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Urban Land Use and Environmental Health Risks: Assessing Human Exposure to Microplastic Pollution in The River Benue Watershed, Makurdi, Nigeria

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Abstract

Rapid urban expansion and unregulated land use change in sub-Saharan African cities intensify the discharge of microplastic contaminants into inland freshwater bodies, leading to human health risks. The River Benue watershed in Makurdi, Nigeria is under mounting pressure from agricultural runoff, industrial effluents and inadequate solid-waste management, yet baseline data on microplastic contamination and associated health risk remain scarce. This study quantifies and characterises microplastic concentrations in surface water and sediments of the River Benue across sites stratified by dominant land use. Water and sediment samples were collected in triplicate from six sites representing urban commercial, peri-urban agricultural and residential land use zones along a 14 km transect of the river during dry and wet seasons (January–June 2024). Microplastics were isolated via density separation and vacuum filtration, characterised morphologically under stereo microscopy, and polymer-typed by micro-Fourier Transform Infrared Spectroscopy (μ-FTIR). Estimated Daily Intake (EDI), Hazard Quotient (HQ), and Monte Carlo simulation were applied for health risk modelling. Microplastic concentrations ranged from 120 ± 18 to 406 ± 43 particles/L in surface water and from 284 ± 31 to 1,142 ± 98 particles/kg dry weight in sediment. Fibres (54.7%) and fragments (26.3%) dominated morphologically; polyethylene terephthalate (PET, 31.2%), polypropylene (PP, 22.8%), and polyethylene (PE, 19.5%) were the most abundant polymers. Concentrations were higher at commercial sites and correlated positively with population density and distance from formal waste disposal infrastructure. The mean EDI for adults via water ingestion was 1.87×10^{-2} mg/kg-bw/day. Monte Carlo-derived HQ values ranged from 0.83 to 2.14, indicating sub-populations near high-load sites may face non-trivial health risk. Urban land use intensity is a primary determinant of microplastic loading in the River Benue, with health risk estimates exceeding safety thresholds for vulnerable sub-populations. Targeted land use regulation, improved solid-waste infrastructure, and systematic riverine monitoring are urgently needed in Makurdi and comparable Nigerian cities

Keywords: Microplastics; Freshwater Contamination; Urban Land Use; Health Risk Assessment; River Benue.

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Introduction

Plastic pollution has escalated as a major environmental health challenges of the twenty-first century. Since commercial-scale polymer production began in the 1950s, an estimated 9.2 billion metric tonnes of plastic have been manufactured globally, with fewer than 10% recycled and over 5 billion tonnes accumulating in landfills or dispersed in natural environments (Jolaosho et al., 2025). A significant fraction of this burden manifests as microplastics, which are particles ≤5 mm in their largest dimension and formed through the intentional manufacture of micro-sized polymers or the fragmentation of larger plastic items under ultraviolet radiation, mechanical abrasion and thermal stress (Napper & Thompson, 2016). Freshwater bodies, particularly in rivers occupy a central position in this global cycle (Zhang et al., 2020), as they receive microplastic inputs from terrestrial runoff, urban drainage and industrial effluents, while transporting them downstream to estuaries and oceans (Lebreton et al., 2017). Sub-Saharan Africa has witnessed some of the fastest urban growth rates over the past three decades (Thompson et al., 2004), with city peripheries expanding into unplanned, informally settled zones where solid-waste collection is inadequate and stormwater drainage channels double as disposal conduits (Ogunkan & Ogunkan, 2025). Makurdi in Benue State have experienced population growth exceeding 4% per annum (Frolking et al., 2024), placing immense pressure on the River Benue, which sustains domestic water use, artisanal fisheries, small-scale agriculture and recreation for millions of residents (Abbas et al., 2023).

Microplastics enter freshwater systems through multiple land-use pathways. Urban commercial zones generate high volumes of single-use plsstic via wastewater; agricultural land contributes plastic mulch fragments, pesticide packaging, and irrigation tube debris; industrial corridors discharge polymer pellets and processing residues. Once in the water, microplastics interact with dissolved organic matter and adsorb persistent organic pollutants (POPs), (Schwabl et al., 2019) heavy metals, and disrupting chemicals (H. Liu et al., 2019), enhancing their toxicological potency relative to the base polymer (Hartmann et al., 2019). Human exposure occurs via multiple pathways: ingestion of contaminated drinking water into aquatic food sources, inhalation of airborne fibres and dermal contact during bathing or fishing (Wright et al., 2020). Epidemiological evidence increasingly links chronic microplastic exposure to gastrointestinal inflammation (Whitmee et al., 2024), oxidative stress, immune dysregulation and potential carcinogenicity of adsorbed chemical contaminants (Rutter et al., 2026). Despite the ecological and socioeconomic importance of the River Benue which drains a watershed exceeding 330,000 km² and receives runoff from extensive agricultural, urban and industrial land uses (Fadare &

Okoffo, 2020). This knowledge gap obstructs the formulation of evidence-based environmental health policy and impedes compliance with Nigeria's Climate Change Act (2021) mandate for pollutant monitoring.

This study addresses the gap by quantifying microplastic concentrations in surface water and sediment samples stratified by land use typology along a representative transect of the River Benue in Makurdi; characterise microplastics morphologically (shape, size) and chemically (polymer type) using μFTIR spectroscopy; evaluate spatial relationships between land use intensity indicators and microplastic loading; and to model human health risk via Estimated Daily Intake (EDI) and Hazard Quotient (HQ) methodologies incorporating Monte Carlo probabilistic simulation. This study generates actionable evidence for urban planners, public health authorities, and environmental regulators in Nigeria and comparable settings across sub-Saharan Africa, by grounding environmental measurements in a health risk framework,

Methodology

Study Area and Land Use Classification

Makurdi (7°44′N, 8°30′E), the capital of Benue State, Nigeria, is situated along banks of the River Benue at an elevation of approximately 100 m above sea level. The city has a tropical wet-and-dry climate (Köppen Aw) with mean annual rainfall of ~1,300 mm concentrated between April and October and a pronounced dry season from November to March (Oche, 2018). Population estimates for 2024 exceed 500,000, supported principally by commerce, smallholder agriculture, artisanal fishing, and civil service employment. The River Benue at Makurdi has a mean channel width of ~900 m during the dry season, expanding to >2,000 m at peak flood and receives tributary inputs from the Katsina-Ala, Donga, and Taraba rivers upstream. Land use along the study transect (approximately 14 km) was classified into three categories validated by field reconnaissance: Urban Commercial (UC) — high-density built-up areas, markets, motor parks and roadside settlements; Peri-Urban Agricultural (PA) — smallholder crop production, floodplain farms, and scattered residential plots; and Riparian Residential (RR) — medium-density housing along the riverbank with limited formal infrastructure. Six sampling sites (two per land use class) were selected to ensure representation of known pollution sources and hydrological variability.

Sample Collection

Sampling was conducted during the dry season (January–March 2024) and the early wet season (April–June 2024) to capture contrasting hydrological conditions. At each site, triplicate surface water samples ($n = 3 \times 6 \times 2$ seasons = 36 water samples) were collected using pre-cleaned 10 L stainless steel buckets from mid-channel by boat, avoiding surface scum. Samples were immediately vacuum-filtered through pre-ashed (450°C, 4 h) glass microfibre filters (GF/F, 0.45 μm pore size; 47 mm diameter) and stored in amber glass jars at 4°C until analysis. Triplicate sediment samples (36 sediment samples) were collected from the top 5 cm of the riverbed using an Ekman grab sampler, homogenised in stainless steel trays, sub-sampled (~200 g wet weight), and stored in aluminium-foil-lined containers at −20°C. Laboratory procedural blanks ($n = 6$) were analysed to assess airborne contamination; personnel wore 100% cotton garments throughout. All equipment was pre-rinsed three times with ultra-pure (Milli-Q) water before use.

Microplastic Isolation and Characterisation

Water sample filters were treated with 10% H_2O_2 at 50°C for 24 h to digest organic matter, then rinsed, dried at 40°C, and examined under a Leica M205C stereo microscope at 10–45× magnification. Sediment samples were freeze-dried, then subjected to density separation using a saturated NaCl solution (density 1.2 g/cm^3) according to the GESAMP harmonised methodology for marine and freshwater microplastic monitoring. The floating fraction was filtered, digested with Fenton's reagent ($H_2O_2/FeSO_4$) to remove residual organic matter, and microscopically enumerated. Particles were categorised by morphology (fibre, fragment, bead/pellet, film, foam) and size class (<100 µm; 100–500 µm; 500–2,000 µm; >2,000 µm). A 20% random sub-sample of visually identified microplastics (n ≥ 100 per site) was subjected to µFTIR spectroscopy (Thermo Nicolet iS50 ATR-FTIR) for polymer identification, using a spectral library (Siris software v.5.1) with a match threshold of ≥70% (Ziajahromi et al., 2017). Results are reported as particles per litre (water) and particles per kilogram dry weight (sediment).

Land Use Intensity Indicators

Quantitative land use intensity proxies were compiled for each 500 m buffer zone centred on each sampling site: (i) impervious surface coverage (%) from Landsat 9 NDISI analysis; (ii) population density (persons/km²) from interpolated 2023 census ward data; (iii) solid-waste management index (SWMI) — a composite score (0–100) derived from average distance to registered waste collection points, frequency of municipal waste pickup, and proportion of households with formal waste contracts (obtained from Benue State Waste Management Authority records); and (iv) proximity to industrial discharge points (m), derived from georeferenced facility registers. Spearman rank correlation (ρ) was used to test associations between land use indicators and microplastic concentrations (SPSS v.28).

Human Health Risk Assessment

Human exposure was estimated through two pathways: water ingestion and fish consumption. For water ingestion, the Estimated Daily Intake (EDI, mg/kg-bw/day) was calculated following United States Environmental Protection Agency (USEPA) guidelines as:

$EDI = (C^{JW} \times IR \times EF \times ED) / (BW \times AT)$

where C_{MP} = microplastic concentration in water (mg/L, converted from particle count using mean polymer density and particle volume for each size class); IR = ingestion rate (2 L/day adults, 1 L/day children); EF = exposure frequency (365 days/year); ED = exposure duration (30 years adults, 6 years children); BW = body weight (60 kg adults, 15 kg children); AT = averaging time (ED × 365). For fish consumption, EDI was calculated using microplastic loads measured in gastrointestinal contents of Nile tilapia (*Oreochromis niloticus*) sampled at each site (n = 10 fish per site) combined with local per-capita fish consumption rates from Benue State NBS (2022) dietary surveys (43 g/day adults). The Hazard Quotient (HQ = EDI / Reference Dose [RfD]) was estimated using a provisional RfD of 1.5×10^{-2} mg/kg-bw/day derived from rodent no-observed-adverse-effect-level (NOAEL) data for polystyrene particles (Rutter et al., 2026; Hartmann et al., 2019). Monte Carlo simulation (10,000 iterations; @Risk v.8.0) was applied to characterise uncertainty in HQ estimates, with input parameters assigned probability distributions derived from measured data ranges. HQ >1 was interpreted as a potential non-trivial health risk.

Statistical Analysis

Microplastic concentrations are reported as mean ± standard deviation (SD). Normality was assessed by the Shapiro–Wilk test. Kruskal–Wallis H-test with Dunn's post-hoc correction compared concentrations across sites and seasons (significance level α = 0.05). Spearman rank correlation assessed land use–concentration relationships. All analyses were conducted in R v.4.3.2 (tidyverse, ggplot2 packages) and SPSS v.28.

Results

Microplastic Concentrations in Surface Water

Microplastics were detected in all water samples across all sites and both seasons. Concentrations showed significant spatial variation (Kruskal–Wallis H = 38.4, df = 5, $p < 0.001$), with urban commercial sites exhibiting the highest loads (Table 1). During the dry season, water concentrations ranged from 120 ± 18 particles/L at the Riparian Residential site RR-2 to 406 ± 43 particles/L at Urban Commercial site UC-1 (Makurdi Gboko Road market corridor). Wet-season concentrations were on average 1.8 times higher across all sites ($p < 0.01$), consistent with stormwater-mediated flushing of terrestrial microplastic deposits into the channel. Procedural blanks yielded <5 particles per filter, confirming minimal laboratory contamination.

Table 1. Microplastic concentrations in surface water (particles/L) and sediment (particles/kg dw) of the River Benue by sampling site and season, Makurdi, Nigeria (2024).

Site (Land Use)	Location	Water–Dry (ptcls/L)	Water–Wet (ptcls/L)	Sed.–Dry (ptcls/kg)	Sed.–Wet (ptcls/kg)	Dominant Polymer
UC-1 (Urban Commercial)	Makurdi–Gboko Rd	406±43	754±68	1,142±98	1,836±145	PET (33%)
UC-2 (Urban Commercial)	Wurukum Bridge	378±39	721±62	1,089±89	1,754±131	PET (31%)
PA-1 (Peri-Urban Agric.)	Kpege Farm Belt	214±26	398±41	648±57	1,012±86	PP (28%)
PA-2 (Peri-Urban Agric.)	Wurukum Floodplain	198±22	362±37	596±49	943±79	PP (26%)
RR-1 (Riparian Resid.)	Water Board Reach	145±19	267±29	345±36	528±52	PE (24%)
RR-2 (Riparian Resid.)	North Bank Residential	120±18	228±24	284±31	441±44	PE (23%)

UC = Urban Commercial; PA = Peri-Urban Agricultural; RR = Riparian Residential. ptcls = particles; dw = dry weight; PET = polyethylene terephthalate; PP = polypropylene; PE = polyethylene. Values are mean ± SD (n = 3). Source: Author's fieldwork, 2024.

Microplastic Concentrations in Sediment

Sediment concentrations were higher than corresponding water concentrations at all sites, reflecting the preferential settling and accumulation of denser and larger microplastics. Dry-season sediment concentrations ranged from 284 ± 31 particles/kg dw (RR-2) to 1,142 ± 98 particles/kg dw (UC-1). Wet-season concentrations were 1.54–1.61-fold higher across all sites, attributed to resuspension of accumulated particles and increased upstream catchment loading during rainfall events. The Wurukum Bridge site (UC-2) consistently registered the second-highest concentrations in both matrices and both seasons, consistent with heavy commercial vessel traffic, market waste discharge, and proximity to Makurdi's central market district.

Morphological and Polymer Characterisation

Morphological analysis revealed fibres as the dominant category (54.7% across all samples), followed by fragments (26.3%), films (8.9%), pellets/beads (6.2%), and foam (3.9%). The predominance of fibres is consistent with synthetic textile washing in urban laundry effluents and discharge from the Makurdi textile market (Napper & Thompson, 2016; Ziajahromi et al., 2017). Fragment dominance at agricultural sites reflects fragmentation of abandoned polyethylene mulch films and pesticide containers. Size-class distribution showed the 100–500 µm range as most prevalent (51.3%), followed by 500–2,000 µm (28.4%), <100 µm (13.2%), and >2,000 µm (7.1%). µFTIR analysis of the sub-sample identified polyethylene terephthalate (PET, 31.2%), polypropylene (PP, 22.8%), polyethylene (PE, 19.5%), polystyrene (PS, 12.4%), nylon-6,6 (8.7%), and other polymers (5.4%).

Table 2. Morphological composition (%) and polymer distribution (%) of microplastics in the River Benue by land use class.

Land Use	Fibres (%)	Fragments (%)	Films (%)	PET (%)	PP (%)	PE (%)	PS (%)
Urban Commercial	60.2	24.1	7.8	37.4	18.6	17.2	14.8
Peri-Urban Agric.	49.8	30.1	11.6	23.7	30.2	22.1	9.4
Riparian Residential	54.2	24.7	7.3	32.5	19.6	19.2	13.0
All sites (pooled)	54.7	26.3	8.9	31.2	22.8	19.5	12.4

PET = polyethylene terephthalate; PP = polypropylene; PE = polyethylene; PS = polystyrene. Source: Author's fieldwork and µFTIR analysis, 2024.

Land Use–Microplastic Correlations

Spearman rank correlations revealed strong associations between land use intensity indicators and microplastic concentrations (Table 3). Impervious surface coverage showed the strongest positive correlation with water microplastic concentration ($\rho = 0.91$, $p < 0.001$). Population density ($\rho = 0.87$, $p < 0.001$) and the Solid Waste Management Index ($\rho = -0.84$, $p < 0.001$; negative coefficient indicating that higher SWMI = better management = lower pollution) were also strongly associated. Proximity to industrial discharge points showed moderate negative correlation ($\rho = -0.72$, $p < 0.01$), indicating higher loads near discharge sources.

Table 3. Spearman rank correlations (ρ) between land use intensity indicators and microplastic concentrations in River Benue surface water (particles/L, pooled seasons).

Land Use Intensity Indicator	ρ (Spearman)	95% CI	p-value
Impervious surface coverage (%)	0.91	[0.82, 0.96]	<0.001
Population density (persons/km²)	0.87	[0.75, 0.94]	<0.001
Solid Waste Management Index (0–100)	−0.84	[−0.93, −0.70]	<0.001
Distance to industrial discharge (m)	−0.72	[−0.86, −0.52]	<0.01

n = 36 site-season observations; significant at α = 0.05 (two-tailed). Source: Author's analysis, 2024.

Human Health Risk Assessment

EDI estimates for the water ingestion pathway ranged from 6.14×10^{-3} mg/kg-bw/day (RR-2, adults) to 3.42×10^{-2} mg/kg-bw/day (UC-1, children). Mean adult EDI via water was 1.87×10^{-2} mg/kg-bw/day; mean child EDI was 2.69×10^{-2} mg/kg-bw/day. Fish consumption added a further estimated 20–35% to total EDI at urban commercial sites, where Nile tilapia gastrointestinal contents yielded 14–28 microplastic particles per individual fish. Hazard Quotient values based on mean concentrations ranged from 0.41 (RR-2, adults, water only) to 2.28 (UC-1, children, combined pathways). Monte Carlo simulation (Table 4) demonstrated that at the 95th percentile of the HQ distribution, children residing near urban commercial sites face HQ values of 3.12, substantially exceeding the safety threshold of 1.

Table 4. Monte Carlo-derived Hazard Quotient (HQ) estimates for human microplastic exposure via water ingestion and fish consumption, River Benue, Makurdi (10,000 iterations).

Site (Land Use)	Population	HQ Mean	HQ Median	HQ 5th %ile	HQ 95th %ile	Risk Level
UC-1 (Urban Comm.)	Adults	1.93	1.88	1.24	2.67	Moderate–High
UC-1 (Urban Comm.)	Children	2.28	2.21	1.46	3.12	High
UC-2 (Urban Comm.)	Adults	1.84	1.79	1.18	2.53	Moderate–High
UC-2 (Urban Comm.)	Children	2.14	2.07	1.38	2.94	High
PA-1 (Peri-Urban)	Adults	1.12	1.07	0.72	1.61	Moderate
PA-1 (Peri-Urban)	Children	1.37	1.31	0.88	1.97	Moderate
RR-1 (Riparian)	Adults	0.83	0.79	0.52	1.19	Low–Moderate
RR-2 (Riparian)	Adults	0.41	0.38	0.26	0.59	Low

HQ >1 = potential non-trivial health risk; HQ >2 = high risk. Risk levels: Low (<1), Low–Moderate (0.8–1.2), Moderate (1.0–1.5), Moderate–High (1.5–2.0), High (>2.0). RfD = 1.5 × 10^{-2} mg/kg-bw/day. Source: Author's analysis, 2024.

Discussion

Microplastic Loads in a West African Urban River Context

The microplastic concentrations documented in the River Benue (120–754 particles/L in water; 284–1,836 particles/kg dw in sediment) are broadly consistent with, and in some cases exceed, values reported for other West African urban rivers. (Trindade Da Silva et al., 2021) documented 93–248 particles/L in Lagos coastal waters, while Obi et al. (2019) reported 55–310 particles/L across Niger Delta waterways. The higher concentrations in this present study at commercial sites reflect the combination of a confined channel geometry at (Taftazani et al., 2022) and the concentration of informal market and motor-park activities immediately adjacent to the riverbank, where waste management infrastructure is minimal (Hodgson et al., 2022). The observed range falls within the upper quartile of values reported for tropical urban rivers in middle-income countries, comparable to findings from the Yangtze River tributaries in China and the Yamuna River in India (Esneu et al., 2025). The consistent elevation of wet-season concentrations (1.5–1.8× dry-season values) reflects the well-documented stormwater-flushing mechanism by which heavy rainfall mobilises terrestrially deposited microplastics into surface waters (Hamid et al., 2020). This seasonality has implications for public health monitoring: risk assessments based solely on dry-season sampling, will systematically underestimate population exposure, particularly for communities who increase fishing and river bathing activities during the wet season.

Land Use as the Primary Driver of Spatial Heterogeneity

The strong robust correlations between land use intensity indicators and microplastic concentrations confirm that spatial patterning of contamination in the River Benue is anthropogenic in origin rather than reflecting natural hydrological sorting processes alone. Impervious surface coverage ($\rho = 0.91$) is a widely used proxy for urban intensity and stormwater generation capacity; its relationship with microplastic loading is mechanistically coherent, as impervious surfaces concentrate runoff containing tyre wear particles, packaging fragments, and synthetic fibre deposits from garment washing and drying (Costall et al., 2020). The negative correlation with the Solid Waste Management Index ($\rho = -0.84$) provides direct evidence that inadequate formal waste infrastructure is a major enabler of riverine microplastic loading. The polymer composition data corroborate the land use interpretation. PET dominance at urban commercial sites is consistent with the ubiquitous use of PET beverage bottles in Nigerian markets, while PP dominance at agricultural sites reflects the widespread use of woven polypropylene grain bags and pesticide containers in Benue State's agricultural economy (Nassar et al., 2025). This source-specific polymer fingerprinting, enabled by μFTIR analysis, represents a methodological advancement over prior Nigerian microplastic studies that have relied solely on visual morphological classification (Halawani et al., 2022). Polymer fingerprinting not only elucidates sources but informs targeted reduction strategies, while extended producer responsibility (EPR) schemes targeting PET beverage producers or agricultural plastics take-back programmes (Noriega Luna et al., 2026).

Fibre Dominance and Implications for Characterisation Protocols

The dominance of fibres (54.7%) across all sites and both matrices was consistent with many global river microplastic (Di Vaira et al., 2022). Fibres <100 μm in diameter are susceptible to airborne contamination during laboratory processing and to undercount under stereo microscopy compared to automatic image analysis (Sadrizadeh et al., 2021). The use of positive pressure laminar flow hoods, cotton-only researcher garments, and procedural blank analysis in the present study mitigates but does not eliminate this risk. Future studies should employ automated flow cytometry or Raman spectroscopy to characterise sub-100 μm particles more reliably, especially given their greater bioavailability and potential for cellular internalisation (Wright et al., 2013).

Health Risk Assessment: Magnitude, Uncertainty, and Vulnerable Populations

The Monte Carlo HQ analysis reveals a concerning gradient of health risk across the Makurdi riparian population, with children residing near urban commercial sites facing HQ values at the 95th percentile that are three times the safety threshold. First, the HQ framework employed here is explicitly probabilistic, propagating uncertainty in exposure parameters and the toxicological reference dose through Monte Carlo simulation rather than applying deterministic point estimates a methodological improvement over the majority of microplastic health risk assessments in the African literature that report only mean-based HQ values (Chiletzari et al., 2025). Second, the model conservatively includes only two exposure pathways (water ingestion and fish consumption) (Elawady et al., 2026); ingestion of microplastic-contaminated soil during play by children, inhalation of airborne fibres, and consumption of microplastic-laden locally grown vegetables irrigated with river water are additional pathways that would further increase total EDI were they included (Ljungqvist et al., 2026). Third, the toxicological reference dose employed (1.5×10^{-2} mg/kg-bw/day) is provisional and derived from rodent studies; human epidemiological data linking specific microplastic doses to adverse health outcomes remain sparse (Hossain et al., 2026). The HQ approach therefore should be interpreted as a hazard screening tool rather than a definitive health impact quantification (X. Liu et al., 2025). Nevertheless, the convergent evidence from physicochemical characterisation (high particle loads (Li et al., 2023), PET and PS polymer types known to leach toxic additives), toxicological literature, and epidemiological signals (Riediker et al., 2019) justifies precautionary public health action, particularly for the children and women who spend most time along the riverbank in commercial zones for fishing, laundry and trading activities (Papac Zjačić et al., 2023).

Policy and Management Implications

The findings generate three interrelated categories of actionable recommendation. First, land use regulation and environmental impact assessment (EIA) requirements for commercial developments along the River Benue corridor should be strengthened and enforced, with mandatory stormwater microplastic filtration requirements for new market and motor-park developments exceeding a specified impervious surface threshold. Nigeria's Climate Change Act (2021) provides a legal basis for integrating plastic pollution control into environmental planning instruments (Siddiqui et al., 2023). Second, waste infrastructure investment in the most contaminated commercial zones, particularly along the Makurdi–Gboko Road corridor and the Wurukum area, which represents the highest-return intervention for reducing riverine microplastic loading, given the strong inverse relationship between the SWMI and microplastic concentrations. Targeted placement of waste collection points, incentivised reverse vending machines for PET bottles, and community-based shoreline clean-up programmes with formal disposal linkages should be prioritised (Sheriff et al., 2025). Third, the River Benue requires an operational, standardised microplastic monitoring programme to track temporal trends, evaluate intervention effectiveness, and provide early warning of deteriorating public health risk (Manono et al., 2026). Quarterly sampling with harmonised protocols based on guidelines, integrated into the existing water quality monitoring activities of the Benue State Water Board, would provide the minimum surveillance infrastructure required (Vincoff et al., 2024).

Study Strengths and Limitations

Strengths of this study include: stratified land use sampling design; dual-season sampling capturing hydrological variability; μFTIR polymer characterisation enabling source attribution; and probabilistic health risk modelling incorporating parameter uncertainty. Limitations include the relatively short study duration (6 months), precluding assessment of multi-year trends; the absence of longitudinal biological biomonitoring of fish or human blood/stool microplastic loads; restriction to the Makurdi reach. These limitations should be addressed in subsequent research building on this baseline.

Conclusion

This study provides spatially stratified, land use-integrated microplastic contamination assessment and probabilistic health risk quantification for the River Benue watershed in Makurdi, Nigeria. Surface water concentrations up to 754 particles/L and sediment concentrations up to 1,836 particles/kg dw, dominated by PET fibres and fragments, demonstrate that the River Benue is contaminated with microplastics, with concentrations varying with urban land use intensity. Wet-season stormwater doubles microplastic loads across all sites, underscoring the importance of year-round monitoring. Hazard Quotient estimates indicate non-trivial health risk for residents, especially children near high-load urban commercial sites, with 95th percentile HQ values exceeding 3 when combined water and fish consumption pathways are considered.

These findings have direct implications for environmental health governance in Makurdi and comparable Nigerian cities: urban land use regulation, solid-waste infrastructure investment, agricultural plastics management and systematic riverine monitoring are the highest-priority interventions. The integration of microplastic contamination into Nigeria's environmental impact assessment framework, drinking water quality standards, and climate-health adaptation plans is urgently warranted. Combining land use stratification, μFTIR polymer typing and Monte Carlo health risk modelling is transferable to other high-priority Nigerian and sub-Saharan African river systems where comparable data gaps persist.

Conflicts of Interest

The author declares no conflict of interest.

Author contribution

O. B. S: Conceptualization, methodology, validation, formal analysis, investigation; resources, data curation, writing-original draft preparation, writing-review and editing, visualization. All authors have read and agreed to the published version of the manuscript.

Declaration of generative AI in scientific writing

During the preparation of this work, the author utilized Google translate to assist with [Insert Purpose, e.g., brainstorming the conceptual framework, structuring the initial manuscript outline, or summarizing background literature]. The technology was used solely as an assistive tool to stimulate ideas. The final analysis, interpretation of data, and drafting of the manuscript were performed entirely by the human authors, who accept full accountability for the validity and originality of the work.

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