Ecological Risk Assessment of Pharmaceutical Waste in Health Facility Effluents Discharged into the Shomolu Central Canal (Lagos, Nigeria)

Evaluación del riesgo ecológico de residuos farmacéuticos en efluentes de centros de salud descargados en el Canal Central de Shomolu (Lagos, Nigeria)

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ABSTRACT

Hospital wastewater in low- and middle-income countries (LMICs) represents a critical but often overlooked interface between pharmaceuticals, health systems and environmental public health. In this study, we evaluated pharmaceutical residue contamination from healthcare facilities. The effluents from six healthcare facilities were sampled; UNILAG Medical Centre, LADDILAK Hospital, DEJI Clinic, R. Jolad Hospital, Shomolu Health Care, Mainland Hospital, along with a reference canal (Shomolu Central Canal), three times in a month, randomly through continuous collection and storage for each individual facility, pooled as a single entity, and analyzed using UPLC-MS/MS for the quantification of nine pharmaceuticals (six antibiotics and three antimalarial drugs). The antibiotics were trimethoprim, doxycycline, ciprofloxacin, metronidazole, amoxicillin and sulfamethoxazole; and the antimalarial drugs were pyrimethamine, artemether and lumefantrine. The results were subjected to risk assessment, including risk quotient, pharmaceutical risk index, mass discharge estimation and statistical analysis (non-parametric comparisons and Spearman's rank correlations), in order to identify the systemic drivers of environmental pharmaceutical discharge. The pharmaceutical loads observed at R. Jolad Hospital (5.01 ppm), UNILAG Medical Centre (0.318 ppm) and Mainland Hospital (0.318 ppm) were higher than the others and those measured in the canal (0.00160 ppm). The total quantified concentrations across all seven sites ranged from 0.00190 ppm to 5.01 ppm. The most contaminated sites were R. Jolad Hospital (2.86 ppm) for all analyzed antibiotics and antimalarial drugs (2.15 ppm), and UNILAG and Mainland Hospital (0.0152 ppm) for doxycycline. Doxycycline and trimethoprim were found to be the most pervasive compounds, with detection frequencies of 71.4% (5/7 sites) and 57.1% (4/7 sites), respectively, while localized treatments in the form of artemether (1.12 ppm) and lumefantrine (1.03 ppm) were restricted to a single site. Extreme ecological risks were observed for ciprofloxacin (RQ = 1,440) and pyrimethamine (RQ = 303). The significant differences in contamination loads ($p < 0.01$) and strong correlations between facility flow rate and discharge ($\rho = 0.91$) underscore the highly localized nature of daily mass loading, peaking dramatically at 2,505 g/day. These findings indicate the critical management implication of setting up targeted, decentralized on-site wastewater treatment facilities at high-volume healthcare centers, in order to mitigate toxic downstream impacts on receiving aquatic ecosystems.

Keywords: *Hospital wastewater, pharmaceutical residues, ecological risk assessment, Lagos, Nigeria*

RESUMEN

Las aguas residuales hospitalarias en países de ingresos bajos y medios (PIBM) representan una interfaz crítica, aunque a menudo pasada por alto, entre los productos farmacéuticos, el sistema sanitario y la salud pública ambiental. Este estudio evalúa la contaminación por residuos farmacéuticos procedentes de centros de atención sanitaria. Se tomaron muestras de los efluentes de seis centros sanitarios (Centro Médico UNILAG, Hospital LADDILAK, Clínica DEJI, Hospital R. Jolad, Centro de Salud Shomolu y Hospital Mainland) y de un canal de referencia (Canal Central de Shomolu) en tres ocasiones durante un mes; las muestras se recolectaron y almacenaron de forma continua y aleatoria para cada hospital, se agruparon como una entidad única y se analizaron mediante UPLC-MS/MS para cuantificar nueve fármacos (seis antibióticos y tres antipalúdicos): trimetoprima, doxiciclina, ciprofloxacino, metronidazol, amoxicilina y sulfametoxazol (antibióticos), y pirimetamina, arteméter y lumefantrina (antipalúdicos). Los resultados se sometieron a una evaluación de riesgos que incluyó el cálculo del cociente de riesgo, el índice de riesgo farmacéutico y la estimación de la carga másica de vertido, así como a análisis estadísticos (comparaciones no paramétricas y correlaciones de rangos

de Spearman) para identificar los factores sistémicos que impulsan el vertido de fármacos al medio ambiente. Las cargas farmacéuticas observadas en el Hospital R. Jolad (5,01 ppm), el Centro Médico UNILAG (0,318 ppm) y el Hospital Mainland (0,318 ppm) fueron superiores a las de los demás centros y a las del canal (0,00160 ppm); las concentraciones totales cuantificadas en los siete puntos de muestreo oscilaron entre 0,00190 ppm y 5,01 ppm. El sitio más contaminado fue el Hospital R. Jolad, tanto en el conjunto de antibióticos analizados (2,86 ppm) como en el de antipalúdicos (2,15 ppm), mientras que los hospitales UNILAG y Mainland presentaron los niveles más altos de doxiciclina (0,0152 ppm). La doxiciclina y la trimetoprima fueron los compuestos más ubicuos, con frecuencias de detección del 71,4 % (5 de 7 sitios) y del 57,1 % (4 de 7 sitios), respectivamente; por el contrario, fármacos asociados a tratamientos específicos, como el arteméter (1,12 ppm) y la lumefantrina (1,03 ppm), se detectaron únicamente en un sitio. Se observaron riesgos ecológicos extremos para la ciprofloxacina (RQ = 1,440) y la pirimetamina (RQ = 303). Las diferencias significativas en las cargas de contaminación ($p < 0,01$) y las fuertes correlaciones entre el caudal de la instalación y la descarga ($\rho = 0,91$) ponen de relieve que la carga másica diaria está altamente localizada, ya que alcanza un pico drástico de 2,505 g/día. Estos hallazgos indican que la implementación de instalaciones de tratamiento de aguas residuales descentralizadas y específicas en centros sanitarios de gran volumen constituye una medida de gestión fundamental para mitigar los efectos tóxicos aguas abajo sobre los ecosistemas acuáticos receptores.

Palabras clave: *aguas residuales hospitalarias, residuos farmacéuticos, evaluación de riesgos ecológicos, Lagos, Nigeria*

Introduction

Pharmaceutical residues in hospital wastewater (HWW) constitute a growing challenge for both environmental sustainability and health-system governance, particularly in low- and middle-income countries (LMICs). Increasing evidence has shown that hospital effluents acts as a concentrated source of antibiotics, antimalarial drugs, antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARGs), thereby creating pathways through which clinical pharmaceutical use directly affects urban ecosystems and public health (Mheidli *et al.*, 2022; Obayiuwana *et al.*, 2021). In West Africa, including Nigeria, the routine discharge of untreated or inadequately treated hospital effluent into municipal drainage channels and waterways is an indicator of broader weaknesses in regulatory enforcement, wastewater infrastructure, pharmaceutical stewardship and environmental health surveillance (Hotor *et al.*, 2025; Odih *et al.*, 2023).

A substantial body of work from diverse regions further corroborates the environmental and governance concerns raised above: antibiotics and other pharmaceuticals frequently escape conventional treatment processes and persist in receiving waters, promoting ecotoxicological effects and selection pressure for resistant microbes (Kümmerer, 2009; Verlicchi *et al.*, 2010; Verlicchi *et al.*, 2012). Studies have demonstrated that inadequate removal efficiencies in wastewater treatment plants and direct discharges from healthcare and pharmaceutical production facilities can create environmental hotspots where resistance genes accumulate and mobile elements facilitate horizontal transfer (Larsson *et al.*, 2018; Bengtsson-Palme *et al.*, 2018). Regional research has also documented socioeconomic and infrastructural drivers, such as limited treatment capacity, inconsistent regulation and gaps in pharmaceutical stewardship, which amplify the risks posed by pharmaceutical residues in LMIC urban settings (Abafe *et al.*, 2018; Kumar *et al.*, 2019; Madikizela *et al.*, 2020).

The situation in Lagos State exemplifies these challenges. Recent studies have documented exceptionally high concentrations of pharmaceutical residues, reaching levels of up to 129 µg/L in rivers and sewage-derived effluents between April 2017 and March 2018, with sewage outfalls serving as major contamination points (Ishmael *et al.*, 2025). These concentrations rank among the highest globally and indicate substantial strain on existing wastewater systems. Seasonal variations further underscore the systemic inconsistencies: some compounds peaked during the dry season, while others increased during periods of rainfall, suggesting influences from diverse pollution sources, such as household waste collection gaps, vacuum truck discharges and unmanaged sewage flows (Obayiuwana *et al.*, 2021).

Hospital effluents in Nigeria have been shown to contain elevated levels of antibiotics, including trimethoprim, sulfadoxine and sulfamethoxazole, at concentrations reaching 118 µg/L. Ecological risk-quotient (RQ) analyses have repeatedly shown levels exceeding acceptable thresholds for sensitive aquatic organisms (particularly algae and fish), indicating substantial ecological risk and failures in wastewater/effluent control systems (Díaz-Gamboa *et al.*, 2025; Niampradit *et al.*, 2024). Robust analytical recovery rates of 53-116% and limits of quantification of <1 µg/L support the accuracy of these findings and reflect the clinical use patterns of the health system.

Beyond chemical contamination, the dissemination of resistance determinants through hospital and industrial wastewater remains a core public health concern. Obayiuwana *et al.* (2021) reported that pharmaceutical industry effluents in Lagos and Ogun States contain diverse ARGs associated with β-lactams, tetracyclines,

sulfonamides and aminoglycosides, along with mobile genetic elements that facilitate horizontal gene transfer (HGT). Genes such as bla_{OXA}, $sul1/sul_{II}$, $tet(_G)$, aad_A, and str_A/str_B were detected widely, highlighting the extent to which poorly regulated effluent discharges contribute to regional AMR burdens.

A recent meta-analysis of West African HWW further highlights systemic concerns. It reported high pooled prevalence of resistant *E. coli* (~42.6%) and K. pneumoniae (~32.1%), in addition to frequent detection of ARGs such as bla_{TEM} (76%) and bla_{SHV} (59%) (Qu *et al.*, 2025). Although pharmaceutical industrial effluents constituted a minority of the studies, they played a disproportionately significant role in the amplification and dissemination of resistance determinants, reinforcing the need for health-system-level interventions targeting stewardship, effluent treatment and surveillance frameworks.

Despite accumulating evidence, substantial gaps remain regarding the issues associated with hospital wastewater in Nigeria, particularly concerning multi-facility quantification of antibiotic and antimalarial residues, spatio-temporal pattern analysis, comprehensive ecological risk assessment and integrated ARG surveillance (Obayiuwana *et al.*, 2021; Qu *et al.*, 2025). In many cases, existing studies are limited to single sites, short timeframes or narrow therapeutic classes, constraining their utility for health-system planning and environmental governance.

In this study, we addressed critical knowledge gaps, with the aim of providing a comprehensive, multi-dimensional assessment of pharmaceutical contamination in an urban low- to middle-income country (LMIC) setting. Specifically, our objectives were to (1) conduct spatio-temporal monitoring in order to quantify concentrations of six widely used antibiotics (trimethoprim, doxycycline, ciprofloxacin, metronidazole, amoxicillin and sulfamethoxazole) and three antimalarial drugs (pyrimethamine, artemether and lumefantrine) across six healthcare facilities and a reference canal in Lagos; (2) evaluate ecological risks through risk quotient (RQ) calculations; and (3) estimate mass discharge, characterize therapeutic class distributions and map contamination hotspots. The uniqueness of the approach adopted by this work lay in its integration of empirical environmental data with systemic healthcare factors, such as health-system performance, stewardship practices and regulatory capacity. Thus, this study offers the empirical evidence required to guide targeted interventions and strengthen policies for environmental and public health protection in Lagos and similar expanding LMIC urban settings.

Materials and methods

Study area

The study was conducted in the Shomolu Local Government Area (LGA) of Lagos State, a densely populated urban district characterized by mixed residential, commercial and healthcare activities. Shomolu LGA covers an area of approximately 11.6 square kilometers. In official National Population Commission (NPC) census data, the population of the area is 402,673, but it has since experienced ongoing urban expansion, establishing it as one of the most densely populated municipal zones in metropolitan Lagos. This high population density exerts immense anthropogenic pressure, resulting in elevated municipal wastewater volumes and a dense spatial clustering of healthcare providers.

A major environmental feature of the Shomolu LGA is the Central Drainage Canal, a strategically engineered municipal canal designed to receive wastewater from multiple points within the community. Given the dense urban matrix it serves, this canal acts as a primary receiving water body for both untreated domestic septage and raw facility effluent, making it a critical conduit for evaluating the collective eco-toxicological burden and environmental loading of pharmaceutical residues within the wider ecosystem.

The canal serves as a primary conduit for stormwater and domestic effluents, ultimately emptying into the Lagos Lagoon, one of the most ecologically significant aquatic bodies in southwestern Nigeria. It is fully cement-lined and sealed, and designed to minimize soil infiltration and reduce direct human interference. Unlike open, accessible drainage channels, the restricted nature of the Shomolu Central Canal makes it less prone to contamination from human activities, and critical as a reference system for assessing background levels of pharmaceuticals and other pollutants. Its hydrological flow is constant throughout the year, except during heavy rainfall events, necessitating the strict avoidance of sampling during the rainy season, in order to prevent dilution effects and contaminant wash-off with the potential to influence concentration measurements.

Sample collection

Wastewater effluent sampling was conducted during the dry season in March 2025 across six healthcare facilities in Lagos (UNILAG Medical Centre, LADDILAK Hospital, DEJI Clinic, R. Jolad Hospital, Shomolu Health Care and Mainland Hospital) and at one reference location (Shomolu Central Canal). In order to capture intra-month variability while ensuring sample integrity under stable, low-flow dry season conditions, collection was executed on three randomly selected days within the month (using a random number generator to select the specific calendar dates).

At each of the six healthcare facilities, samples were collected directly from the impounded discharge pipes which empty from the facilities into the canal. At the Shomolu Central Canal control site, sampling was restricted to the sealed mid-section, where flow is stable and isolated from household dumping, non-target source wastes or direct anthropogenic disruptions.

All the sample collecting was conducted during peak operational hours, between 9:00AM and 11:00AM, in order to ensure a representative diagnostic and therapeutic discharge. A total of 21 discrete grab samples were collected (3 independent samples per site across the 7 designated stations). To facilitate robust spatio-temporal tracking, each of the three collections per site was stored, processed and analyzed separately, rather than being pooled into a composite sample.

At each site, 1-L samples were collected in sterile amber glass bottles, preserved on ice at 4°C, transported immediately to the laboratory for storage and continuous accumulation, and subsequently pooled as individual samples for analysis, following established environmental sampling protocols (Van Hoi *et al*., 2021). This design ensured reliable comparison of pharmaceutical loading patterns across healthcare facilities and the Central Canal system.

Analytical methods: UPLC-MS/MS

Target pharmaceutical residues were isolated, detected and quantified using ultra-performance liquid chromatography coupled with tandem mass spectrometry (UPLC-MS/MS). The sample preparation and extraction protocols followed methods adapted from Vumazonke *et al*. (2020). Briefly, effluent samples were filtered through 0.45 µm membranes to remove suspended solids, after which 250 mL aliquots were concentrated by solid-phase extraction (SPE) utilizing Oasis HLB cartridges (200 mg bed). The resulting eluates were evaporated to dryness under a gentle stream of nitrogen, reconstituted in 1 mL of 10% methanol, and transferred to UPLC vials for instrumental analysis.

Chromatographic separation was performed on a Waters ACQUITY UPLC BEH C_{18} column (2.1 × 100 mm, 1.7 µm) maintained at 40 °C. The mobile phase consisted of 0.1% formic acid in water, solvent A, and 0.1% formic acid in acetonitrile, solvent B. A gradient elution program from 5% to 95% B over 10 min was applied at a flow rate of 0.3 mL/min, as reported by Vumazonke *et al*. (2020).

A Waters Xevo TQS mass spectrometer with electrospray ionization in positive MRM mode was used for compound detection. Cone voltages and collision energies were optimized individually for each analyte.

Quantification and calibration

Nine target pharmaceutical compounds, comprising six antibiotics and three antimalarial drugs, were quantified in this study. The target antibiotics included trimethoprim, doxycycline, ciprofloxacin, metronidazole, amoxicillin and sulfamethoxazole, while the antimalarial drugs monitored were pyrimethamine, artemether and lumefantrine. Method performance was validated using procedural blanks, duplicate determinations and matrix-spike recoveries (84% to 108%), consistent with the quality control protocols established by Van Hoi *et al*. (2021). Multi-point calibration curves constructed over a concentration range of 0.01 to 2.0 ppm demonstrated strong linearity, with coefficients of determination (R^2) ≥ 0.995 for all analytes. The limits of detection (LOD) across the target compounds ranged from 0.002 to 0.005 ppm, while the limits of quantitation (LOQ) ranged from 0.006 to 0.01 ppm, establishing high method sensitivity prior to sample analysis.

Risk assessment and statistical analysis

Ecological risk assessment

Pharmaceutical ecological risk was evaluated using the risk quotient (RQ) approach:

$$RQ = \frac{MEC}{PNEC}$$

Where MEC represents the maximum measured environmental concentration (µg/L) of each specific pharmaceutical compound across the sampled locations, and PNEC (Predicted No Effect Concentration) represents the predicted no-effect concentration (µg/L). Values were sourced from Duarte *et al*. (2022). Potential eco-toxicological risks were categorized using established environmental assessment criteria RQ interpretation, following established categories:

- Low risk: RQ < 0.1
- Medium risk: 0.1 ≤ RQ < 1
- High risk: RQ ≥ 1

This framework aligns with regional ecological risk evaluation protocols (Bialkowska-Jelińska *et al*., 2025).

Index (PRI) calculation and concentration statistics

In order to integrate pharmaceutical concentration levels with ecological relevance across sampling sites, a Pharmaceutical Risk Index (PRI) was computed. Composite indices of this nature are widely used in environmental contamination studies to synthesize chemical burden, toxicity potential and diversity into a single interpretable metric (Backhaus and Faust, 2012; Aus der Beek *et al*., 2016).

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$$PRI = \frac{\text{Total Load} \times \text{Maximum Risk Quotient (RQ)} \times \text{Compound Diversity}}{100}$$

Where Total Load (ppm) represents the cumulative concentration of all detected pharmaceuticals at a site, Maximum Risk Quotient (RQ) is derived as the ratio of the measured environmental concentration (MEC) to the predicted no-effect concentration (PNEC), and Compound Diversity corresponds to the number of distinct pharmaceuticals detected. The use of the maximum RQ follows a conservative risk assessment approach, ensuring that the compound with the highest potential ecological risk drives site-level evaluation (European Commission, 2003; Hernando *et al*., 2006). Normalization by a factor of 100 facilitates comparison among sites with differing contamination intensities.

Mass discharge estimation

Daily pharmaceutical mass discharge (g/day) was estimated using:

$$\text{Mass Discharge} = \text{Concentration (mg/L)} \times \times \text{Flow Rate (m}^3\text{/day)} \times 1{,}000$$

Because direct flow measurements were unavailable at the time of sampling, effluent flow rates were inferred from established sector averages for Nigerian healthcare facilities: 10,000 m^3/day for the reference canal and a representative range of 200-500 m^3/day for the hospitals (Ishmael *et al*., 2025). Given that these volumetric flow rates represent a major source of hydrodynamic uncertainty, the resulting mass discharge values must be interpreted as indicative potential loads rather than as precise, measured absolute values. Nevertheless, utilizing these standardized sector benchmarks allows for a valuable, order-of-magnitude comparison of pharmaceutical discharge potential across different healthcare tiers.

Statistical analysis

Non-parametric comparisons across sites were performed using the Mann-Whitney U test ($\alpha = 0.05$), while Spearman's rank correlations examined relationships between pharmaceutical load, flow rate and ecological risk indices. All statistical analyses were conducted using R version 4.2.0.

Results

Occurrence and distribution of pharmaceutical residues

Pharmaceutical residues were detected across all sampled sites, although their distribution varied considerably in both composition and concentration. Overall, antibiotics were the most widely distributed class of compounds, occurring in nearly all locations, while antimalarial drugs showed a more restricted but concentration-intensive pattern.

A detailed breakdown of the identified compounds, their retention times, concentrations and detection status across sites is presented in Figure 1. The results show that trimethoprim and doxycycline were the most consistently detected antibiotics, appearing across multiple sites at relatively low concentrations. In contrast, antimalarial compounds such as pyrimethamine were detected in fewer locations but at substantially higher concentrations, suggesting localized point-source contamination.

The canal environment exhibited minimal contamination, with only trace levels of antibiotics detected and no measurable antimalarial residues. In comparison, healthcare-associated sites showed more complex contamination profiles, reflecting differences in pharmaceutical usage and waste management practices.

Figure 1. Pharmaceutical residues across all sampled sites. Color intensity represents log10 (1+ concentration in ppm) across compounds and sites, indicating levels of residues concern ranging from different sample sites. a. Antibiotic residues across sampling sites b. Antimalarial residues across sampling sites.

Site-specific contamination patterns

Clear spatial variation in pharmaceutical contamination was observed among the sampling locations. A comparative summary of compound counts, total loads and dominant compounds is provided in Figure 2.

One site emerged as a major contamination hotspot, exhibiting the highest number of detected compounds as well as the greatest total pharmaceutical load. This site was characterized by a mixed contamination profile comprising both antibiotics and antimalarial drugs, with several compounds present at elevated concentrations. Two other healthcare facilities displayed similar contamination patterns, both dominated by pyrimethamine, which contributed the overwhelming majority of the total pharmaceutical load at these

locations. The concentrations recorded at these sites were notably higher than those observed elsewhere, indicating significant pharmaceutical input.

In contrast, other sites, such as smaller clinics and community healthcare facilities, exhibited relatively low contamination levels, typically characterized by the presence of one or two antibiotic residues at trace concentrations.

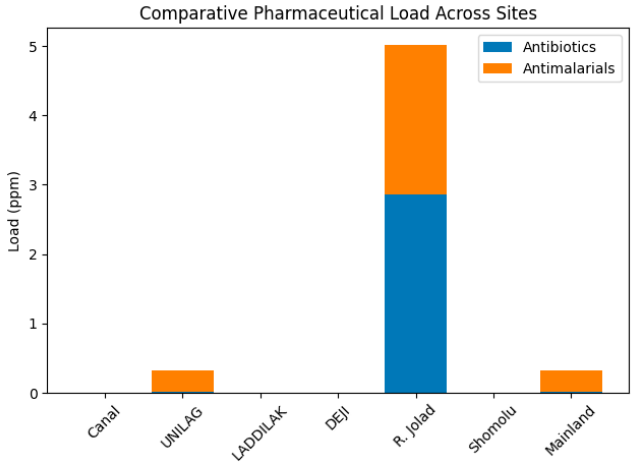

Figure 2. Comparative distribution of pharmaceutical residues across sampled sites. The stacked bar chart illustrates total pharmaceutical load (ppm) partitioned into antibiotic and antimalarial contributions.

Detection frequency and dominant compounds

The frequency of occurrence of individual pharmaceutical compounds across the study area is summarized in Table 1. Doxycycline was the most frequently detected compound, followed by trimethoprim, confirming their widespread environmental presence.

Conversely, several compounds, including artemether, lumefantrine, ciprofloxacin and metronidazole, were detected exclusively at a single site. This suggests that these compounds are associated with localized usage and may originate from direct discharge or inefficient waste handling. Although detected less frequently, pyrimethamine exhibited the highest mean concentration among all compounds, highlighting its dominant contribution to overall contamination where present.

Therapeutic class distribution

The contribution of different therapeutic classes to overall pharmaceutical contamination is presented in Table 2. Antibiotics accounted for the largest proportion of total contamination across all sites, reflecting their widespread use and environmental persistence.

However, antimalarial drugs contributed a comparable proportion of the total load, due to their high concentrations at specific locations. In particular, artemisinin-based therapies were a major contributor at the most contaminated site, while antifolate anti-malarial drugs dominated at selected healthcare facilities.

This pattern underscores the dual burden of antibiotic and antimalarial contamination in the study area, driven by prevailing disease treatment practices.

Table 1. Compound detection frequency in the sampled sites

Compound	Detection rate	Sites detected	Mean concentration (ppm)	Maximum concentration (Site)
Trimethoprim	57.1% (4/7)	Canal, Laddilak, Deji, Shomolu	0.00087	0.00200 (DEJI)
Doxycycline	71.4% (5/7)	Canal, UNILAG, Laddilak, Shomolu, and Mainland	0.00608	0.01520 (UNILAG and Mainland Hospital)
Pyrimethamine	28.6% (2/7)	UNILAG, and Mainland	0.30321	0.30321 (UNILAG and Mainland Hospital)
Artemether	14.3% (1/7)	R. Jolad Hospital	1.12000	1.12000 (R. Jolad Hospital)
Lumefantrine	14.3% (1/7)	R. Jolad Hospital	1.03000	1.03000 (R. Jolad Hospital)
Amoxicillin	14.3% (1/7)	R. Jolad Hospital	0.61000	0.61000 (R. Jolad Hospital)
Metronidazole	14.3% (1/7)	R. Jolad Hospital	0.95000	0.95000 (R. Jolad Hospital)
Sulfamethoxazole Antibiotic (Sulfonamide)	14.3 (1/7)	R. Jolad Hospital	1.09300	0.580 (R. Jolad Hospital)
Ciprofloxacin	14.3% (1/7)	R. Jolad Hospital	0.72000	0.72000 (R. Jolad Hospital)

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Table 2. Distribution of detected pharmaceutical residues by therapeutic class and pharmacological subclass across sampled healthcare facilities

Therapeutic class	Pharmacological subclass	Detected compound(s)	Total load (ppm)	Detection frequency (sites)	Highest concentration (ppm)	Most contaminated site
Major therapeutic classes						
Antibiotics	—	Trimethoprim, doxycycline, ciprofloxacin, metronidazole, amoxicillin, aulfamethoxazole	2.898	7/7 (100%)	2.860	R. Jolad Hospital
Antimalarial drugs	—	Artemether, lumefantrine, pyrimethamine	2.756	3/7 (42.9%)	2.150	R. Jolad Hospital
Pharmacological subclasses						
Antibiotics	Diaminopyrimidine	Trimethoprim	—	4/7 (57.1%)	—	Multiple sites
Antibiotics	Tetracycline	Doxycycline	—	5/7 (71.4%)	—	UNILAG Medical Centre & Mainland Hospital
Antibiotics	Fluoroquinolone	Ciprofloxacin	0.720	1/7 (14.3%)	0.720	R. Jolad Hospital
Antibiotics	Nitroimidazole	Metronidazole	—	—	—	R. Jolad Hospital
Antibiotics	β-Lactam	Amoxicillin	—	—	—	R. Jolad Hospital
Antibiotics	Sulfonamide	Sulfamethoxazole	0.580	1/7 (14.3%)	0.580	R. Jolad Hospital
Antimalarial drugss	Artemisinin derivatives	Artemether + Lumefantrine	2.150	1/7 (14.3%)	2.150	R. Jolad Hospital
Antimalarial drugs	Antifolate	Pyrimethamine	0.606	2/7 (28.6%)	0.303	UNILAG Medical Centre & Mainland Hospital

Concentration variability across sites

Descriptive statistical analysis revealed substantial variability in pharmaceutical concentrations across the sampling locations, as summarized in Figure 2. Sites with high contamination loads exhibited greater variability and wider concentration ranges, reflecting the presence of multiple compounds at elevated levels.

In contrast, sites with low contamination levels showed minimal variability, consistent with the detection of only a few compounds at trace concentrations. The distribution patterns indicate that pharmaceutical pollution is highly skewed toward specific high-impact locations.

Ecological risk assessment

The ecological implications of the detected pharmaceutical residues were evaluated using risk quotient analysis, the results of which are presented in Figure 4. Several compounds posed significant environmental risks, particularly at sites with elevated concentrations.

Pyrimethamine and ciprofloxacin exhibited extremely high risk levels, with concentrations far exceeding predicted no-effect thresholds. Artemether and metronidazole were associated with high ecological risk, while commonly detected antibiotics such as trimethoprim and doxycycline generally posed low to negligible risks.

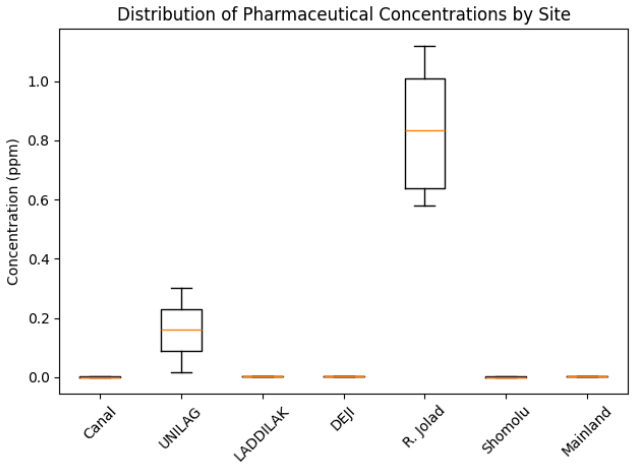

Figure 3. Distribution of pharmaceutical concentrations across sampling sites. Box-and-whisker plots show median, interquartile range and variability of detected compounds, emphasizing differences in concentration spread and outliers among sites.

These findings identify key compounds of concern and highlight specific sites where ecological impacts are likely to be most pronounced.

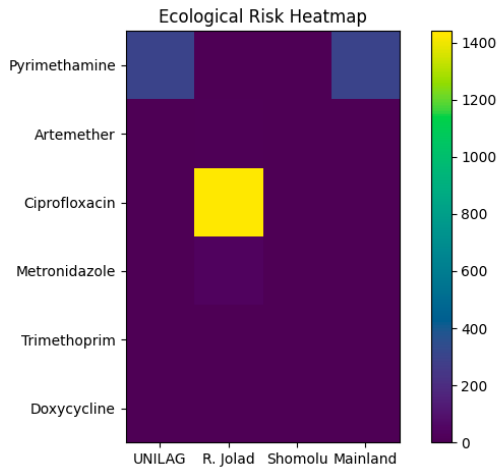

Figure 4. Ecological risk heatmap of detected pharmaceutical residues. Color intensity represents risk quotient values across compounds and four (4) concerned sites, indicating levels of ecological concern ranging from negligible to extreme risk.

Mass discharge and environmental loading

Estimates of daily pharmaceutical discharge revealed substantial differences in environmental loading across sites, as shown in Table 3. The most contaminated site contributed disproportionately to total pharmaceutical discharge, with significantly higher daily loads compared to all other locations.

At this site, both antibiotics and anti-malarial drugs contributed substantially to the overall discharge, with certain compounds dominating the daily load. In contrast, other sites contributed relatively minor loads, reflecting lower concentrations and/or reduced flow rates.

Statistical differences between sites

Non-parametric comparisons demonstrated significant differences in pharmaceutical concentrations between sites, particularly between high-contamination and low-contamination locations. The results of these comparisons are presented in Figure 5.

Sites identified as contamination hotspots differed significantly from most other locations, with large effect sizes indicating substantial environmental heterogeneity. However, some low-contamination sites showed no statistically significant differences between them, suggesting similar pollution profiles.

Relationships between key variables

Correlation analysis revealed strong relationships between several key variables, as summarized in Figure 6. Total pharmaceutical load showed a near-perfect positive correlation with compound diversity, indicating that sites with more detected compounds also exhibited higher contamination levels. Additionally, strong positive correlations were observed between maximum concentration and ecological risk, as well as between flow rate and daily discharge. A notable inverse relationship was observed between antibiotic and antimalarial loads, suggesting differing usage or discharge patterns across sites.

Identification of contamination hotspots

Based on combined metrics of concentration, diversity and ecological risk, sites were ranked according to their contamination severity, as presented in Table 6. One site was clearly identified as a critical hotspot, characterized by multiple compounds, high concentrations and extreme ecological risk.

Other high-ranking sites were primarily driven by elevated concentrations of specific compounds, particularly antimalarial drugs. In contrast, lower-ranked sites exhibited limited contamination and minimal ecological concern.

Table 3. Mass discharge estimation (g/day)

Site	Flow rate (m^3/day)	Total daily load (g/day)	Antibiotics	Antimalarial drugs	Dominant compound
Canal	10,000	0.019	0.019	0	Doxycycline (0.016 g/day)
UNILAG	200	0.064	0.003	0.061	Pyrimethamine (0.061 g/day)
R. Jolad Hospital	500	2,505	1,430	1,075	Artemether (560 g/day)
LADDILAK	150	0.00038	0.00038	0	Doxycycline
Shomolu Health Care	300	0.00138	0.00138	0	Doxycycline
DEJI Clinic	150	0.00300	0.00300	0	Trimethoprim
Mainland Hospital	200	0.064	0.003	0.061	Pyrimethamine

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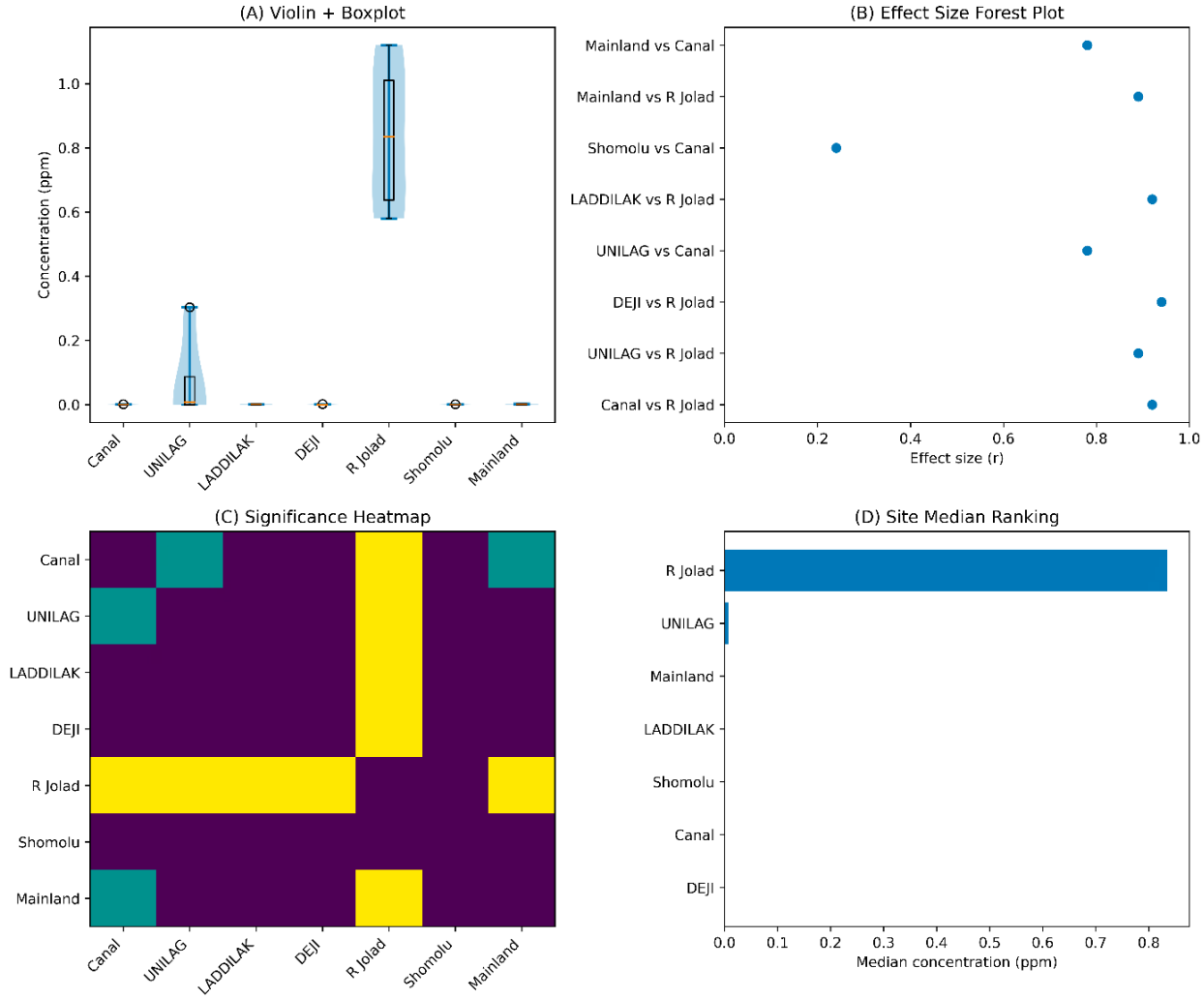

Figure 5. Spatial distribution and statistical comparison of pharmaceutical residues across sampling sites. (A) Violin plots with embedded boxplots illustrating concentration distributions at each sampling location. (B) Forest plot of Mann-Whitney effect sizes (r) for significant site comparisons. (C) Heatmap showing pairwise statistical significance between sites (*p < 0.05, **p < 0.01, ns = not significant). (D) Ranking of sites according to median pharmaceutical residue concentrations with interquartile range error bars. Together, these analyses highlight the distinct contamination profile of R. Jolad Hospital, relative to other healthcare and environmental sampling locations.

Figure 6. Correlation matrix of environmental and pharmaceutical variables. The heatmap displays the strength and direction of relationships between key variables, including total load, compound diversity, flow rate and ecological risk.

Table 4. Contamination hotspot ranking

Rank	Site	Contamination Index	Priority	Inference
1	R. Jolad Hospital	98.7	Critical	6 compounds, extreme RQs
2	UNILAG	85.4	High	Very high pyrimethamine
3	Mainland Hospital	85.4	High	Identical profile to UNILAG
4	DEJI Clinic	12.1	Moderate	Single antibiotic
5	LADDILAK	10.8	Moderate	Low but consistent
6	Shomolu Health Care	8.9	Low	Similar to Canal
7	Canal	5.0	Low	Diluted contamination

Discussion

The results of our study indicate clear spatial variation in pharmaceutical contamination across sampled healthcare facilities and the canal, with consistently higher loads recorded at R. Jolad Hospital, UNILAG Medical Centre and Mainland Hospital. These differences are better interpreted as reflecting differences in clinical activity and wastewater discharge intensity, rather than as isolated contamination events. The elevated values at these sites likely reflect higher patient turnover and more frequent drug use, resulting in greater pharmaceutical release into wastewater streams. This interpretation aligns with previous evidence that larger and more active hospitals tend to discharge higher pharmaceutical loads (Verlicchi *et al*., 2012; WHO, 2014).

Antibiotics accounted for 55.7% of total contamination across all sites (Table 2), indicating widespread and consistent antibiotic presence in the study area. Doxycycline and trimethoprim were the most frequently detected compounds, while ciprofloxacin and pyrimethamine contributed disproportionately to ecological risk due to their high toxicity-weighted RQ values, particularly at R. Jolad Hospital (Table 1). This pattern suggests intensive antibiotic usage in hospital settings, although prescribing behavior was not directly measured in this study. The universal detection of antibiotics across all sampling points indicates continuous environmental release and persistence in the aquatic system.

The extremely high ecological risk value for ciprofloxacin (RQ = 1440) (Figure 4) is particularly significant, as it exceeds thresholds associated with predicted no-effect concentrations. This indicates a high probability of selection pressure for resistant bacteria in receiving waters, consistent with reports that hospital-associated antibiotic residues contribute to antimicrobial resistance selection, even at low concentrations (Kümmerer, 2009; Bengtsson-Palme *et al*., 2018).

In contrast, antimalarial drugs contributed 53% of total pharmaceutical loads, with pyrimethamine showing the highest concentrations, particularly at UNILAG Medical Centre and Mainland Hospital (Table 1 and Table 2). This pattern reflects the continued high incidence of malaria in Nigeria and routine use of antimalarial drugs in both treatment and preventive care (WHO, 2023). The similar concentration profiles observed at UNILAG and Mainland Hospital (Table 1 and Table 2) suggest shared prescribing and usage patterns across these facilities, rather than site-specific anomalies.

Unlike antibiotics, antimalarial drugs did not show uniform distribution across all compounds, but instead were dominated by a few high-concentration residues, particularly pyrimethamine. This indicates targeted drug use patterns, rather than broad-spectrum pharmaceutical dispersion.

The canal contained detectable antibiotic residues, such as doxycycline and trimethoprim, indicating the transporting of pharmaceutical residues from hospital effluents and surrounding urban runoff. This suggests that the canal functions as a receiving pathway for untreated or partially treated wastewater from adjacent healthcare facilities. The downstream movement of these compounds indicates environmental connectivity between point sources (hospitals) and the wider aquatic system.

The consistently higher contamination at R. Jolad Hospital, UNILAG Medical Centre and Mainland Hospital (Figure 1 and Figure 2) indicates that these facilities act as primary contributors to pharmaceutical loading in the study area. The evidence for this pattern is further supported by the strong correlations between compound count and total load (r = 0.97) and between flow rate and daily discharge (r = 0.91) (Figure 6), indicating that both pharmaceutical diversity and discharge volume influence overall contamination levels.

The estimated discharge of 2,505 g/day (Table 3) from R. Jolad Hospital is substantially higher than that of other facilities, reinforcing its role as a major emission source. Similar patterns have been observed in other hospital-based studies, where discharge volume correlates with pharmaceutical burden (Verlicchi *et al*., 2010).

The ecological risk assessment indicates that ciprofloxacin and pyrimethamine present extreme risk, while artemether and metronidazole present high risk (Figure 4). These risks are directly linked to observed environmental concentrations, as shown by the strong correlation between maximum concentration and ecological risk (r = 0.96). This indicates that compounds present at high concentrations disproportionately drive overall ecological risk.

The presence of these high-risk compounds suggests sustained exposure of aquatic organisms to biologically active pharmaceuticals, which may contribute to selection pressure in microbial communities and disruption of aquatic ecological balance (Larsson *et al*., 2018).

Overall, the results of the study indicate distinct and compound-specific contamination patterns, rather than uniform pollution. Antibiotics dominate in terms of distribution and resistance-related risk, while antimalarial drugs dominate in concentration-driven load at specific sites. The canal acts as a transport pathway linking hospital effluents to downstream aquatic environments. These patterns are primarily driven by differences across facilities in pharmaceutical usage intensity and wastewater discharge characteristics.

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Conclusion

The results of our study demonstrate the presence of pharmaceutical residues in effluents from selected hospitals in Lagos and an associated municipal canal, confirming continuous environmental discharge of clinically used drugs. Clear spatial variation was observed, with R. Jolad Hospital, UNILAG Medical Centre and Mainland Hospital identified as contamination hotspots, based on higher total pharmaceutical loads.

Across all sites, antibiotics were the dominant class of contaminants, with ciprofloxacin displaying an extremely high ecological risk quotient, indicating strong potential for selection pressure in aquatic environments. Antimalarial drugs were also prominent, with pyrimethamine showing elevated concentrations and contributing substantially to overall pharmaceutical loads at key hospitals.

The canal findings confirm downstream transporting of pharmaceutical residues from hospital sources into surface waters, indicating environmental connectivity between healthcare discharge points and urban aquatic systems.

Overall, the results show that hospital effluents contribute measurable pharmaceutical burdens to the environment, with site-specific differences in intensity and associated ecological risks. These findings highlight the need for continued monitoring of hospital wastewater and a focus of attention on high-risk compounds, such as ciprofloxacin and pyrimethamine.

Authors' contributions (CRediT statement)

Isiaka Adio Hassan: Conceptualization, methodology, investigation, project administration, writing - original draft, funding acquisition.

Olatayo Michael Ogunbanwo: Methodology, validation, resources, data curation.

Jimoh Ishola Taylor: Formal analysis, investigation, software.

Afeez Olabisi Yusuf: Validation, writing - review and editing, visualization.

Peter Adedayo Oladetuyi: Formal analysis, mathematical modeling, software.

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Conflicts of interest

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper. No institutional or economic conditions exist that would affect the unbiased interpretation of these results.

Artificial Intelligence disclosure

During the preparation of this manuscript, the authors utilized Gemini (Google AI) to improve the clarity of the academic language, optimize the title for high-impact journal standards, and ensure the technical accuracy of the Spanish translation. The authors reviewed and edited the output as needed and maintain full responsibility for the integrity and accuracy of the final content.

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