

Evaluation of Organochlorine Pesticides in River Galma Sediments: Passive Sampling Approach

S. J. Mohammad*, A. D. Bello, A. Ishaq, N. I. Abdullahi, Y. Owoseni, B. S. Sani

Department of Water Resources and Environmental Engineering, Ahmadu Bello University, 1045, Zaria, Kaduna Nigeria.



ABSTRACT: Organochlorine pesticides (OCPs) are persistent organic pollutants that pose significant risks to environmental and human health. This study assessed the spatial distribution, sources, and ecological risks of OCPs in sediments of the River Galma, northern Nigeria, using passive sampling with low-density polyethylene (LDPE) membranes. Samplers were deployed at ten locations along the river, representing diverse land-use practices, to determine the freely dissolved concentrations of hexachlorocyclohexane (HCH) isomers, dichlorodiphenyltrichloroethane (DDT) and its metabolites, and chlordane-related compounds. Concentrations of OCPs varied markedly among locations with total OCP concentrations ranging from 5,355.32 ng/L to 8,231.62 ng/L, with the highest levels recorded at sites influenced by intensive agriculture and industrial discharges. Diagnostic isomer and metabolite ratios indicated recent inputs of lindane alongside historical DDT residues. Multivariate analyses (principal component and factor analysis) attributed 74% of the variance to widespread agricultural sources, particularly HCH isomers, while localized industrial inputs were linked to hexachlorobenzene and chlordane derivatives. Ecological risk assessment identified γ -HCH as the compound of greatest concern, indicating a high potential risk to aquatic organisms at the most contaminated sites. These findings highlight the need for stricter enforcement of pesticide bans, targeted remediation of hotspots, adoption of sustainable agricultural practices, and long-term monitoring. This is the first application of passive sampling for OCP monitoring in northern Nigeria, and it provides useful insight into contamination sources and degradation pathways.

KEYWORDS: Organochlorine Pesticides (OCPs), Passive Sampling, Sediment Contamination, River Galma, Ecological Risk Assessment, Agricultural Runoff

[Received May. 29, 2026; Revised Jul. 30, 2026; Accepted Sep. 08, 2026]

Print ISSN: 0189-9546 | Online ISSN: 2437-2110

1. INTRODUCTION

Chlorinated pesticides which are often grouped under the umbrella term Organochlorine Pesticides (OCPs), are one class of persistent organic pollutants (POPs) that have been extensively used in agriculture worldwide (Mishra et al., 2022). These chemicals, which include well-known pesticides such as DDT (Dichlorodiphenyltrichloroethane), Aldrin, and Lindane, are highly toxic and persistent in the environment. Their stability and lipophilic nature allow them to accumulate in the tissues of organisms, leading to biomagnification in the food chain, which is a significant environmental and health concern (Soman et al., 2024). OCPs are of particular concern in aquatic ecosystems because they can be transported through water bodies and eventually sequestered in sediments, thereby acting as long-term reservoirs for these harmful substances (Benson et al., 2023).

In Nigeria for example, which is a country with an extensive agricultural sector, the use of OCPs remains widespread, particularly in regions where crop cultivation is a dominant activity. While much of the research on OCP contamination has been concentrated in southern Nigeria, particularly the Niger Delta and southwestern regions (Omayuli et al., 2024; Tesi et al., 2020), studies on the northern parts of the country remain scant. The River Galma, a key water resource in northern Nigeria, is used for irrigation, domestic purposes, and recreational activities. Despite all the stated importance of OCPs, there has been limited research on

the levels of contamination in its sediments. Due to the prevalence of pesticide use in agriculture in this region, it is quite important to assess the extent of contamination to ensure the safety of both the aquatic ecosystem and local communities that rely on this water source.

This study will address this gap by using passive sampling techniques to assess the spatial distribution of OCPs in the sediments of River Galma. Passive sampling is a powerful tool in environmental monitoring which provide a time-integrated measure of contaminant levels over a longer period, rather than a snapshot of concentration at a particular time as provided by traditional grab sampling methods (Jonker et al., 2020b). Unlike active sampling, where contaminants are collected from water or sediments at specific points in time, passive samplers absorb pollutants continuously, making them particularly effective for measuring persistent pollutants like OCPs that may accumulate over time in sediment deposits (Jonker et al., 2020a).

The novelty of this research lies in its pioneering application of passive sampling materials in northern Nigeria, where such techniques have not yet been employed. Although passive sampling is widely used for the monitoring of contaminants such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) in global studies (Taylor et al., 2021), there has been little focus on OCPs, particularly in the northern regions of Nigeria. To the

*Corresponding author: mjumande@abu.edu.ng

doi: <http://doi.org/10.63746/njtd.v23i3.3290>

best of our knowledge, this is the first study in northern Nigeria to apply low-density polyethylene (LDPE) membranes for the assessment of OCP contamination in river sediments.

The use of low-density polyethylene (LDPE) membranes in passive sampling offers an effective way to assess contamination in both water and sediment samples (Jonker *et al.*, 2020b). LDPE is particularly useful for sampling hydrophobic organic contaminants, such as OCPs, due to its high affinity for these compounds. The material is affordable, durable, and easy to deploy, making it an ideal choice for large-scale environmental monitoring projects. In comparison to active sampling methods, passive sampling offers several advantages. First, it allows for continuous monitoring over a longer period, providing a better representation of long-term pollutant trends rather than transient spikes in contamination. Second, passive samplers can be deployed in multiple locations, giving a more detailed understanding of spatial distribution patterns. Third, passive samplers can be cost-effective and simpler to deploy in remote areas where access may be limited (Kovács *et al.*, 2023; Kreutzer, 2022; Kreutzer *et al.*, 2023). These benefits make passive sampling an ideal choice for environmental monitoring in regions like northern Nigeria, where the lack of advanced monitoring infrastructure and resources has hindered extensive research on environmental contamination.

The primary objective of this research is to evaluate the spatial distribution of OCP contamination in River Galma sediments through passive sampling, providing a more holistic understanding of the extent of contamination in this important waterway. This study represents the first attempt to assess the spatial distribution of chlorinated pesticide contamination in River Galma sediments using passive sampling methods, which have not been previously applied in

northern Nigeria. The findings will enhance our understanding of pesticide contamination in northern Nigeria and lay the groundwork for future environmental monitoring initiatives. Given the persistence and toxicity of OCPs, it is critical to address this gap in research to protect both the environment and public health.

II. METHODOLOGY

This section describes the approach used to assess the occurrence, sources, and ecological risks of organochlorine pesticides (OCPs) in the River Galma. It begins with a description of the study area and the sampling locations, which represent different land-use practices along the river. It then outlines the deployment of low-density polyethylene (LDPE) passive samplers, the extraction and analysis of the target compounds, and the calculation of freely dissolved concentrations. Finally, it presents the statistical and ecological risk assessment methods used to interpret the data, namely diagnostic ratios, principal component and factor analysis, and toxicity quotients.

A. Study area

The Galma River is an important waterway in northern Nigeria, flowing through Kaduna State. It originates from the highlands of the Jos Plateau and winds its way southwest, passing through Zaria and its neighboring agricultural areas, before merging with the Kaduna River. This river plays a vital role in the region by providing water for domestic, agricultural, and industrial purposes. The Galma River's catchment area lies in the northeastern section of the Kaduna River basin, a region known for its intensive agricultural activities (Samuel, 2015). Year-round farming thrives along the riverbanks, reflecting the area's reliance on this essential resource.

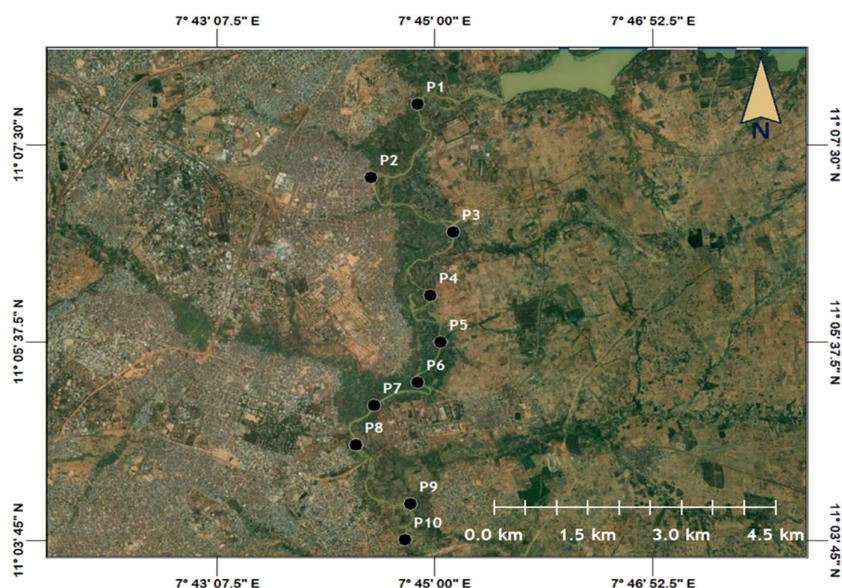


Figure 1 Study Area

To better understand the presence and distribution of chlorinated pesticides in the river's sediments, ten sampling points were strategically selected along the Galma River.

These locations, shown in Figure 1, were carefully chosen to represent a variety of geographic and environmental conditions, as well as diverse land-use practices. By covering

such a wide range, the study aims to provide a comprehensive analysis of the river's health and contamination levels.

B. Materials and equipment

1) Reagents:

- i. Acetone: GC grade, specifically for residue analysis.
- ii. n-Hexane: GC-MS grade, ideal for residue analysis.
- iii. Dichloromethane: High-purity solvent used during sample preparation.
- iv. Milli-Q Water: Ultra-pure water with a resistance of 18.2 MΩ·cm.
- v. Sodium Azide (NaN₃): For chemical stabilization.
- vi. Sediment Samples: Containing OCPs for which C_{free} (freely dissolved concentration of OCPs in sediments) needs to be determined.

2) Equipment

An analytical balance was used to weigh sediment samples, PE strips, and reagents, and a fume hood was used for all solvent handling. Sediment was transferred with metal spoons and sieved (2 mm mesh) to remove coarse material. The 50-μm low-density polyethylene (PE) sheets used as passive samplers were cut with scissors and a scalpel and handled with tweezers, and aluminum foil (30-50 μm) was used to wrap and handle samples during preparation. Extraction was carried out in clean glassware (250 and 500 mL beakers and Erlenmeyer flasks with ground-glass stoppers) on a reciprocal shaker table (180 rpm, 3-5 mm amplitude), with the vortex mixer used to mix the extracts. Micro-pipettes were used to add internal standards and transfer measured volumes (100-1,000 μL). Extracts were stored in 20 mL scintillation vials with foil-lined caps and transferred to 1.5 mL amber autosampler vials for analysis of the organochlorine pesticides (OCPs) by using a Hewlett-Packard 5890 Series II gas chromatograph. The procedures are described in the following subsections.

C. Reagent Setup and Sample Preparation

The experimental setup and PE preparation, extraction and analysis were done in accordance with the standardized protocols set by Jonker et al. (2020b) which are briefly described in subsequent subsections.

1) Preparation of Standard Aqueous Solution (SAS)

The standard aqueous solution (SAS) was prepared by dissolving 200 mg of sodium azide (NaN₃) in one liter of Milli-Q water. This process was performed in a clean glass bottle with a plastic cap. The solution was shaken thoroughly to ensure complete dissolution and homogenization. Since sodium azide is highly toxic, the solution was used within one week of preparation. The bottle was kept tightly closed and stored at room temperature until it was needed.

2) Cutting and Preconditioning of Polymer Strips

Small polyethylene (PE) polymer strips were cut from an untreated polymer sheet using sharp scissors. The width of the strips was kept between 4–6 mm to ensure they would fit into autosampler vials, while the length was adjusted based on the desired mass. The strips were weighed with an analytical balance to an accuracy of ± 0.20 mg. Once prepared, the strips were placed together in a 20-mL scintillation vial with a screw cap. For preconditioning, approximately 18 mL of

high-purity n-hexane was added to the vial containing the strips. The vial was sealed tightly and placed horizontally on a reciprocal shaker set to 180 r.p.m., where it was shaken for 30 minutes. After shaking, the hexane was carefully poured off while keeping the strips in the vial, and the process was repeated with fresh n-hexane for another 30 minutes. This washing step was repeated twice more using high-purity acetone instead of hexane. After the final acetone wash, all solvent was discarded. The solvent exchange process was carried out in a fume hood, and the specific order of solvents (n-hexane followed by acetone) was adhered to, as it was critical for proper cleaning due to the miscibility of acetone with water and methanol.

3) Preparation of Equilibration Systems

For the equilibration systems, 120-mL bottles designated for polymer strip samplers were washed and labeled. SAS was prepared in an ultraclean bottle that had been thoroughly washed with soap and rinsed with high-purity acetone and Milli-Q water. The required volume of SAS was calculated based on ~90 mL per container to be prepared. Sediment samples were thoroughly homogenized prior to use. Larger debris such as leaves, twigs, and stones were manually removed, and the sediment was mixed thoroughly with a metal spoon to ensure uniformity. The organic carbon fraction of the sediment samples was determined, and 30 g of dry-weight sediment was placed into each 120-mL bottle. The bottles were then filled with approximately 100 mL of SAS, leaving sufficient headspace to allow proper mixing. The air-dried polymer strips were retrieved from the storage vial, weighed directly without additional drying, and added individually to the equilibration bottles. To seal the bottles, a 5 × 5 cm piece of acetone-cleaned thick aluminum foil was placed over the bottle. The foil was wound around the neck of each bottle to ensure a complete seal, leaving no creases or gaps. This setup ensured proper equilibration conditions for the polymer strip samplers.

4) Equilibrating the Systems

The bottles containing polymer strips were placed horizontally on a one-dimensional reciprocal shaker set to operate at 150–180 r.p.m. The equilibration was performed in the dark at a controlled temperature of 20 ± 3 °C. Because there is a large number of bottles that require this equilibration, they were all stacked securely in a box to ensure they remain stable during shaking. This same process was continued for six weeks thereby allowing sufficient time for equilibrium to be reached between the polymer strips and the surrounding solution.

5) Collecting and Cleaning the Samplers

After the equilibration, all the bottles and vials were carefully removed from the shaker and then placed on a clean laboratory table. The setup for the cleaning process included the preparation of a vial box, sufficient autosampler vials, a clean siphon with freshly drawn Milli-Q water, and a beaker for collecting sediment waste. Additional equipment such as a tea sieve, tweezers, scissors, folded lint-free laboratory tissues, a pipette with tips, and an Erlenmeyer flask containing the solvent for polymer extraction was arranged on a clean surface. A waste receptacle was also prepared to

collect sediment suspensions. The samplers were gently cleaned after collection. This involved drying the strips by patting them lightly with a clean lint-free tissue while ensuring the strips remained on a clean, dry surface. The polymer strips were then transferred into autosampler vials, ensuring the vials were immediately sealed with screw caps after the solvent had been added. Care was taken to ensure all polymer pieces lay flat at the bottom of the vials, fully submerged in the solvent. To secure the vials, they were lightly tapped on the table to settle the contents without shaking. Each vial was separated from others by organizing them in a separate vial box to maintain clear identification and prevent cross-contamination. This procedure was repeated for all equilibration systems until all samplers were cleaned and transferred.

6) Extracting the Samplers

For extraction, the cap of the first vial was removed, and an internal standard solution was added using a gas chromatography (GC) syringe. The vial was then tightly resealed with its screw cap. This step was repeated for each vial in turn. The vials were left undisturbed at room temperature in the dark for at least 24 hours to begin the extraction process. After this period, each vial was vortexed at the highest speed for exactly one minute to ensure thorough mixing and effective extraction of the analytes.

7) Chemical analysis

For the quantification of OCPs in the extracts, a Hewlett-Packard 5890 Series II gas chromatograph equipped with an electron capture detector (ECD) was used. The chromatographic separation was carried out using a fused-silica capillary column (30 m × 0.32 mm × 0.52 μm). The GC conditions were as follows: the initial temperature was set from 70°C to 280°C at a rate of 5°C/min, and held at 280°C for 20 minutes. The detector and injector temperatures were set at 300°C and 270°C, respectively. Helium was used as the carrier gas at a flow rate of 1.5 ml/min, with nitrogen serving as the makeup gas at a flow rate of 60 ml/min (Okbah *et al.*, 2024). A robust Quality Assurance and Quality Control (QA/QC) procedure was followed to ensure accuracy in the analysis of chlorinated pesticides. An internal standard concentration of 100 μg/L was maintained across all samples to normalize analyte responses. The surrogate standard used was 2,4,5,6-tetrachloro-m-xylene, added at a concentration of 10 μg/L to each sample prior to extraction. This surrogate helped assess the extraction efficiency and matrix effects by ensuring that analyte recovery rates were within acceptable limits—75% to 125% for quantification and 65% to 135% for qualification. Instrument calibration was achieved using multi-level calibration curves, with correlation coefficients (r^2) above 0.99 to ensure precision.

8) Calculation of C_{free}

The freely dissolved concentrations of target OCPs in sediment (C_{free}) were determined as the final outcome of the passive sampling analyses. These values were calculated using the following equations (Jonker *et al.*, 2020b):

$$C_{free} = \frac{1000 \times C_p}{K_{pw}} \quad (1)$$

$$C_p = \frac{1000 \times V_{ext} \times C_{ext}}{M_p} \quad (2)$$

where C_{free} = freely dissolved concentrations of target OCPs in sediment (ng/L), C_p = Concentrations of OCPs in PE (μg/kg), C_{ext} = Concentrations in the extract (μg/L), V_{ext} = extract volume (1.5 mL), K_{pw} = polymer–water partition coefficient for the target OCPs (L/kg), M_p = mass of sampler (mg). To fulfil non-depletion criteria, the maximum mass of sampler (M_p) was estimated using the equation;

$$M_p = \frac{10^6 \times M_s \times f_{oc} \times K_{oc}}{K_{pw} \times \left(\frac{1}{0.05} - 1\right)} \quad (3)$$

where M_s = the standardized dry mass of sediment used in the system (30 g), f_{oc} = fraction of organic carbon in the sediment sample, K_{oc} = the organic carbon–water partition coefficient for the target OCPs (L/kg), and the value 0.05 indicates the maximum depletion criterion, set at 5%. K_{pw} and K_{oc} values were obtained from literature (Khairy *et al.*, 2019). Total Organic Carbon Analyser equipped with SSM-5000A was used to determine total organic carbon (TOC) contents in the sediments samples.

D. Data analysis

The freely dissolved concentrations of OCPs in the sediments were analyzed to identify spatial patterns, probable sources, and ecological risks. The analysis comprised multivariate statistical methods (principal component analysis and factor analysis), followed by diagnostic ratios and toxicity quotient calculations. These methods are described in the subsections below.

1) Principal component analysis and factor analysis

To analyze the freely dissolved concentrations (C_{free}) of OCPs in sediments, we used principal component analysis (PCA) and factor analysis, conducted in Jupyter Notebook. The data was first cleaned and standardized using Z-scores which is done to ensure comparability. Exploratory analysis i.e. descriptive statistics and correlation matrices were done and they provided initial insights into variable relationships. PCA was performed using Python's *sklearn* library to reduce dimensionality and identify components explaining most of the variance. The number of components retained was determined by the Kaiser Criterion and scree plots. Variable loadings on the components were analyzed to uncover patterns and clusters. Factor analysis, implemented with the *factor_analyzer* package, explored latent structures influencing C_{free} . *Varimax* rotation enhanced interpretability, and factors were labelled based on variable loadings. Results were visualized using bi-plots, and explained variance plots, providing insights into sources and behaviour of OCPs in sediments.

2) Toxicity quotients (TQ)

The toxicity quotient (TQ) method was used to assess the potential ecological risk of organochlorine pesticides (OCPs) in sediments. Freely dissolved concentrations (C_{free}) of OCPs in sediments, obtained through passive sampling, were compared to sediment quality benchmarks (SQBs) provided by the USEPA (Jones *et al.*, 1996). These benchmarks represent threshold concentrations associated with adverse ecological effects. For each compound, the TQ was calculated as

$$TQ = \frac{C_{free}}{SQB} \quad (4)$$

where SQB is the corresponding benchmark converted to ng/L units. TQs were computed for all OCPs across sampling locations. A TQ value greater than 1 indicates potential ecological risk, while values below 1 suggest minimal risk. Data analysis and visualization were performed using Python in Jupyter Notebook.

III. RESULTS & DISCUSSION

This section presents and discusses the occurrence of organochlorine pesticides (OCPs) in the River Galma

sediments. It first describes the spatial distribution of the freely dissolved concentrations across the ten sampling locations (P1-P10), then examines the likely sources of the contamination using diagnostic ratios and multivariate analysis, and finally assesses the ecological risks posed by the detected compounds.

A. Spatial distribution of OCPs

The spatial distribution of organochlorine pesticides (OCPs) along the Galma River sediments, as shown in Figure 2, reveals significant variation in freely dissolved concentrations (C_{free}) of different OCP compounds across sampling locations (P1–P10).

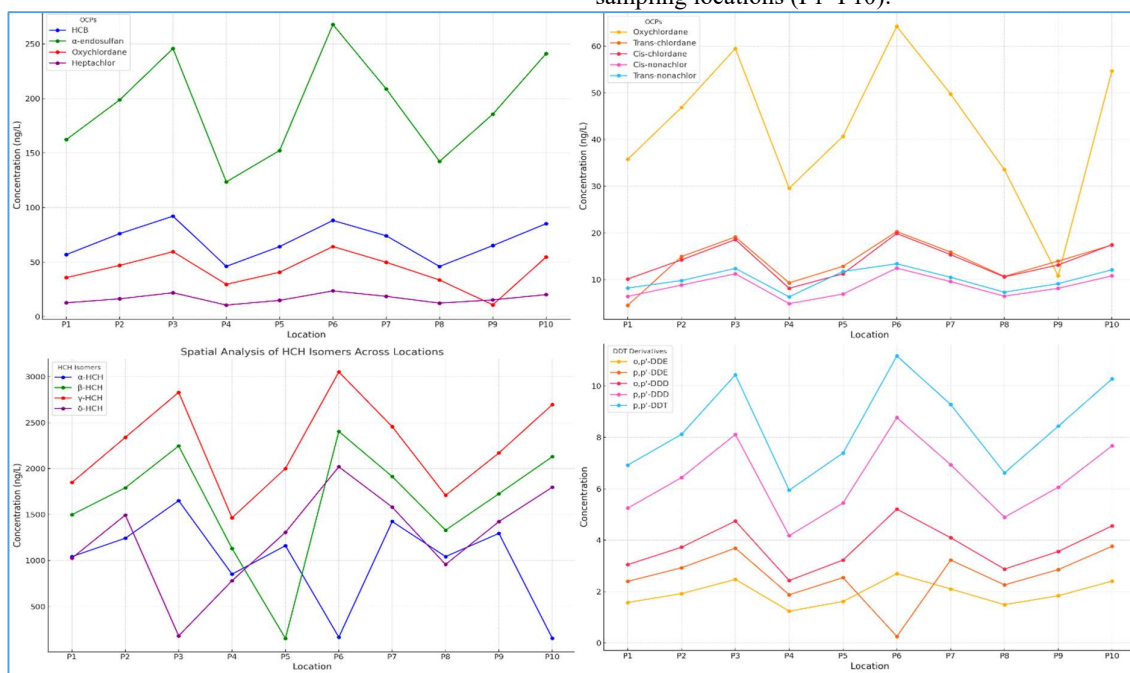


Figure 2 Spatial distribution of C_{free} of OCPs

The analysis of freely dissolved concentrations of organochlorine pesticides (OCPs) in the sediments of the River Galma reveals significant differences in concentrations across the sampled locations, pointing to both historical and recent pollution sources. Among the compounds studied, HCB showed the highest concentrations, with a peak of 275 ng/L at P6 and a slightly lower but still significant level of 260 ng/L at P9. These elevated levels are likely tied to industrial activities or pesticide manufacturing, which aligns with previous studies documenting HCB as a major contaminant in sediment environments (Wang et al., 2022). For the HCH isomers, β -HCH was the most prominent, reaching concentrations as high as 3,000 ng/L at P6 and 2,700 ng/L at P9. These values suggest contamination from technical-grade HCH or lindane, both of which were commonly used in agricultural practices (Chen et al., 2016). The persistence of β -HCH, due to its chemical stability, makes it a frequent environmental pollutant in agricultural regions, as reported in prior research (Liu et al., 2021).

Other isomers, such as α -HCH and γ -HCH, were also detected at moderately high levels, with α -HCH peaking at

1,800 ng/L at P3, further implicating agricultural runoff as a key contributor (Feng et al., 2016; Qiang et al., 2021). When it comes to DDT and its derivatives, p,p'-DDT concentrations were particularly notable at 8 ng/L at P3 and 7 ng/L at P9. These levels suggest recent DDT application, possibly linked to ongoing agricultural use in the area (Zhu et al., 2023). At the same time, the detection of degradation products like p,p'-DDE and p,p'-DDD, at concentrations of 4 ng/L and 3 ng/L, respectively, at P4, indicates historical use of DDT and its gradual breakdown in the environment. This pattern of both parent and degradation products is consistent with findings from other studies in agricultural sediment systems (Barr et al., 2024; Saadati et al., 2012). Among the chlordane-related pesticides, oxychlordane stood out, with its highest concentration reaching 50 ng/L at P3. This suggests that residues from historical chlordane use continue to degrade, contributing to pollution in the river sediments, which has also been observed in other tropical aquatic ecosystems (Adelodun et al., 2024).

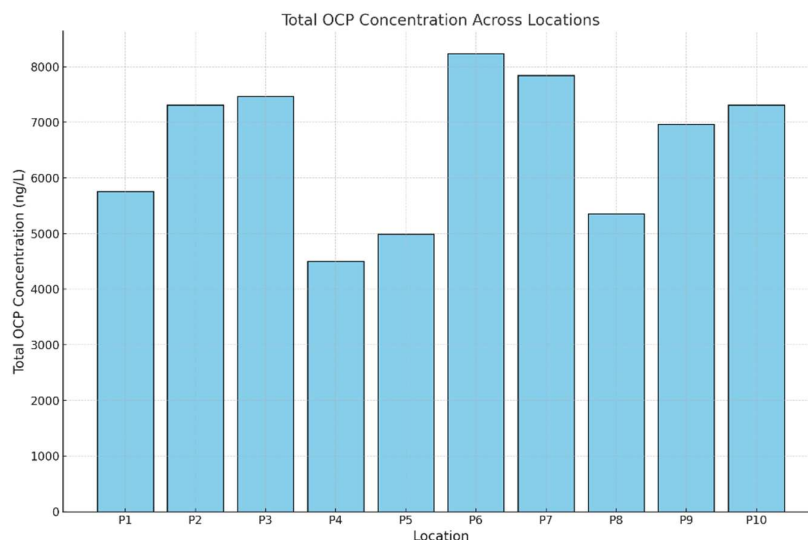


Figure 3 Total OCP C_{free} Concentrations across locations

The total concentrations of organochlorine pesticides (OCPs) across the ten locations in the River Galma (Figure 3) show distinct spatial variability. For example P6 exhibits the highest total concentration which exceeds 8,000 ng/L. This is followed closely by P7 and P3, both nearing similar values. Locations P4, P5 and P8 display significantly lower concentrations, around 4,000–5,000 ng/L which suggests that these areas are relatively less impacted by OCP contamination. The pronounced peaks at P6, P7, and P9 strongly indicate specific hotspots of pollution which is likely linked to agricultural runoff or industrial discharges upstream, consistent with patterns observed in other sediment studies involving persistent organic pollutants (Edjere *et al.*, 2020). The variability across locations highlights the influence of

localized sources and shows the need for targeted intervention and pollution mitigation in the identified hotspots to prevent downstream ecological impacts.

B. Principal component analysis and Factor analysis

PCA was used to help identify patterns, highlight dominant factors, and simplify the interpretation of the data. The explained variance ratio plot in Figure 4 reveals that PC1 accounts for approximately 74% of the total variance, indicating that a single, dominant factor largely influences the spatial distribution of OCPs. PC2 contributes an additional 10–15% of the variance, capturing secondary patterns or factors influencing the data.

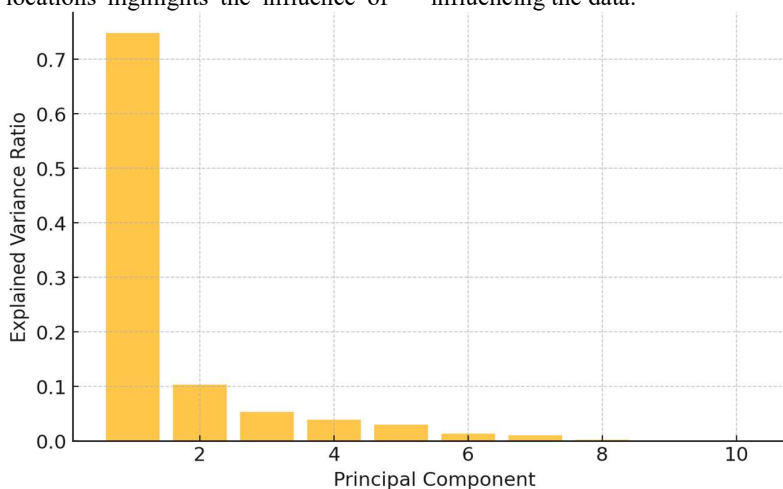


Figure 4 PCA: Explained variance ratio

The principal component analysis (PCA) of organochlorine pesticide (OCP) data from the Galma River sediments (Figure 5) shows some important insights into the environmental factors driving contamination and also highlights distinct patterns that can inform effective management strategies. PC1, heavily influenced by γ -HCH

and β -HCH, reflects regional-scale contamination associated with the agricultural use of lindane and technical HCH products. The prominence of γ -HCH suggests recent contamination, while β -HCH points to legacy pollution due to its chemical stability and persistence in sediments (Aamir *et al.*, 2017; Saadati *et al.*, 2012). This dual presence highlights

the long-lasting impact of HCH isomers on sediment quality. PC2, characterized by high levels of heptachlor and trans-chlordane, signals localized or legacy pollution from urban or industrial sources, possibly linked to improper disposal or the historical application of chlordane-based pesticides (Wang Guang et al., 2011). The presence of trans-chlordane derivatives further supports degradation of legacy pesticides

which is consistent with trends observed in other aquatic systems (Bose et al., 2021). Meanwhile, PC3 and subsequent components capture site-specific variations driven by localized factors like sediment transport, hydrodynamics, or minor pollution inputs, emphasizing the complexity of OCP distribution processes.

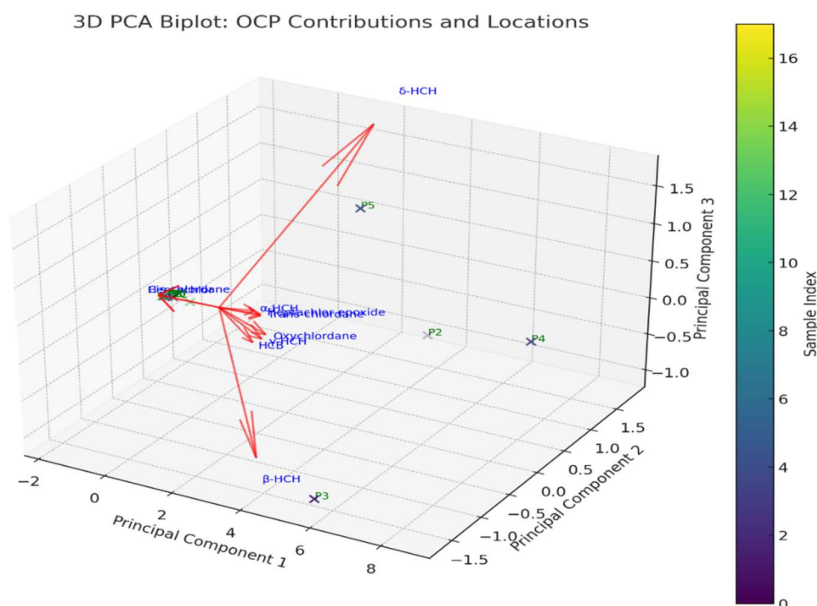


Figure 5 3D PCA biplot showing OCP contributions

From a management perspective, sites with high PC1 and PC2 scores, such as P3, P6, and P9, stand out as contamination hotspots requiring immediate attention. These locations show elevated inputs from both widespread agricultural activities (HCHs) and localized industrial or urban discharges (heptachlor and chlordane derivatives). The clear differentiation between PC1 and PC2 sources allows for tailored strategies, such as mitigating agricultural runoff to address widespread contamination and focusing remediation efforts on industrial areas to manage legacy pesticide residues. These findings are in agreement with previous research thus emphasizing the importance of identifying specific pollution sources for effective intervention (Ouyang et al., 2024). The persistence of ̢-HCH and chlordane derivatives further highlights the need for long-term monitoring and management because these compounds can remain active in sediments for decades (Sedeek et al., 2021). Regular sampling at critical hotspots will help track the

success of remediation efforts thereby ensuring sustained improvements in sediment quality and ecological health.

C. Factor analysis

The factor analysis of organochlorine pesticides (OCPs) in River Galma sediments (Figure 6) highlights two key contamination drivers, offering critical insights for environmental monitoring and remediation. Factor 1 is strongly linked to chlordane derivatives such as trans-nonachlor, heptachlor epoxide, and oxychlordane, with additional contributions from HCB and heptachlor. This suggests that Factor 1 represents contamination from chlordane-based pesticides which are chemicals well-known for their chemical stability and persistence (Thiombane et al., 2018). The proximity of p,p'-DDT to these compounds further implies overlapping sources, such as agricultural use of chlordane and industrial effluents, or shared degradation pathways.

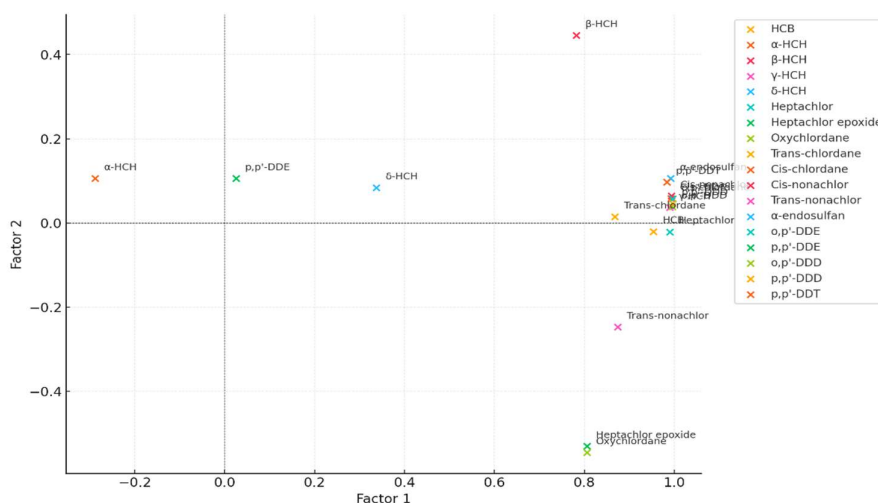


Figure 6 Factor analysis

In contrast, Factor 2 is dominated by HCH isomers (β -HCH, α -HCH, and γ -HCH), clearly pointing to agricultural contamination from lindane (γ -HCH) or technical HCH products. This reflects the widespread use and long-term persistence of HCH-based pesticides in soils and sediments (X. Liu *et al.*, 2021). Compounds like δ -HCH and p,p'-DDE, which contribute minimally to either factor, may represent localized pollution patterns or legacy degradation products with less influence on the primary drivers of contamination.

Hotspots of Factor 1 contamination such as P6 and P9 indicates historical pesticide use and industrial pollution, requiring targeted remediation of chlordane derivatives and HCB residues. Sites with high Factor 2 scores such as P4 and P3 highlights agricultural contamination from lindane, necessitating strategies to address these persistent residues. The weaker relationships between p,p'-DDE and p,p'-DDD suggests ongoing degradation of legacy contaminants thus emphasizing the need for long-term monitoring to track their

environmental fate (Wormington *et al.*, 2024). This factor-based analysis provides a valuable framework for distinguishing contamination sources and developing effective remediation strategies.

D. Source apportionment

The observed ratios of various chemical markers provide significant insights into environmental degradation processes, chemical transformations, and pollution sources.

1) Ratio of α -HCH/ γ -HCH

As illustrated in Figure 7a, the α -HCH/ γ -HCH ratio predominantly remained below 1.0, indicative of Lindane (pure γ -HCH) inputs (Kumari *et al.*, 2024). The absence of values exceeding the threshold of 4.0 suggests minimal influence from technical HCH formulations. This pattern across all sites highlights the dominance of specific industrial sources over agricultural practices, showing the use of Lindane.

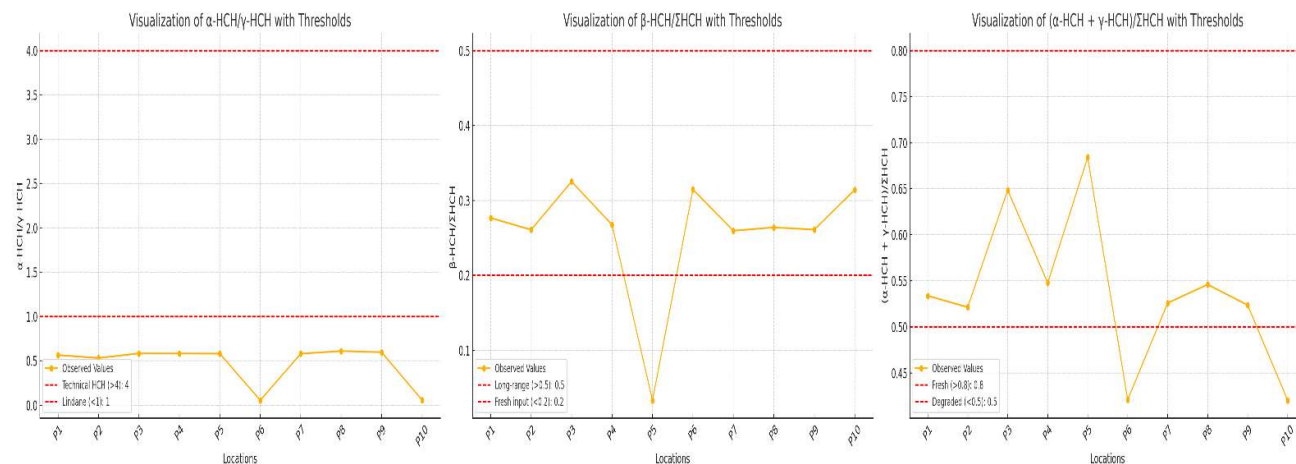


Figure 7 Ratios of (a) $(\alpha\text{-HCH} + \gamma\text{-HCH})/\Sigma\text{HCH}$, (b) $\beta\text{-HCH}/\Sigma\text{HCH}$, and (c) $\alpha\text{-HCH}/\gamma\text{-HCH}$

2) Ratio of β -HCH/ Σ HCH

The β -HCH/ Σ HCH ratio, shown in Figure 7b, fluctuated between 0.20 and 0.40. β -HCH isomers are known for their persistence due to their lower susceptibility to microbial degradation. Values below the 0.20 threshold signify fresh inputs, while those above 0.50 indicate long-range atmospheric transport (Aamir et al., 2017; Saadati et al., 2012). The notable dip at P6 reflects localized contamination with fresh HCH residues, while elevated levels at P4 and P9 suggest long-range transport phenomena.

3) Ratio of $(\alpha$ -HCH + γ -HCH)/ Σ HCH

The ratio of $(\alpha$ -HCH + γ -HCH)/ Σ HCH, depicted in Figure 7c, ranged between 0.45 and 0.70 across locations. Values below the threshold of 0.50 indicate advanced degradation,

while values exceeding 0.80 reflect fresh inputs (Kumari et al., 2024). Locations P1, P5, and P6 exhibited ratios near or below the degradation threshold, suggesting significant biodegradation. Conversely, the relatively higher values at P3 and P7 reflect potential fresh inputs of HCH isomers, possibly from recent agricultural applications.

4) Ratio of p,p'-DDT/(p,p'-DDE + p,p'-DDD)

The p,p'-DDT/(p,p'-DDE + p,p'-DDD) ratio, as depicted in Figure 8a, fluctuated between 0.80 and 1.20. Values exceeding 1.0 denote recent DDT applications, while lower values suggest ongoing degradation (Nevado et al., 2007). The elevated value at P6 points to fresh inputs, whereas ratios below 1.0 at other locations indicate predominantly degraded residues, possibly resulting from enhanced microbial activity.

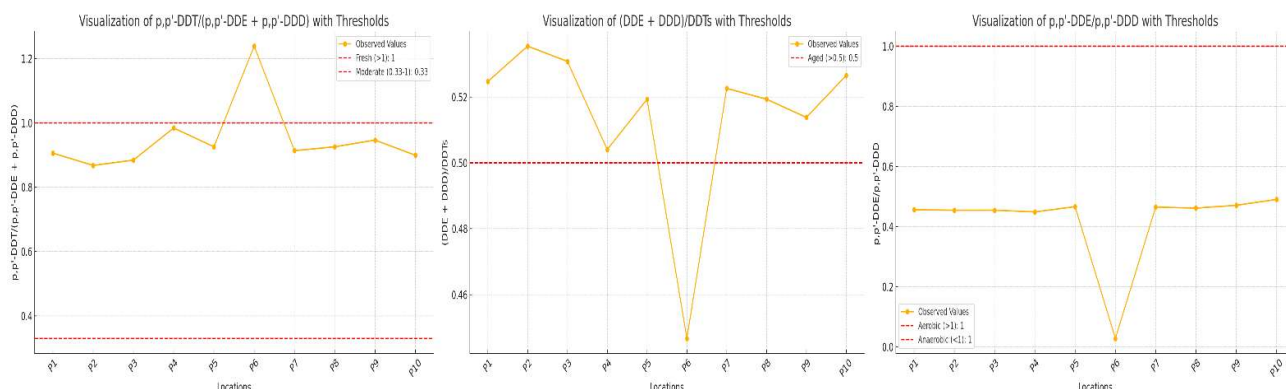


Figure 8 Ratios of (a) p,p'-DDE/p,p'-DDD, (b) (DDE + DDD)/DDTs, and (c) p,p'-DDT/(p,p'-DDE + p,p'-DDD)

5) Ratio of (DDE + DDD)/DDTs

The (DDE + DDD)/DDTs ratio, displayed in Figure 8b, ranged between 0.48 and 0.53, generally near the threshold of 0.50, which marks aged inputs (Zhang et al., 2018). The sharp drop at P6 reflects fresh inputs of DDT, potentially from untreated agricultural runoff. Locations such as P3 and P7, with ratios exceeding 0.50, align with the presence of aged DDT residues from historical usage.

6) Ratio of p,p'-DDE/p,p'-DDD

Figure 8c highlights the stability of the p,p'-DDE/p,p'-DDD ratio, with values clustering around 0.40-0.50. Ratios exceeding 1.0 are indicative of aerobic degradation, while values below 1.0 suggest anaerobic conditions (Pinkney & McGowan, 2006). The significant dip at P6 suggests enhanced anaerobic activity, likely influenced by localized anoxic conditions, while stable values at other locations imply aerobic or mixed degradation pathways. Table 1 provides a summary of key locations and hotspots.

Table 1 Summary of hotspots

Location	Diagnostic Ratio	Threshold Exceeded	Implication
P3	α -HCH/ γ -HCH > 4	Technical HCH contamination	Legacy contamination, assess historical pesticide use.
P5	α -HCH/ γ -HCH < 1	Lindane inputs	Fresh contamination, possible illegal use.
P2, P3	β -HCH/ Σ HCH > 0.5	Aged residues	Monitor long-term transport and degradation.
P1, P5	$(\alpha$ -HCH + γ -HCH)/ Σ HCH > 0.8	Fresh inputs	Recent HCH applications, regulatory action required.
P3, P4	p,p'-DDT/(p,p'-DDE + p,p'-DDD) > 1	Fresh DDT inputs	Possible illegal DDT use, urgent investigation needed.
P2, P3	(DDE + DDD)/DDTs > 0.5	Aged DDT residues	Focus on natural degradation or bioaugmentation.
P1, P2	p,p'-DDE/p,p'-DDD > 1	Aerobic degradation	Favourable for DDE formation, no immediate action.
P4, P5	p,p'-DDE/p,p'-DDD < 1	Anaerobic degradation	Explore remediation techniques to improve conditions.

a. Ecological risk assessment

The heatmap (Figure 9) depicting toxicity quotients (TQs) for various organochlorine pesticides (OCPs) valuable insights into the spatial distribution of contamination and its associated ecological risks. The

results clearly demonstrate that while some compounds remain below the critical threshold ($TQ = 1.0$), others significantly exceed it, signalling potential adverse effects on the aquatic ecosystem and necessitating targeted management interventions (Siddique *et al.*, 2024).

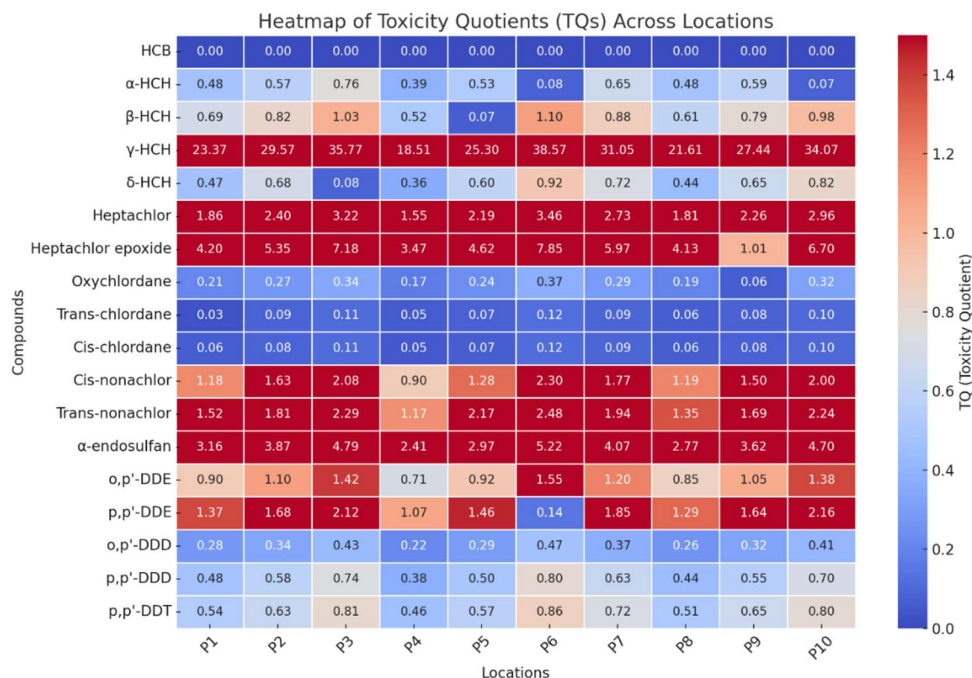


Figure 9 Heatmap of toxicity quotients across locations

Among the compounds studied, γ -HCH emerges as the most concerning due to its consistently high TQ values across all locations, with a dramatic peak at P6 ($TQ = 38.57$). This suggests pervasive contamination, likely stemming from historical use in agriculture or industrial processes, and raises serious ecological concerns (Kumari *et al.*, 2024). The exceptionally high values observed at P6 point to it being a pollution hotspot, possibly due to local sources or accumulation dynamics. These findings underline the urgent need for intervention at this location. Efforts such as sediment removal, bioremediation, or other site-specific cleanup strategies should be prioritized to reduce its environmental impact (G. Liu *et al.*, 2013). Furthermore, stricter enforcement of existing bans on the use and disposal of γ -HCH is critical to prevent additional inputs into the ecosystem.

Heptachlor Epoxide and α -Endosulfan also exhibit worrying patterns, with TQs exceeding 1.0 at multiple locations and peaking at P6 (7.85 and 5.22, respectively). These compounds, alongside γ -HCH, represent significant ecological threats, particularly at P5 and P6, where the combination of high concentrations and toxic potential indicates the presence of substantial contamination sources. Possible contributors to this pollution could include agricultural runoff, poorly managed waste discharge, or residual deposits from past usage (Guo *et al.*, 2022; Thiombane *et al.*, 2018). Addressing these hotspots should involve not only remediation efforts but also the identification of key pollution sources. Tracing upstream agricultural or

industrial activities could provide essential information for preventing future contamination (Muhammed *et al.*, 2023).

While compounds such as HCB, Oxychlordane, and DDT degradation products (e.g., o,p'-DDD, p,p'-DDT) remain below the TQ threshold across most locations, their persistence in the environment demands attention. These chemicals, though not immediately threatening, have the potential to accumulate in sediments or biota, posing long-term risks to aquatic life and food webs (Sun *et al.*, 2022). Continuous monitoring of these compounds, particularly in sediments and higher trophic levels, would provide a more accurate picture of their ecological impact.

The spatial trends evident in the dataset point to P5 and P6 as areas of heightened concern, with multiple compounds consistently exceeding $TQ = 1.0$. These locations may be receiving concentrated pollution inputs, potentially due to localized agricultural or industrial discharges, or acting as natural accumulation zones due to hydrodynamic factors (Pizzini *et al.*, 2022). In contrast, locations such as P1 and P2 exhibit relatively lower toxicity levels, which may reflect either effective dilution or less intense pollutant inputs. This variability shows the importance of location-specific management strategies, as blanket approaches may fail to address the nuances of localized contamination.

b. Correlation with land use

The results of the C_{free} analysis provide a clear picture of how land use directly influences pesticide contamination along the river. Each sampling location reflects the impact of

surrounding activities, ranging from pristine areas to agricultural zones, industrial sites, and residential regions. The concentrations of organochlorine pesticides (OCPs) show significant variability, with hotspots of contamination correlating with intensive land-use practices (Figure 10).

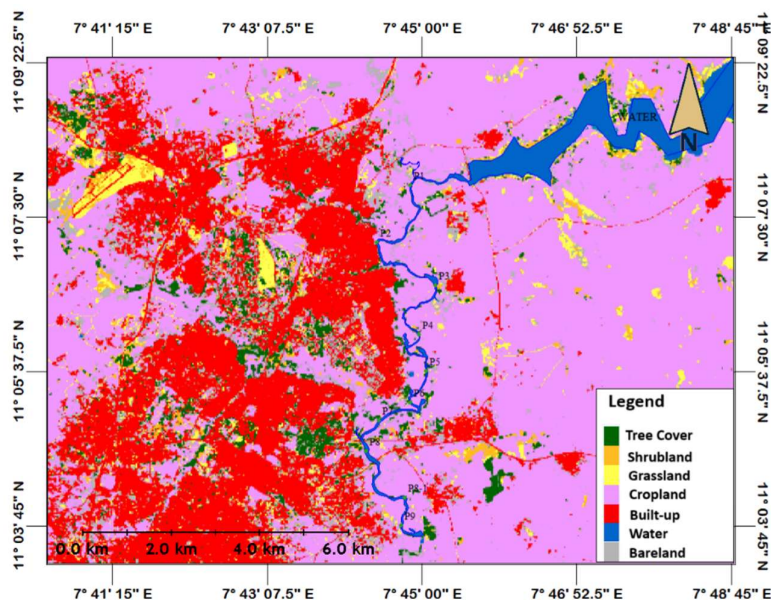


Figure 10 Map showing land use land cover

At **P1**, situated in a relatively untouched section of the river, the total OCP concentration is the lowest at 5,760.44 ng/L. This is expected, as minimal human activity upstream reduces potential pesticide inputs. However, the concentration increases markedly at **P2** (7,313.28 ng/L), where small-scale farming dominates the landscape. This rise shows how even moderate agricultural runoff can introduce pesticides like α -HCH and β -HCH into the river system, a pattern observed in other studies linking pesticide use to runoff contamination (Schönenberger et al., 2022). The situation becomes more pronounced at **P3**, a site influenced by intensive agriculture near a tributary confluence. Here, the total OCP concentration peaks at 7,465.76 ng/L, driven by high levels of γ -HCH, β -HCH, and α -HCH. These compounds, often associated with heavy pesticide application in farming, highlight the risks posed by intensive agricultural activities. Such findings align with previous research emphasizing the role of agricultural hotspots in exacerbating pesticide contamination (Li et al., 2023). This indicates the urgent need for sustainable farming practices to reduce reliance on persistent pesticides.

Further downstream, at **P4**, the land use shifts to a mix of agriculture and small-scale industrial activities. The total OCP concentration drops to 4,505.26 ng/L, likely due to some dilution effects or reduced pesticide inputs compared to upstream sites. However, industrial contributions become evident through elevated levels of compounds like Oxychlordane and α -Endosulfan. These patterns indicate that mixed land use introduces diverse contamination sources, even if the overall intensity appears lower than in intensive

agricultural zones (Yang et al., 2020). At **P5**, a site influenced by domestic waste and agricultural runoff, the total OCP concentration rises slightly to 4,989.52 ng/L. The persistent presence of compounds like γ -HCH highlights the cumulative impact of human settlement and farming on contamination levels. This suggests that while domestic contributions may not dominate, they amplify the existing agricultural impact, a finding consistent with research on combined land-use effects on river systems (Hellar-Kihampa et al., 2013).

The highest total OCP concentration, 8,231.62 ng/L, is observed at **P6**, a predominantly agricultural zone with extensive pesticide use. Here, γ -HCH (3,051.3 ng/L) and Heptachlor Epoxide (31.4 ng/L) reach alarming levels, reflecting the intense pesticide application in the area. This site demonstrates the critical role of agricultural runoff in driving contamination, highlighting the need for immediate intervention to regulate pesticide use and explore alternatives with lower persistence and toxicity (Liang et al., 2022). Interestingly, **P7**, near a livestock grazing area, shows slightly lower contamination (7,843.82 ng/L) but still retains high levels of γ -HCH and β -HCH. This suggests that even non-cropland activities like grazing can contribute to pesticide contamination, possibly through soil erosion or indirect runoff. At **P8**, near a small-scale industrial zone, the total OCP concentration decreases to 5,355.32 ng/L, but certain compounds like Oxychlordane remain elevated. This reflects the influence of industrial discharges, which may introduce specific pesticides into the river. These observations are consistent with studies showing localized contamination from industrial effluents (Benson et al., 2023).

The pattern shifts again at **P9**, where mixed land use (agriculture and residential areas) results in a higher total OCP concentration (6,966.80 ng/L). The combined impact of multiple activities highlights the complexity of managing contamination in areas with diverse land-use practices. Finally, **P10**, at the river's confluence with the Kaduna River, exhibits a total OCP concentration of 7,308.88 ng/L. This site integrates all upstream activities, providing a cumulative measure of the river's contamination. Persistent compounds like γ -HCH and β -HCH dominate, emphasizing how upstream pollution sources accumulate downstream, a phenomenon widely reported in riverine studies (Qadeer *et al.*, 2019).

The spatial trends make it clear that land-use practices, particularly intensive agriculture and industrial activities, significantly impact pesticide contamination levels. The highest risks are observed in agricultural hotspots like P3 and P6, where runoff directly introduces high concentrations of persistent pesticides. Meanwhile, areas with mixed or industrial land uses, such as P8 and P9, contribute specific contaminants that reflect their respective activities.

IV. CONCLUSION

The findings of this study reveal significant contamination of River Galma sediments by organochlorine pesticides (OCPs), driven by both historical and contemporary sources. Using 50 μ m low-density polyethylene (LDPE) membranes for passive sampling, we identified pollution hotspots, with concentrations exceeding 8,000 ng/L at key locations such as P6. Agricultural runoff emerged as a dominant contributor, as evidenced by high levels of β -HCH (3,000 ng/L) and γ -HCH (3,051 ng/L). Diagnostic ratios further confirmed inputs of fresh lindane and aged DDT residues, showing the persistence of these pollutants in the environment.

The spatial variability in OCP concentrations highlights the relationship between agricultural, industrial, and residential activities in shaping the contamination profile. Principal component and factor analyses identified agriculture and industrial discharges as the primary drivers, while toxicity quotient analysis identified γ -HCH as posing severe ecological risks, particularly at hotspots such as P6 and P9. These results highlight the urgent need for localized interventions, and the persistence and toxicity of OCPs demand both immediate and sustained efforts to protect sediment quality, aquatic ecosystems, and community health.

Based on these findings, two measures are recommended. First, bans on harmful pesticides such as lindane and DDT should be more strictly enforced, supported by a long-term monitoring programme using passive sampling to track contamination trends. Second, remediation should be targeted at the identified hotspots, particularly P6 and P9, using approaches such as sediment dredging, bioremediation, or constructed wetlands to reduce pollutant loads and promote ecosystem recovery.

REFERENCES

- Aamir, M., Khan, S., Niu, L., Zhu, S., & Khan, A. (2017). Occurrence, enantiomeric signature and ecotoxicological risk assessment of HCH isomers and DDT metabolites in the sediments of Kabul River, Pakistan. *Environmental Geochemistry and Health*, 39, 779–790.
- Adelodun, A. A., Ajibade, S., Fadaini, O., Oluwasina, O., & Ibigbami, O. (2024). Organochlorine Pesticide and Total Petroleum Hydrocarbon Pollution of Ilaje Coastal River Sediments, Ondo State, Nigeria. *Environmental Protection Research*, 60–75.
- Barr, K. J., Panuwet, P., & Saikawa, E. (2024). The effect of farming techniques on degradation of DDT in historical cotton farms. *Environmental Pollution*, 351, 123961.
- Benson, N. U., Unyimadu, J. P., & Tenebe, I. T. (2023). Distribution of organochlorine pesticides (OCPs) in surface-mixed layer water and intertidal sediments of Lagos lagoon, Gulf of Guinea. *Regional Studies in Marine Science*, 67, 103187.
- Bose, S., Kumar, P. S., Vo, D.-V. N., Rajamohan, N., & Saravanan, R. (2021). Microbial degradation of recalcitrant pesticides: a review. *Environmental Chemistry Letters*, 19, 3209–3228.
- Chen, X., Liu, W., Zhou, Y., Qiao, X., Zhao, J., Li, H., Han, Y., Liao, X., Wang, M., & Liu, W. (2016). Analysis of hchs and ddts in a typical pesticide contaminated site. *FEB-FRESENIUS ENVIRONMENTAL BULLETIN*, 5145.
- Edjere, O., Ukpebor, J. E., Emebu, S., & Okieimen, F. E. (2020). Preliminary studies of organochlorine pesticides (OCPs) in sediment, water and fish samples from Ethiopia River, Abraka Axis, Southern Nigeria. *International Letters of Natural Sciences*, 80.
- Feng, J., Hu, P., Zhang, F., & Sun, J. (2016). HCHs and DDTs in Yellow River of Henan section—a typical agricultural area in China: levels, distributions and risks. *Environmental Geochemistry and Health*, 38, 1241–1253.
- Guo, L., Gu, C., Huang, T., Gao, H., Zhao, Y., Mao, X., & Ma, J. (2022). Signatures of Indian endosulfan usage in China's environment. *Chemosphere*, 306, 135644.
- Hellar-Kihampa, H., De Wael, K., Lugwisha, E., Malarvannan, G., Covaci, A., & Van Grieken, R. (2013). Spatial monitoring of organohalogen compounds in surface water and sediments of a rural-urban river basin in Tanzania. *Science of the Total Environment*, 447, 186–197.
- Jones, D. S., Suter, I. I., & Hull, R. N. (1996). *Toxicological benchmarks for screening contaminants of potential concern for effects on sediment-associated biota: 1996 revision*. Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States).
- Jonker, M. T. O., Burgess, R. M., Ghosh, U., Gschwend, P. M., Hale, S. E., Lohmann, R., Lydy, M. J., Maruya, K. A., Reible, D., & Smedes, F. (2020a). Ex situ determination of freely dissolved concentrations of hydrophobic organic chemicals in sediments and soils: basis for interpreting toxicity and assessing bioavailability, risks and remediation necessity. *Nature Protocols*, 15(5), 1800–1828. <https://doi.org/10.1038/s41596-020-0311-y>.
- Jonker, M. T. O., Burgess, R. M., Ghosh, U., Gschwend, P. M., Hale, S. E., Lohmann, R., Lydy, M. J.,

- Maruya, K. A., Reible, D., & Smedes, F. (2020b).** Passive sampling protocol for ex situ determination of freely dissolved concentrations of hydrophobic organic chemicals in sediments and soils: Basis for interpreting toxicity and assessing bioavailability, risks, and remediation necessity and efficiency. *Nature Protocols*, 15(5), 1800.
- Khairy, M. A., Noonan, G. O., & Lohmann, R. (2019).** Uptake of hydrophobic organic compounds, including OCPs and PBDEs, and perfluoroalkyl acids (PFAAs) in fish and blue crabs of the lower Passaic River (NJ, USA). *Environmental Toxicology and Chemistry*, 38(4), 872.
- Kovács, Z., Jordán, G., Szabó, P., & Bálint, M. (2023).** Development, data modelling of environmental geochemical monitoring of fluvial (suspended, river bottom, floodplain) sediments using unique automated and passive sampling for the contamination risk assessment according to the EU WFD in the Danube Basin. *EGU General Assembly Conference Abstracts*, EGU-15997.
- Kreutzer, A. (2022).** Passive sampling and passive dosing: novel approaches for the holistic assessment of marine sediment contamination by hydrophobic organic pollutants. <http://publikationen.ub.uni-frankfurt.de/frontdoor/index/doi/68990>.
- Kreutzer, A., Reininghaus, M., Meyer, J., Kröncke, I., Seiler, T.-B., Hollert, H., & Witt, G. (2023).** Application of equilibrium passive sampling to assess the influence of anthropogenic activities and bioturbation on the distribution of hydrophobic organic chemicals in North Sea sediment cores. *Environmental Pollution*, 318, 120876.
- Kumari, K., Shahbaz, M., & Raghunathan, K. (2024).** Hexachlorocyclohexane (α , β -HCH) and Lindane (γ -HCH). In *Pollutants of Global Concern: A Comprehensive Overview of Persistent Organic Pollutants* (pp. 165–180). Springer.
- Liang, X.-H., Xie, Q.-L., Zheng, Q., Yang, B.-C., Ye, J.-M., & Tang, C.-J. (2022).** Soil-crop Distribution and Health Risk Assessment of Organochlorine Pesticides on Typical Agricultural Land in Southern Leizhou Peninsula. *Huan Jing Ke Xue= Huanjing Kexue*, 43(1), 500–509.
- Li, C., Qi, X., Wang, Y., Meng, Q., Li, W., Liu, L., Zheng, Y., & Cui, H. (2023).** Organochlorine pesticides in soil-groundwater-plant system in a famous agricultural production area in China: Spatial distribution, source identification and migration prediction. *Water*, 15(23), 4147.
- Liu, G., Bi, R., Wang, S., Li, F., & Guo, G. (2013).** The use of spatial autocorrelation analysis to identify PAHs pollution hotspots at an industrially contaminated site. *Environmental Monitoring and Assessment*, 185, 9549–9558.
- Liu, X., Li, W., Kummel, S., Merbach, I., Sood, U., Gupta, V., Lal, R., & Richnow, H. H. (2021).** Soil from a hexachlorocyclohexane contaminated field site inoculates wheat in a pot experiment to facilitate the microbial transformation of β -hexachlorocyclohexane examined by compound-specific isotope analysis. *Environmental Science & Technology*, 55(20), 13812–13821.
- Mishra, A., Kumari, M., Kumar, R., Iqbal, K., & Thakur, I. S. (2022).** Persistent organic pollutants in the environment: Risk assessment, hazards, and mitigation strategies. *Bioresource Technology Reports*, 19, 101143.
- Muhammed, H. A., Yahaya, A., Abdullahi, S. S., Jagaba, A. H., & Birniwa, A. H. (2023).** Mitigating water contamination by controlling anthropogenic activities of organochlorine pesticides (OCPs) for surface water quality assurance. *Case Studies in Chemical and Environmental Engineering*, 8, 100474.
- Nevado, J. J. B., Martín-Doimeadiós, R. C. R., Bernardo, F. J. G., & Fariñas, N. R. (2007).** Development and validation of an analytical methodology for the determination of p, p'-DDT, p, p'-DDE and p, p'-DDD in fish oil pills. *Microchemical Journal*, 86(2), 183–188.
- Okbah, M. A., Ibrahim, M. S., Said, T. O., Nassar, M. E. M., & El-Gammal, M. I. (2024).** Spatial Distribution and Ecological Risk of OCPs and PCBs in Sediments from Lake Edku, Egypt. *Blue Economy*, 2(1). <https://doi.org/10.57241/2805-2994.1021>.
- Omayuli, M. O., Emakunu, O. S., Emeife, O., & Tesi, J. N. (2024).** Distribution, associated risks and sources of organochlorine pesticides in farmland soils from Ethiopia West Area of Delta State, Nigeria. *Int J Res Rev*, 11(2), 304–315.
- Ouyang, K., Lu, X., Meng, J., Wang, C., Feng, S., Shi, B., Su, G., & Li, Q. (2024).** Which pollutants and sources should be prioritized for control in multi-pollutants complex contaminated areas? *Journal of Hazardous Materials*, 478, 135547.
- Pinkney, A. E., & McGowan, P. C. (2006).** Use of the p, p'-DDD: p, p'-DDE concentration ratio to trace contaminant migration from a hazardous waste site. *Environmental Monitoring and Assessment*, 120(1), 559–574.
- Pizzini, S., Giuliani, S., Polonia, A., Piazza, R., Bellucci, L. G., Gambaro, A., & Gasperini, L. (2022).** PAHs, PCBs, PBDEs, and OCPs trapped and remobilized in the Lake of Cavazzo (NE Italy) sediments: temporal trends, quality, and sources in an area prone to anthropogenic and natural stressors. *Environmental Research*, 213, 113573.
- Qadeer, A., Liu, S., Liu, M., Liu, X., Ajmal, Z., Huang, Y., Jing, Y., Khalil, S. K., Zhao, D., & Weining, D. (2019).** Historically linked residues profile of OCPs and PCBs in surface sediments of typical urban river networks, Shanghai: Ecotoxicological state and sources. *Journal of Cleaner Production*, 231, 1070–1078.
- Qiang, L., Jinping, Z., Zhongling, G., & Chunnan, F. (2021).** Sources and health risk of organochlorine pesticides in surface water from Buerhatong river and Hunchun river in northeast China. *Water, Air, & Soil Pollution*, 232, 1–14.
- Saadati, N., Abdullah, M. P., Zakaria, Z., Rezayi, M., & Hosseinizade, N. (2012).** Distribution and fate of HCH isomers and DDT metabolites in a tropical environment—case study Cameron Highlands—Malaysia. *Chemistry Central Journal*, 6, 1–15.
- Samuel, P. O. (2015).** Temporal and Spatial Physico-Chemical Parameters of River Galma, Zaria, Kaduna State, Nigeria.
- Schönenberger, U. T., Beck, B., Dax, A., Vogler, B., & Stamm, C. (2022).** Pesticide concentrations in agricultural storm drainage inlets of a small Swiss catchment. *Environmental Science and Pollution Research*, 29(29), 43966–43983.
- Sedeek, F. A., Sobhy, H. M., Aly, M. Z. M., & Hekal, S. H. A. (2021).** Residues of chlorinated organic pesticide in

sediments and fish from the Egyptian river Nile. *Plant Archives*, 21(1), 2469–2474.

Siddique, S., Chaudhry, M. N., Ahmad, S. R., Nazir, R., Javed, R., Hafeez, M. R., Alraey, Y., Sivasamugham, L. A., & Mahmood, A. (2024). Risk surveillance with spatial distribution of Organochlorine Pesticides (OCPs) from sedimentary samples of Chenab River. *Science of The Total Environment*, 912, 169256.

Soman, S., Rex, K. R., & Chakraborty, P. (2024). Environmental occurrence of pesticidal endocrine disrupting chemicals. In *Endocrine-Disrupting Chemicals* (pp. 147–168). Elsevier.

Sun, J., Xu, C., Peng, H., Wan, Y., Luo, K., Barrett, H., & Hu, J. (2022). Behaviors and trophodynamics of o, p'-dichlorodiphenyltrichloroethane (o, p'-DDT) in the aquatic food web: Comparison with p, p'-DDT. *Science of The Total Environment*, 821, 153447.

Taylor, A. C., Fones, G. R., Vrana, B., & Mills, G. A. (2021). Applications for passive sampling of hydrophobic organic contaminants in water—A review. *Critical Reviews in Analytical Chemistry*, 51(1), 20–54.

Tesi, J. N., Tesi, G. O., Ossai, J. C., & Agbozu, I. E. (2020). Organochlorine pesticides (OCPs) in agricultural soils of Southern Nigeria: spatial distribution, source identification, ecotoxicological and human health risks assessment. *Environmental Forensics*, 1–13. <https://doi.org/10.1080/15275922.2020.1850570>.

Thiombane, M., Petrik, A., Di Bonito, M., Albanese, S., Zuzolo, D., Cicchella, D., Lima, A., Qu, C., Qi, S., & De Vivo, B. (2018). Status, sources and contamination levels of organochlorine pesticide residues in urban and agricultural areas: a preliminary review in central–southern Italian soils.

Environmental Science and Pollution Research, 25, 26361–26382.

Wang Guang, W. G., Lv YongLong, L. Y., Shi YaJuan, S. Y., Luo Wei, L. W., & Wang TieYu, W. T. (2011). *Source and vertical distribution of organochlorine pesticide residues in soils from a typical chemical industrial area.*

Wang, Y., Liu, T., Tang, J., Xiong, Z., Song, L., & Ma, T. (2022). Vertical distribution and effect of historical residual organochlorine pesticides on microbial community structure in sediment cores from an abandoned oxidation pond after dredging for 15 years. *Environmental Science and Pollution Research*, 1–17.

Wormington, A. M., Gabrielli, D. J., Nouri, M.-Z., Lin, A. M., Robinson, S. E., Bowden, J. A., Denslow, N. D., Sabo-Attwood, T., & Bisesi Jr, J. H. (2024). Effects of the organochlorine pesticide metabolite p, p'-DDE on the gastrointestinal lipidome in fish: A novel toxicity pathway for a legacy pollutant. *Environmental Pollution*, 363, 125191.

Yang, J., Zhao, Y., Zhen, Q., Chen, X., & Zhang, Y. (2020). Concentrations and sources of persistent organochlorine residues in the sediments and soils from an industrially impacted area in Anhui, China. *Soil & Water Research*, 15(3).

Zhang, C., Liu, L., Ma, Y., & Li, F. (2018). Using isomeric and metabolic ratios of DDT to identify the sources and fate of DDT in Chinese agricultural topsoil. *Environmental Science & Technology*, 52(4), 1990–1996.

Zhu, Y., Chai, Y., Xu, C., & Guo, F. (2023). Status, sources, and human health risk assessment of DDT pesticide residues in river sediments in a highly developed agricultural region in the upper Yangtze River in China. *Environmental Science and Pollution Research*, 30(27), 71120–71130