1,2,3-cd)pyrene	8.23×10^{-3}	1.40×10^{-3}	5.03×10^{-3}

Table 8: Cancer Risk (CR) for PAHs in sediment from Aluu River

Compound	CSF	L1	L2	L3
Naphthalene	0.12	2.40e-09	3.48e-07	2.80e-07
Fluoranthene	0.04	1.19e-07	5.60e-08	5.48e-08
Chrysene	0.017	7.74e-08	3.57e-09	4.39e-08
Benzo[a]anthracene	0.1	4.00e-09	3.42e-07	1.41e-07
Benzo[a]pyrene	7.3	1.50e-05	1.31e-05	1.10e-05
Benzo[k]fluoranthene	0.7	2.41e-06	1.45e-06	8.61e-07
Dibenz[a,h]anthracene	7.3	1.70e-05	2.60e-05	3.80e-06
Indeno(1,2,3-cd)pyrene	0.042	1.04e-07	1.76e-08	6.34e-08
Total Cancer Risk		**3.57×10^{-5}**	**4.25×10^{-5}**	**1.67×10^{-5}**

Table 9: Source apportionment of PAH compound based on their loading

PAH Compound	PC1 Loading	PC2 Loading
Naphthalene	-0.189	-0.348
Acenaphthene	0.317	-0.087
Acenaphthylene	0.297	-0.169
Anthracene	0.323	0.012
Fluorene	0.277	-0.221
Phenanthrene	-0.108	0.405
Pyrene	-0.186	-0.351
Fluoranthene	0.317	-0.087
Chrysene	-0.246	0.279
Benzo[a]anthracene	0.307	-0.134
Benzo[a]pyrene	0.138	0.388
Benzo[k]fluoranthrene	0.297	-0.169
Dibenz[a,h]anthracene	0.224	0.309
Benzo[ghi]perylene	-0.305	-0.144
Indeno(1,2,3-cd)pyrene	-0.208	-0.329
Total Variance	63.8%	36.2%

Table 10: Source apportionment of PAH compound based on their loading from sediment

Compound	PC1	PC2
Phenanthrene	0.307	-0.014
Acenaphthene	0.307	-0.025
Fluoranthene	0.300	-0.100
Benzo[ghi]perylene	0.296	0.128
Chrysene	0.286	0.176
Indeno(1,2,3-cd)pyrene	0.288	0.168
Pyrene	0.230	0.316
Benzo[a]pyrene	0.225	-0.324
Anthracene	-0.023	-0.474

Dibenz[a,h]anthracene	-0.027	-0.474
Benzo[a]anthracene	-0.279	-0.201
Naphthalene	-0.307	0.004
Acenaphthylene	-0.299	0.114
Variance	**70.54%**	**29.46%**

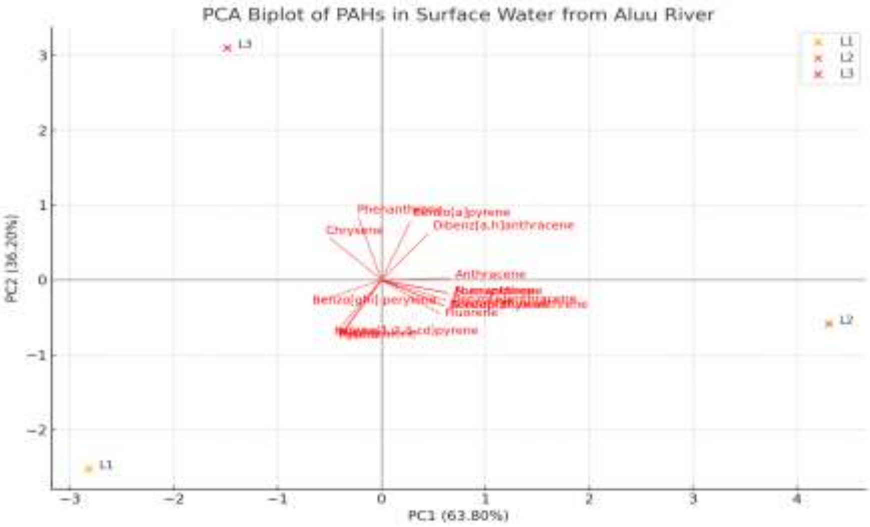

Figure 1: PCA biplot for PAHs concentrations in surface water

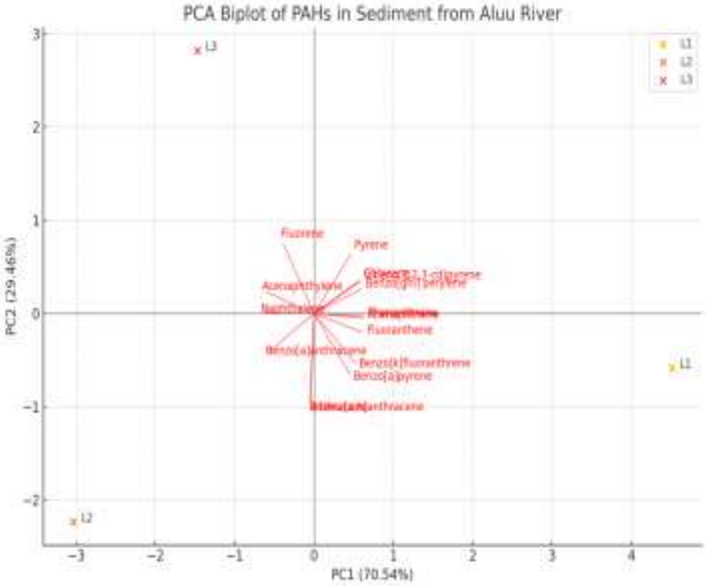

Figure 2: PCA biplot for PAHs concentrations in sediment

Discussion

PAHs in Surface water from Aluu River

Polycyclic aromatic hydrocarbons (PAHs) are a group of organic pollutants known for their persistence, hydrophobicity, and potential carcinogenicity.. The analysis of surface water samples from three locations (L1, L2, and L3) along the Aluu River revealed varying concentrations of low molecular weight PAHs (LPAHs) and high molecular weight PAHs (HPAHs), indicating anthropogenic influence across all sites. Total PAHs ranged from 3.329 µg/L at L3 to 6.408 µg/L at L2, suggesting L2 is the most impacted site, likely due to its proximity to potential sources such as industrial activities, urban runoff, or waste discharges.

LPAHs, which typically include two to three aromatic rings and are more soluble in water, showed elevated levels at L2 (1.987 µg/L), followed by L1 (0.796 µg/L) and L3 (0.689 µg/L). Notably, anthracene (1.12 µg/L) and fluorene (0.45 µg/L) recorded high concentrations at L2. These compounds are often associated with petroleum products and low-temperature combustion processes, indicating both petrogenic and pyrogenic contamination [6]. L1 showed a higher concentration of naphthalene (0.46 µg/L), which is known to be a volatile and relatively soluble PAH, suggesting recent input or proximity to a discharge point [7]

In contrast, HPAHs, comprising four or more aromatic rings and typically associated with persistent and carcinogenic pollution, were highest at L1 (4.861 µg/L), followed by L2 (4.551 µg/L) and L3 (2.64 µg/L). L1 exhibited a significant concentration of benzo[ghi]perylene (1.73 µg/L) and pyrene (0.97 µg/L), compounds often linked to vehicular emissions and the combustion of organic materials [9]. This pattern suggests that L1 may be closer to a roadway, urban area, or other combustion-related source. Interestingly, L2 had elevated levels of benzo[a]anthracene (1.27 µg/L) and benzo[k]fluoranthene (1.006 µg/L), both of which are classified as probable human carcinogens by the U.S. EPA [10]. This further supports the hypothesis that L2 is receiving significant pollutant loads, possibly from mixed sources including industrial effluents.

Although L3 showed the lowest total PAHs (3.329 µg/L), the presence of benzo[a]pyrene (0.680 µg/L) and phenanthrene (0.291 µg/L) indicates that contamination is still present and potentially harmful. Benzo[a]pyrene, in particular, is considered one of the most toxic PAHs and has been linked to genotoxic and carcinogenic effects in humans and aquatic organisms. The relatively lower levels at L3 could be due to greater dilution, natural attenuation, or increased distance from pollution sources. The research conducted by China. Liu et al. reported low polycyclic aromatic hydrocarbons (PAHs) in surface water and sediment from the upper reach of the Huaihe River, China [11]. However, they estimated 79.94 to 421.07 ng/L PAHs for surface water and 10.87 to 201.42 ng/L for sediment. The finding of this research is also supported by Zhao et al. (2015), who recorded the total PAH concentrations in the range of 548 to 2598 ng/L in water and 1502 to 11,562 ng/g in SPMs in the Yellow River, Northwestern China.

The result is consistent with Chen et al., who reported 351 to 4427 ng/L in water dissolved phase (WDP) and 3557 ng/L to 147,907 ng/L for surface water in Weihe River, Northwest China [12]. These findings underscore the need for regular monitoring, pollution source identification, and remediation strategies to mitigate environmental and public health risks associated with PAH contamination in aquatic ecosystems. The PAH concentrations in Aluu River surface water suggest significant anthropogenic pollution, especially at L1 and L2. The data highlight a mix of petrogenic and pyrogenic sources, with implications for aquatic life and human health, particularly in communities that rely on the river for domestic or agricultural use [11].

PAHs in Sediment from Aluu River

The result of the PAHs analysis in the sediment in Aluu River is shown in Table 4.6. The sediment profile of the Aluu River shows a substantial accumulation of polycyclic aromatic hydrocarbons (PAHs), with notable variation across the three sampling locations. Total PAHs were highest at L1 (31.004 µg/g), followed by L2 (24.68 µg/g) and L3 (22.325 µg/g), suggesting that L1 is the most heavily contaminated site. PAHs in sediment typically reflect long-term deposition and accumulation of pollutants, particularly from hydrophobic compounds that bind to particulate matter [7]. The elevated levels across all sites indicate chronic pollution likely from petroleum products, combustion residues, and industrial discharges.

In terms of low molecular weight PAHs (LPAHs), L1 again exhibited the highest concentration (16.404 µg/g), with phenanthrene (8.15 µg/g) as the dominant compound. This is significantly higher than the levels observed at L2 (13.67 µg/g) and L3 (11.915 µg/g). Phenanthrene, anthracene, and fluorene, all present in notable quantities, are indicative of pyrogenic inputs, particularly from the incomplete combustion of fossil fuels or biomass [7]. Interestingly, naphthalene, which is typically more volatile and less likely to persist in sediment, showed very low levels at L1 (0.018 µg/g) but surprisingly high concentrations at L2 (2.12 µg/g) and L3 (1.70 µg/g), suggesting localized or recent petrogenic contamination in those sites.

High molecular weight PAHs (HPAHs), which tend to be more carcinogenic and persistent, were also highest at L1 (14.6 µg/g), followed by L2 (11.01 µg/g) and L3 (10.41 µg/g). L1 recorded particularly high concentrations of chrysene (3.32 µg/g), benzo[k]fluoranthene (2.51 µg/g), and benzo[ghi]perylene (3.07 µg/g). These compounds are often used as markers for traffic-related pollution and high-temperature combustion processes. On the other hand, L2 showed elevated levels of benzo[a]anthracene (2.50 µg/g) and dibenz[a,h]anthracene (2.6 µg/g), both of which are classified as probable human carcinogens and associated with industrial and urban discharges (Nna et al., 2024).The result of this research is consistent with Chen et al. [13], who reported 351 to 4427 ng/L in water dissolved phase (WDP) and 3557 ng/L to 147,907 ng/L for surface water in Weihe River, Northwest China. Liu et al. (2016) reported low polycyclic aromatic hydrocarbons (PAHs) in surface water and sediment from the upper reach of the Huaihe River, China.

Health risk assessement of PAHs in surface water from Aluu River

The estimated daily intake (EDI) for polycyclic aromatic hydrocarbons (PAHs) in surface water from the Aluu River provides valuable insights into the potential health risks associated with waterborne exposure to these toxic compounds. The data spans three different locations (L1, L2, and L3), showing notable variation in PAH concentrations and consequently, in human exposure levels. EDIs are calculated to estimate the amount of a chemical substance a person is likely to ingest daily, per kilogram of body weight, primarily through drinking water. Elevated EDI values for certain PAHs, particularly those with known carcinogenic and mutagenic properties, are concerning and warrant public health attention.

Among the sampling sites, Location 2 (L2) generally recorded the highest EDI values for many PAHs. For instance, anthracene at L2 was reported at 0.0320 mg/kg/day, significantly higher than at L1 (0.00223) and L3 (0.00863). Similarly, benzo[a]anthracene (0.03629 mg/kg/day), benzo[k]fluoranthrene (0.02874 mg/kg/day), and benzo[a]pyrene (0.01600 mg/kg/day) were substantially elevated at L2. These compounds are of particular concern because of their classification by the International Agency for Research on Cancer (IARC) as probable or possible human carcinogens (IARC, 2010; Abdel-Shafy et al. 2016). The data suggest that L2 may be more heavily impacted by anthropogenic activities such as industrial discharges, petroleum spills, or urban runoff, contributing to higher PAH levels [15].

On the other hand, Location 1 (L1) exhibited the highest individual EDI value for benzo[ghi]perylene at 0.04943 mg/kg/day. This indicates that even in locations where overall PAH levels may be moderate, certain compounds can still pose acute risks. The presence of PAHs such as chrysene, benzo[a]pyrene, and pyrene across all three locations—often in elevated concentrations—suggests that contamination is widespread along the Aluu River. These compounds are commonly associated with incomplete combustion of organic matter, oil spills, and industrial pollution. Their persistence and bioaccumulative nature make them especially hazardous in aquatic environments.

Several PAHs, including naphthalene, acenaphthene, and fluorene, showed relatively lower EDI values, but their presence remains significant as chronic exposure—even at low levels—can contribute to cumulative health risks over time. The consistent detection of chrysene across all sites, with values ranging from 0.01314 to 0.01777 mg/kg/day, highlights its potential to persist and bioaccumulate. Sustained exposure to even low levels of PAHs can increase the risk of cancer and other adverse health outcomes, particularly in vulnerable populations such as children [15].

Non-Cancer Risk of PAHs in Surface water

The Non-Cancer Risk (Hazard Quotient, HQ) values for polycyclic aromatic hydrocarbons (PAHs) in surface water from the Aluu River reveal significant potential health risks associated with prolonged exposure. The HQ value is used to evaluate non-carcinogenic health risks by comparing estimated daily intake to a reference dose (RfD). A value of $HQ > 1$ suggests that the exposed population may experience adverse health effects. The data from the Aluu River indicate that several PAHs significantly exceed this threshold, particularly in certain locations, raising serious environmental and public health concerns.

Among all the locations, Location 2 (L2) consistently presents the highest non-cancer risks, with numerous compounds showing extremely elevated HQs. For example, benzo[a]anthracene at L2 has a HQ of 362.857, which is dramatically higher than the safety limit. Similar trends are observed for benzo[k]fluoranthrene (95.810) and benzo[a]pyrene (53.333). These compounds are classified as priority pollutants by the U.S. Environmental Protection Agency due to their toxicity and potential for bioaccumulation. Their high HQ values suggest possible adverse effects on human health, including liver and kidney damage, immunotoxicity, and developmental disorders [17].

Location 1 (L1) also demonstrates significant non-cancer risks, particularly for benzo[ghi]perylene (HQ = 164.762) and indeno(1,2,3-cd)pyrene (HQ = 83.810). These elevated values indicate a substantial exposure hazard that cannot be overlooked. Although L1 shows relatively lower HQs for some lower molecular weight PAHs, such as acenaphthene (0.0138) and phenanthrene (0.015), the overall risk remains elevated due to the presence of highly toxic compounds. The situation at Location 3 (L3) is similarly concerning, with benzo[a]pyrene (HQ = 64.762), chrysene (HQ = 17.771), and dibenz[a,h]anthracene (HQ = 13.333) all far exceeding safe exposure levels. These values suggest that even areas with moderate pollution still pose significant non-cancer health risks, particularly with cumulative exposure over time [16].

It is important to note that several PAHs show consistently low HQs across all locations, such as acenaphthene, acenaphthylene, and phenanthrene. While these individual values are below the threshold of concern ($HQ < 1$), their presence in combination with more toxic PAHs could contribute to an overall additive risk. According to USEPA guidelines, when multiple contaminants are present, a Hazard Index (HI)—the sum of all HQs—should be calculated to assess cumulative non-cancer risk [14]. Given the elevated HQs for many compounds, the cumulative HI for each location is likely to be significantly higher than 1, underscoring a high probability of adverse health outcomes.

The high HQ values for several PAHs across all locations underscore the persistent and pervasive nature of PAH contamination in the Aluu River. These pollutants are often introduced into the environment through activities such as fossil fuel combustion, oil spills, industrial discharge, and the improper disposal of petroleum products. The chronic exposure of local populations to such hazardous substances—particularly in communities that rely on untreated surface water for drinking, cooking, or bathing—poses a serious public health threat that requires immediate intervention.

Cancer Risk (CR) for of PAHs in surface water from the Aluu River

The assessment of cancer risk (CR) associated with exposure to polycyclic aromatic hydrocarbons (PAHs) in surface water from the Aluu River indicates potentially significant health hazards, especially for populations with long-term exposure to this water. The cancer risk was calculated using the Cancer Slope Factor (CSF) in Figure 4.10 for individual PAHs, which estimates the increased cancer risk per unit of chemical intake over a lifetime. According to the United States Environmental Protection Agency (USEPA), an acceptable lifetime cancer risk ranges from 1×10^{-6} to 1×10^{-4}, beyond which risks are considered unacceptable and warrant intervention.

In this study, the total cancer risk values recorded for the three locations—L1 (0.03903), L2 (0.09041), and L3 (0.07259)—exceed the upper acceptable limit by several orders of magnitude. These findings suggest that residents or users of Aluu River water could face a significant lifetime risk of developing cancer, particularly if they are exposed through drinking, bathing, or other domestic activities. Such elevated risk levels are indicative of severe contamination, potentially from petroleum products, industrial effluents, or urban runoff, which are common in oil-producing regions of the Niger Delta.

Among the PAHs, Benzo[a]pyrene presented the highest individual cancer risk values, especially in L2 (0.05006) and L3 (0.06078). This compound is classified as a Group 1 human carcinogen by the International Agency for Research on Cancer (IARC), due to its well-documented genotoxic and mutagenic properties (IARC, 2010). The extremely high cancer risk associated with Benzo[a]pyrene underscores its critical role in driving the overall carcinogenic potential of the water in these locations. Similarly, Benzo[a]anthracene, Benzo[k]fluoranthene, and Dibenz[a,h]anthracene also showed concerning risk levels, further highlighting the cumulative and potentially synergistic carcinogenic burden of these PAHs. Spatial variation in cancer risk was evident, with L2 exhibiting the highest total cancer risk (0.09041). This could be attributed to proximity to pollutant discharge zones, industrial activities, or natural hydrological factors that limit dispersion and enhance pollutant accumulation. While L1 had the lowest total risk among the three, its value (0.03903) is still far above the acceptable limit, indicating that no location along the river is free from concern.

The elevated cancer risk values observed in this study are particularly worrisome given the potential for cumulative exposure, including through bioaccumulation in aquatic life and additional exposure routes such as inhalation of volatilized PAHs during water use. Chronic exposure may disproportionately impact children, the elderly, and immune-compromised individuals, who are more susceptible to chemical carcinogens.

Estimated Daily Intake Risk of PAHs of sediment

Among the PAHs detected, Phenanthrene in L1 exhibited the highest EDI value (1.12×10^{-5} mg/kg/day), indicating significant contamination at that site. This elevated value may point to localized pollution sources such as petroleum leakage or urban runoff. Other PAHs, such as Acenaphthylene, Fluorene, and Anthracene, were also found at relatively moderate EDI levels across all sites, highlighting their persistent presence in the sediment. These compounds are known to arise from both pyrogenic and petrogenic origins and have been associated with toxicity to aquatic organisms and potential risks to human health.

Importantly, several carcinogenic PAHs—such as Benzo[a]pyrene, Chrysene, and Dibenz[a,h]anthracene—were detected with EDI values ranging from 10^{-6} to 10^{-8} mg/kg/day. Although these concentrations appear low, carcinogenic PAHs are known for their bioaccumulative and genotoxic properties, and even minute quantities can pose significant health risks over long-term exposure. For example, Benzo[a]anthracene recorded an EDI of 3.42×10^{-6} mg/kg/day in L2, suggesting a potential hotspot for cancer risk due to contaminated sediments.

The variation in EDI values among the three locations indicates site-specific pollution patterns. L1 generally exhibited higher EDIs for PAHs such as Phenanthrene, Chrysene, and Benzo[ghi]perylene, suggesting proximity to pollution sources or higher rates of deposition. L2, on the other hand, showed elevated levels of Benzo[a]anthracene and Acenaphthylene, while L3 had more moderate EDI values across most PAHs, implying comparatively lesser contamination. These differences could result from industrial activity, surface runoff, or hydrodynamic sediment transport mechanisms within the river system.

While the EDIs remain within what might be considered low-risk thresholds, the cumulative exposure to multiple PAHs, particularly the carcinogenic ones, could increase the long-term risk of adverse health effects for communities relying on the river for livelihood or domestic use. Thus, regular environmental monitoring and risk assessment are necessary to inform mitigation strategies and protect public health. Remediation of sediment hotspots and the enforcement of environmental regulations are critical to reducing human exposure risks from PAHs in the Aluu River ecosystem [16].

Non-Cancer Risk (Hazard Quotient - HQ) of PAHs of sediment

The result of EDI analysis in the sediment in Aluu River is shown in Table 4.11. In the case of sediments from the Aluu River, HQ values have been calculated for various PAHs at three sampling locations (L1, L2, and L3), and the results provide important insights into localized human health risks due to chronic environmental exposure. An HQ less than 1 typically implies that non-cancer health effects are unlikely; however, values approaching this threshold can still be cause for concern, particularly when multiple contaminants are present.

Among the PAHs assessed, compounds such as Benzo[ghi]perylene, Benzo[a]pyrene, Benzo[k]fluoranthrene, and Dibenz[a,h]anthracene exhibit relatively high HQ values across all three sampling points. For instance, Benzo[ghi]perylene in L1 recorded the highest HQ (1.40×10^{-2}), indicating a higher relative exposure dose in that area. Though these values remain below the critical HQ threshold of 1, their persistence, lipophilicity, and bioaccumulative potential suggest that even low-level, chronic exposure could lead to adverse health effects over time.

Another noteworthy observation is the spatial variation in risk levels. L1 consistently shows higher HQ values for several PAHs, including Benzo[a]pyrene (6.83×10^{-3}) and Chrysene (4.55×10^{-3}), suggesting that this site may be subject to greater pollutant inputs, possibly from industrial discharges, oil exploration activities, or urban runoff. Similarly, L2 is particularly elevated in Benzo[a]anthracene (3.42×10^{-2}), a compound associated with mutagenic and genotoxic effects. The high HQ values for these compounds, even though individually under the safety threshold, raise concerns when considering cumulative and synergistic effects, especially in vulnerable populations such as children or those with prolonged sediment contact.

Although L3 appears to be comparatively less contaminated, it still presents concerning HQ levels for Benzo[a]pyrene (5.03×10^{-3}) and Benzo[ghi]perylene (9.13×10^{-3}), both of which are known for their immunotoxic and reproductive toxicity risks. These findings indicate that no location is entirely free from PAH-related risk, emphasizing the need for a comprehensive, location-specific risk management plan.

Cancer Risk of PAHs in sediment from Aluu River

The assessment of cancer risk due to exposure to polycyclic aromatic hydrocarbons (PAHs) in sediment samples from the Aluu River reveals concerning but still acceptable levels of incremental lifetime cancer risk (ILCR) across three sampled locations: L1, L2, and L3. The total cancer risks at these sites were estimated to be 3.57×10^{-5} (L1), 4.25×10^{-5} (L2), and 1.67×10^{-5} (L3), respectively. According to the U.S. Environmental Protection Agency (USEPA), an acceptable risk range for carcinogens lies between 1×10^{-6} and 1×10^{-4}. While all locations fall within this range, the values at L1 and especially L2 approach the upper limit, indicating moderate to significant concern for potential human health impacts from long-term exposure.

A closer examination of compound-specific contributions reveals that the most potent carcinogens—Benzo[a]pyrene and Dibenz[a,h]anthracene, both with cancer slope factors (CSFs) of 7.3 mg/kg/day^{-1}—dominate the overall cancer risk at all locations. Benzo[a]pyrene, widely recognized as the most carcinogenic PAH, contributes a substantial portion of the total cancer risk: approximately 41.9% at L1, 30.8% at L2, and 65.9% at L3. Similarly, Dibenz[a,h]anthracene makes up an even larger share at L2 (over 61%), highlighting its critical role in elevating the cancer risk at this site. These results align with prior studies indicating the prominent role of these compounds in driving carcinogenic risk in PAH-contaminated environments.

In addition to the two primary contributors, Benzo[k]fluoranthene, with a lower but still significant CSF of 0.7, also contributes notably to the total cancer risk—particularly at L1, where it accounts for over 6% of the total value. Other PAHs such as Fluoranthene, Chrysene, and Indeno(1,2,3-cd)pyrene contribute to a lesser extent due to their lower CSFs. While compounds like Naphthalene and Benzo[a]anthracene have moderate CSFs (0.12 and 0.1, respectively), their contribution varies based on concentration levels observed at each site. For example, Naphthalene contributes more prominently at L2 and L3 due to relatively higher EDI values in those locations.

The spatial distribution of cancer risk indicates that L2 presents the highest risk, followed by L1 and L3. This suggests a potential localized source of PAHs near L2, which could stem from industrial discharge, hydrocarbon spills, or urban runoff. The results underscore the need for regular environmental monitoring and pollution source identification. Given the persistence and bioaccumulative nature of PAHs, their continued presence in sediments could pose long-term health risks to humans, especially local communities engaging in fishing, agriculture, or recreational activities that involve direct sediment contact.

In light of these findings, it is recommended that sediment remediation efforts be prioritized in areas like L2 to prevent further accumulation and potential biomagnification of carcinogenic PAHs. Additionally, community education programs should be implemented to raise awareness about the risks of prolonged exposure to contaminated sediments. From a policy standpoint, enforcement of industrial discharge regulations and monitoring of PAH levels in both sediments and aquatic life are crucial to safeguarding public health.

Source apportionment of polycyclic aromatic hydrocarbons (PAHs) in surface water from Aluu River

Principal Component Analysis (PCA) is a widely used multivariate statistical tool for identifying potential sources of environmental contaminants such as polycyclic aromatic hydrocarbons (PAHs). In the present study, PCA was applied to PAHs concentrations in surface water from three sampling locations (L1, L2, and L3) along the Aluu River. The objective was to identify the potential sources of these PAHs by examining their loading patterns on the first two principal components (PC1 and PC2).

The loading values indicate the degree to which each PAH contributes to the principal components. Compounds such as anthracene, acenaphthene, fluoranthene, and benzo[a]anthracene had high positive loadings on PC1, suggesting their association with petrogenic sources. These compounds are typically derived from unburned fossil fuels or oil-related activities [9]. The dominance of these PAHs in sample L2, which had higher concentrations of industrially linked PAHs, supports the inference that this site is likely impacted by petroleum-based pollution, possibly from oil spills or effluents from nearby facilities.

In contrast, PAHs such as benzo[ghi]perylene, indeno(1,2,3-cd)pyrene, and naphthalene exhibited negative loadings on PC1, implying a different origin. These compounds are commonly associated with pyrogenic sources, which involve high-temperature combustion of organic matter, including vehicular emissions, biomass burning, and industrial combustion processes. Their prevalence in L1 and L3 suggests atmospheric deposition or urban runoff as significant contributors.

PC2 also captured variance attributed to environmental behaviour and degradation potential. Phenanthrene, benzo[a]pyrene, and dibenz[a,h]anthracene had high positive loadings on PC2, indicating their semi-persistent nature in aquatic environments. These compounds tend to bind strongly to organic matter and resist degradation, thus accumulating in certain water bodies. This reinforces the importance of both local input sources and environmental fate in shaping PAH profiles.

The first principal component (PC1) accounts for approximately 63.80% of the total variance, while the second principal component (PC2) explains an additional 36.20%, bringing the cumulative variance explained by the first two components to approximately 100%.This high cumulative variance indicates that most of the information in the original data set can be represented in the two-dimensional space defined by PC1 and PC2, making the biplot a reliable visual interpretation tool

Source apportionment of PAHs in sediment from Aluu River

The analysis yielded two dominant components: PC1 and PC2. PC1 displayed strong positive loadings for several high-molecular-weight (HMW) PAHs such as phenanthrene, acenaphthene, fluoranthene, benzo[ghi]perylene, chrysene, and indeno(1,2,3-cd)pyrene. These compounds are commonly associated with pyrogenic sources, typically resulting from high-temperature combustion of organic material including fossil fuels, biomass, and refuse [9]. The presence of these PAHs in high concentrations and their clustering on PC1 suggest that site L1, which had the highest PC1 score, is most impacted by combustion-related emissions—likely from industrial or vehicular activities nearby.

In contrast, PC2 included both positively and negatively loading PAHs. Pyrene and indeno(1,2,3-cd)pyrene showed moderate positive loadings, while anthracene and dibenz[a,h]anthracene had strong negative loadings. The mixed nature of PC2 suggests the influence of both petrogenic and pyrogenic sources. Pyrene and related compounds may be derived from diesel emissions or residential burning, while the negative association of anthracene and dibenz[a,h]anthracene could reflect degradation or environmental transformation processes, such as photolysis or microbial activity, that affect PAHs differently depending on their chemical structure and environmental conditions [8,9]

Notably, naphthalene, a low-molecular-weight (LMW) PAH, exhibited a strong negative loading on PC1, differentiating it from the combustion-derived compounds. This pattern suggests a petrogenic origin for naphthalene, likely from petroleum products, oil spills, or untreated wastewater discharges. Achten and Hofmann have highlighted the role of naphthalene as an indicator of unburned fossil fuel contamination, which aligns with its behavior in this study [10].

The Principal Component Analysis (PCA) of the PAH concentrations in sediment samples from the Aluu River revealed that the first two principal components (PC1 and PC2) accounted for 100% of the total variance in the dataset. Specifically, PC1 contributed approximately 70.54%, while PC2 contributed 29.46%. This complete capture of variance by just two components highlights a highly structured dataset with strong underlying patterns, which is ideal for interpreting potential sources of contamination.

The dominance of PC1 suggests the presence of a major contributing factor that influences the concentration of multiple PAHs across the sampled locations. Given the high loadings of high-molecular-weight PAHs (HMW PAHs) typically linked to combustion sources—such as phenanthrene, chrysene, and benzo[ghi]perylene—on PC1, it is reasonable to infer that pyrogenic inputs (e.g., combustion of fossil fuels or biomass) are the predominant source at some locations, especially L1. This is consistent with previous findings that PC1 often represents contributions from vehicular and industrial emissions in urban and peri-urban sediments [8].

PC2, while accounting for a smaller portion of the variance, still plays a critical role in distinguishing between different sources or environmental processes. For instance, PC2 helps separate low-molecular-weight PAHs (LMW PAHs) like naphthalene and petrogenic indicators from the combustion-related compounds. This component may also reflect localized contamination events or differential degradation behaviors in sediments, as LMW PAHs tend to be more biodegradable and volatile [9]. The combined interpretation of PC1 and PC2 thus enables the apportionment of sources between pyrogenic and petrogenic origins and allows for a nuanced understanding of the pollution dynamics in the Aluu River sediment. Overall, the high explanatory power of these two components validates the use of PCA in environmental forensics and supports its effectiveness in tracing pollution sources in aquatic ecosystems [10]. This information is essential for environmental monitoring and for designing targeted remediation strategies.

Conclusion

The study focuses on health risk analysis and source apportionment of polyaromatic hydrocarbons in water and sediment in Aluu River. The river showed contamination by both low molecular weight (LPAHs) and high molecular weight (HPAHs) PAHs. Sediment samples contained higher PAH concentrations than water. Both non-cancer hazard quotients (HQs) and cancer risks (CRs) exceeded safe thresholds, especially for compounds like Benzo[a]pyrene and Benzo[ghi]perylene. Water and sediment at all locations present moderate to high health risks. Principal Component Analysis (PCA) suggested both petrogenic (e.g., oil-derived) and pyrogenic (combustion-derived) sources of PAHs and microplastics, with multiple loadings pointing to complex pollution profiles influenced by human and industrial activities.

Recommendations

1. Establishment of a long-term environmental monitoring program to track PAHs trends and evaluate effectiveness of mitigation strategies.
2. Given the high pollutant load in sediment, consider dredging or bioremediation to reduce long-term ecological risks.
3. Strengthen environmental regulations and enforce pollution control laws, particularly around petrochemical industries and urban settlements.

Contribution to Knowledge

1. The use of PCA for PAHs advances understanding of pollutant origin, crucial for targeted remediation.
2. It combines HQ and CR models to offer a comprehensive health risk profile, particularly for developing regions with poor environmental regulations.
3. The study emphasizes the synergistic effect of microplastics and PAHs in aquatic ecosystems and their potential bioaccumulation.

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