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Drivers of Microplastic Contamination in Tropical Freshwater: Evidence from Three Ethiopian Rift Valley Lakes

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ABSTRACT: Freshwater lakes in the Main Ethiopian Rift Valley are increasingly exposed to agricultural, urban, and industrial pressures, yet the drivers governing microplastic contamination across tropical lake systems remain poorly resolved. We quantified microplastics and water-quality parameters in Lakes Ziway, Hawassa, and Koka across 24 sites during the wet (July 2021) and dry (February 2022) seasons using coordinated manta trawling and depth-integrated bulk-water filtration, followed by wet peroxide oxidation, NaI density separation, and ATR-FTIR polymer identification. Microplastics were dominated by secondary particles, with fibers (45%) and fragments (32%) comprising the principal morphologies and Polyamide (48.2%), Polypropylene (30.1%), and Polyethylene (21.7%) as the dominant polymers. Mean microplastic concentrations increased significantly from 311 ± 34 particles m^{-3} in the dry season to 418 ± 34 particles m^{-3} during the wet season ($p < 0.001$), while Lakes Koka (485 ± 42 particles m^{-3}) and Hawassa (452 ± 42 particles m^{-3}) exhibited substantially greater contamination than Lake Ziway (288 ± 42 particles m^{-3}). Water chemistry showed pronounced seasonal variation, with elevated turbidity, sulfate, and nutrient concentrations during the wet season. Integration of ESA WorldCover land-use data with multivariate modeling revealed that the primary land-use gradient (PC1; 73% of variance), representing an urbanization–naturalness continuum, was significantly associated with microplastic density ($\beta = -35.44$, $p = 0.014$), explaining approximately 27% of the observed spatial variation, while substantial site-level effects indicated strong local environmental controls. Comparison of sampling methods further demonstrated that manta trawling underestimated microplastic abundance by approximately 288 particles m^{-3} relative to bulk-water filtration, indicating that surface-net surveys provide conservative estimates of contamination. Collectively, these findings demonstrate that microplastic pollution in tropical Rift Valley lakes is governed by interacting catchment-scale land use and seasonal hydrological transport, with local lake characteristics further modulating contamination patterns. This study provides one of the first integrated watershed-to-lake assessments of freshwater microplastics in East Africa and establishes a framework for understanding microplastic dynamics in rapidly urbanizing tropical catchments.

Keywords: Catchment urbanization, Microplastics, Multivariate modeling, Tropical African lakes, Wastewater management, Watershed disturbance

INTRODUCTION

Plastic pollution has emerged as one of the most pervasive environmental challenges of the Anthropocene, with microplastics (MPs; <5 mm) receiving particular attention because of their persistence, widespread occurrence, and potential ecological impacts (Thompson *et al*., 2004; Cole *et al*., 2011; Eriksen *et al*., 2014). Although research has largely focused on marine environments, freshwater ecosystems are increasingly recognized as important reservoirs, transport pathways, and sources of microplastics to downstream aquatic systems (Blettler *et al*., 2019; Koelmans *et al*., 2019).

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Lakes and reservoirs are especially susceptible to microplastic accumulation owing to their hydrodynamic retention, high shoreline-to-volume ratios, and close proximity to urban, agricultural, and industrial activities. Understanding the processes governing microplastic occurrence and distribution in inland waters is therefore essential for predicting their ecological fate and informing effective management, particularly in rapidly developing regions where plastic consumption and environmental pressures are increasing.

Across sub-Saharan Africa, freshwater ecosystems are undergoing rapid transformation driven by urbanization, agricultural intensification, industrial expansion, and population growth. These pressures are particularly evident in the Main Ethiopian Rift Valley, where lakes provide critical ecosystem services including drinking water, fisheries, irrigation, hydropower, and biodiversity conservation. However, accelerating watershed disturbance, shoreline modification, untreated wastewater discharge, and inadequate solid-waste management have substantially increased the risk of plastic pollution in these freshwater systems. Despite these growing pressures, the occurrence, transport, and environmental controls of microplastics in African inland waters remain poorly understood relative to Europe, North America, and Asia.

Existing studies from Ethiopian Rift Valley lakes have confirmed the presence of microplastics in sediments and aquatic biota, demonstrating that plastic contamination has become an emerging environmental concern. Sediment investigations in Lakes Ziway and Hawassa revealed moderate contamination levels and spatial differences in polymer composition associated with local anthropogenic activities (Mathewos Hailu *et al*., 2025), while commercially important fish species from Lake Hawassa exhibited widespread microplastic ingestion, highlighting potential ecological and food-web implications (Asrat Fekadu & Girma Tilahun, 2024). Jeevanandam *et al*. (2022) provided the first evidence of microplastics in Lake Hawassa, primarily focusing on sediment-associated contamination. Although these studies establish the presence of microplastics within Ethiopian Rift Valley lakes, they provide only limited insight into contamination within the water column, where particles remain mobile, biologically available, and directly influenced by hydrological processes. Consequently, the relative roles of watershed land use, seasonal hydrology, and lake-specific characteristics in regulating surface-water microplastic contamination remain largely unresolved.

Addressing this knowledge gap requires moving beyond single-lake assessments toward comparative studies that capture environmental gradients in watershed disturbance and hydrological connectivity. The Ethiopian Rift Valley provides an ideal natural laboratory because its lakes differ markedly in watershed land use, basin morphology, hydrological connectivity, and anthropogenic pressure while experiencing similar regional climatic conditions. Comparative analysis across these systems offers a unique opportunity to distinguish local influences from broader catchment-scale processes governing microplastic contamination.

In this study, we investigated microplastic abundance, composition, and distribution in the surface waters of three contrasting Ethiopian Rift Valley lakes, Lake Hawassa, Lake Ziway, and Lake Koka, during wet and dry hydrological seasons. We integrated standardized microplastic sampling with water-quality measurements and catchment-scale land-use characterization derived from ESA WorldCover datasets to evaluate the environmental drivers of microplastic contamination. We hypothesized that microplastic pollution is governed by a dual-control system in which (i) watershed land use establishes the baseline pollution potential through wastewater discharge, stormwater runoff, agricultural activities, and direct litter inputs, while (ii) seasonal hydrological processes regulate the transport, redistribution, and retention of microplastics within lake systems. Accordingly, we expected the urban, closed-basin Lake Hawassa to sustain consistently elevated microplastic concentrations, the agriculturally dominated open-basin Lake Ziway to exhibit pronounced wet-season increases associated with runoff, and the river-fed industrial reservoir Lake Koka to integrate cumulative upstream contamination. By combining watershed-scale analysis with seasonal field observations across three contrasting tropical lakes, this study provides one of the first mechanistic assessments of freshwater microplastic dynamics in East Africa and advances a conceptual framework for understanding how land use and hydrological processes jointly shape microplastic pollution in rapidly urbanizing tropical freshwater ecosystems.

MATERIALS AND METHODS

Study Area

Lakes in the Main Ethiopian Rift Valley are experiencing escalating contamination from microplastics, driven by intensifying agriculture, industry, and urban expansion (Mathewos Hailu et al., 2025; Lemessa Merga et al., 2020). To assess these pressures, we examined three lakes represent contrasting hydrological settings (open-basin, closed-basin and riverine reservoir) spanning a gradient of watershed disturbance. Lake Ziway is a shallow, open basin system receiving primarily agricultural and floriculture runoff (Dessie Tibebe et al., 2021). The closed basin Lake Hawassa is heavily impacted by untreated discharges from the adjacent city of Hawassa (Lencha et al., 2021), while the Koka Reservoir accumulates upstream urban, industrial, and agricultural pollutants from the Addis Ababa catchment, including inputs from the heavily contaminated Akaki rivers (Kassahun Tessema. et al., 2020). Collectively, these lakes provide a robust natural framework for disentangling the drivers of microplastic pollution and their relationships with water chemistry (Table 1).

Table 1. Morphometric and representative physicochemical characteristics of the study lakes in the Main Ethiopian Rift Valley (Dessie Tibebe. 2021, Lencha 2021, Lemessa 2020, Zinabu, 2002 and This Study).

Parameter	Lake Ziway	Lake Hawassa	Lake Koka
Elevation (m a.s.l.)	1636	1685	1590
Surface Area (km²)	440	94	180
Maximum Depth (m)	9	22	15
Mean Depth (m)	2.5-4	11	9.0
pH	8.0-9.5	7.5-9.0	8.0-9.0
Electrical Conductivity (µS/cm)	200-450	700-1300	350-680
Total Phosphorus (µg/L)	100-370	370-1900	100-920
Chlorophyll-a (µg/L)	20-150	25-150	100-215

Sampling design

Sampling was conducted during the wet (July 2021) and dry (February 2022) seasons. Across the three lakes, 96 samples were collected (48 per season) from a total of 24 stations (4-12) per lake, with station numbers allocated based on lake surface area and shoreline complexity). Stations were selected to capture the full spatial heterogeneity of each lake, including inflow zones, pelagic sites, and densely impacted nearshore areas (Figure 1). All water samples were collected at 0-50 cm depth to target the surface microlayer, where buoyant pollutants and high biological activity are concentrated. In situ parameters (temperature, dissolved oxygen, pH, electrical conductivity) were measured using a calibrated multiparameter probe (HI9829; Hanna Instruments).

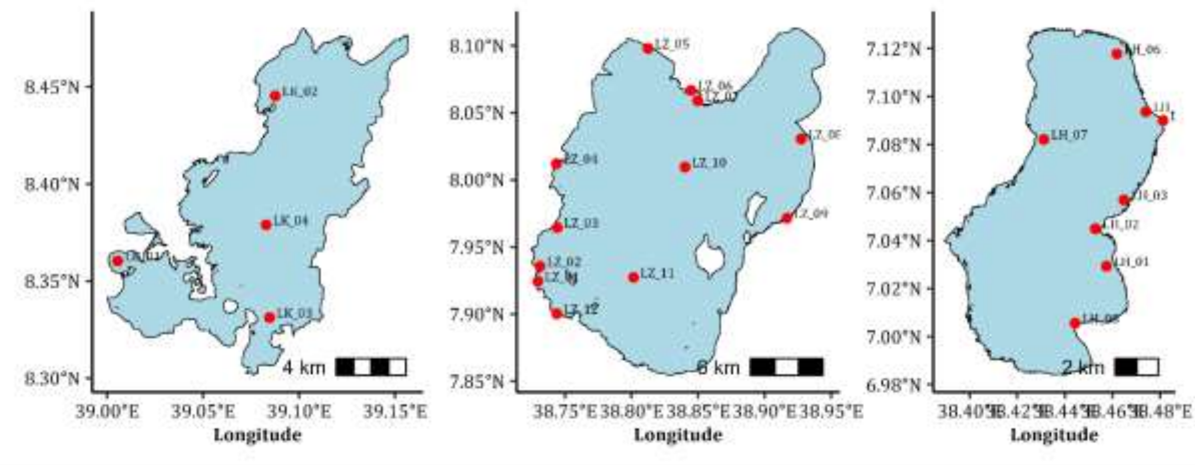

Figure 1 Lakes Koka, Ziway and Hawassa (with sampling points)

Chemical analysis

Water samples for nutrient and ion analyses were field-filtered (0.45 µm) into acid washed bottles, stored on ice, and processed within 24 h. Major cations (Na^{+}, K^{+}, Ca^{2+}, Mg^{2+}) were quantified using flame photometry (FP910 Flame Photometer). Nutrients (NO_3^{-}, NO_2^{-}, NH_4^{+}, SRP, SO_4^{2-}) were measured with a discrete Analyzer (SEAL Analytical AQ400) following standard colorimetric protocols.

Microplastic sampling and processing

Microplastics (MPs) were sampled using two complementary approaches (Bottle sampling and Manta Trawling) targeting different size fractions. Buoyant macro and meso-sized particles were collected via surface trawling with a 150 µm Manta net towed for ~5 min at 2–3 knots, with water volume measured by a flowmeter. Smaller particles were captured through depth-integrated filtration of 20 L of surface water through a 150 µm stainless steel sieve. To minimize contamination, equipment was rinsed with filtered deionized water, cotton laboratory coats were worn, and field and laboratory blanks were processed concurrently; procedural blanks contained <3 particles per filter or trawl and were subtracted from counts. Organic matter was removed via wet peroxide oxidation conducted using 30% H_2O_2 at 65°C for 48 hours. This temperature was maintained to ensure efficient organic matter digestion without damaging the structural integrity of the microplastics, and density separation was performed using Sodium iodide (NaI) ($\rho \approx 1.8$ g cm^{-3}) and repeated three times with to maximize recovery. Particles were sieved (150 µm), dried, and stored until analysis. The lower size limit of 150 µm for microplastic analysis was determined by the smallest mesh size of the sieves used in this study. We acknowledge that this excludes smaller microplastics (<150 µm) and therefore our results likely represent an underestimation of the total microplastic abundance. Sorted particles were photographed and classified by morphology, color, and size. A minimum of 30% of particles from each lake were analyzed by ATR-FTIR (Bruker ALPHA II, 4000–400 cm^{-1}, 32 scans at 4 cm^{-1}) using a diamond ATR and DTGS detector. Spectra were processed with OPUS software, corrected for CO_2 and humidity, and matched to the KnowItAll™ polymer library (Wiley Science Solutions, 2023). Polymer identity was confirmed at ≥90% match confidence, with most exceeding 95%, and the lowest accepted value being 92.84% after manual verification.

Catchment land use analysis

Catchment boundaries were delineated using HydroBASINS and HydroLAKES (Linke *et al*, 2019), and land-use/land-cover (LULC) characteristics were derived from ESA WorldCover 2021 (10 m resolution) (Buchhorn *et al*, 2020). LULC fractions were extracted for each lake's immediate hydrological sub-catchment. Principal Component Analysis (PCA) was used to summarize LULC variation across catchments. Particular emphasis was placed on the proportion of built-up area as a proxy for urbanization intensity (Figure 2).

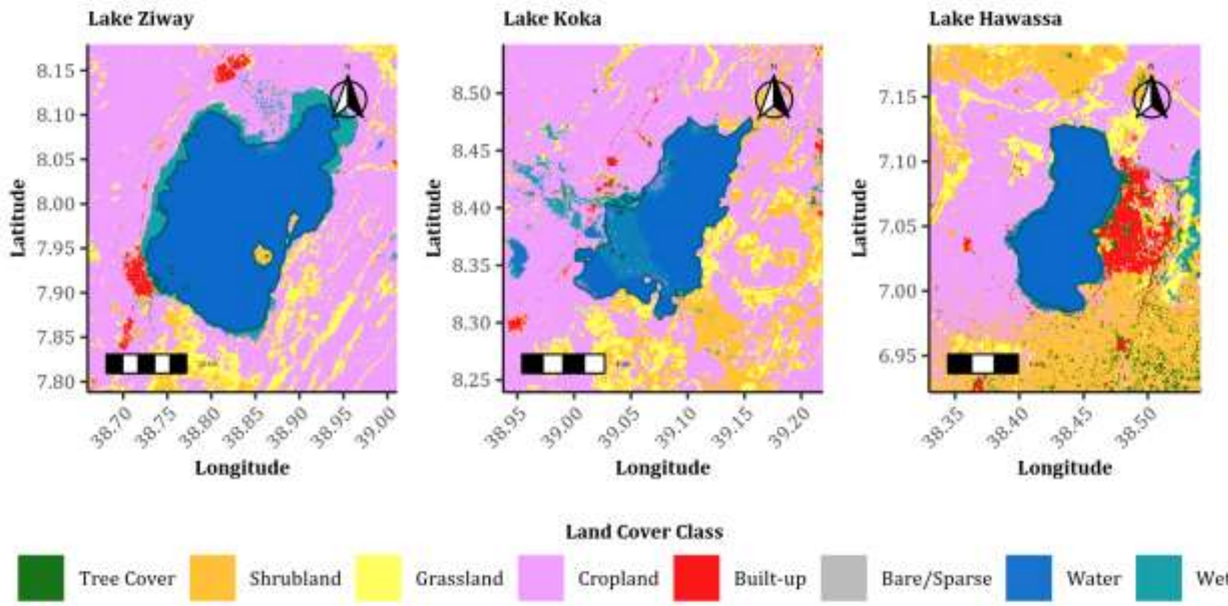

Figure 2. Land use/ Land cover around the watershed of Ethiopian rift valley lakes

Statistical Analysis

All analyses were performed in R (v4.4.3) (R Core Team, 2025). Microplastic densities were log-transformed prior to modeling to stabilize variance and reduce skewness. Seasonal effects on water chemistry and microplastic concentrations were assessed using linear mixed-effects models (LMMs; lme4 package), with Season and the first two principal components of environmental variables (PC1, PC2) as fixed effects and Lake as a random intercept to account for repeated measurements across lakes. Model assumptions, including homoscedasticity, normality, and leverage, were evaluated via residual diagnostics using the DHARMa package (Hartig, 2023), and conditional and marginal R^2 values were calculated using MuMIn (Barton, 2023). Multivariate variation in water chemistry was examined using PERMANOVA (adonis2, 999 permutations) following standardization and verification of homogeneous dispersion. Principal Component Analysis (PCA) was used to visualize major environmental gradients, while Redundancy Analysis (RDA) assessed the influence of land use and land cover (LULC) predictors. Methodological differences between trawling and filtration were evaluated using Bland–Altman analysis and Deming regression. Finally, variance partitioning was performed to quantify the relative contributions of spatial (lake, site) and temporal (season) factors to observed variability.

RESULTS

Spatial and Seasonal Controls on Water Chemistry

Water chemistry showed clear spatial and seasonal differentiation across the three lakes. A Principal Components Analysis (PCA) identified two major gradients influencing this variation. The dominant gradient, PC1 (64.5% of total variance) represented a spatial gradient dominated by ionic composition, with strong negative loadings for conductivity, sodium, and potassium. PC2 (18.2% of total variance) captured a seasonal gradient characterized by increases in turbidity, sulfate, SRP, and nitrate during the wet season.

This seasonal effect was statistically confirmed, with mixed-effects modeling showing several parameters increasing significantly during the wet period, notably SRP ($\beta = 0.025 \pm 0.010$ mg L^{-1}, $p = 0.012$). A PERMANOVA test further established the strong and significant spatial separation of the lakes ($R^2 = 0.91$, $p < 0.001$), confirming that each lake possesses a unique chemical fingerprint. While all three systems were chemically responsive to the change in seasons, the magnitude of the shift differed geographically: Lake Koka experienced the most intense ionic changes, while Lake Ziway displayed broader, more comprehensive seasonal variations across multiple chemical parameters.

Microplastic Concentrations and Spatial Hierarchy

Microplastic densities displayed pronounced spatial and seasonal patterns. Concentrations were significantly higher during the wet season ($F_{1,69}$ = 21.38, $p < 0.001$) and importantly, this seasonal increase was consistent across all three lakes, as indicated by the non-significant lake × season interaction. However, a significant spatial effect was also observed, with Lakes Koka and Hawassa exhibiting higher overall microplastic densities compared to Lake Ziway ($F_{2,21}$ = 9.85, $p < 0.001$).

Seasonal patterns differed by lake: Lake Ziway showed 12% wet-season increase; Lake Hawassa showed 22.7% increase; Lake Koka showed 23% increase (strongest signal), consistent with its riverine hydrology transporting upstream contamination.

Variance partitioning revealed a strong hierarchical spatial structure, with differences among lakes and sampling sites explaining 82% of total variance. A high degree of within-lake clustering (Intraclass Correlation Coefficient ICC = 0.63) suggests that local, site-level conditions within each lake contribute meaningfully to the final microplastic distribution, including tributaries, shoreline activities, and local hydrodynamics.

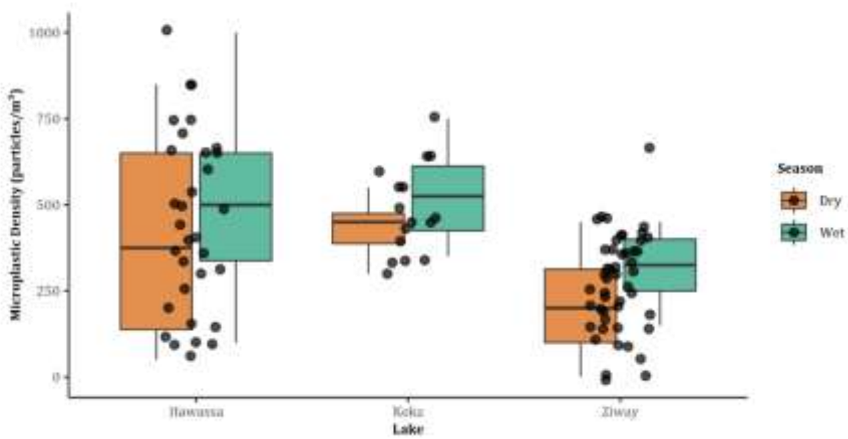

Figure 3. Microplastic Density (particles/m³) across Lakes and Seasons

Catchment Land Use as a Driver of Microplastic Contamination

The land use patterns within the catchments surrounding the three lakes differed significantly, and these differences were directly linked to microplastic contamination levels. A Principal Components Analysis (PCA) of the Land Use/Land Cover (LULC) variables identified two key components driving catchment differences. PC1 (73.0% of variance) represented a naturalness gradient, with positive loadings for natural and aquatic cover and negative loadings for urban and shrubland areas. PC2 (27.0% of variance) reflected the relative extent of agricultural and grassland areas (

Figure 4).

Mixed-effects modeling confirmed the strong influence of catchment land use on microplastic accumulation by identifying a significant negative association between microplastic density and the naturalness gradient (PC1: β = –35.44, p = 0.014). This suggests that catchments with less natural cover (i.e., higher urban/shrubland areas) exhibited greater microplastic contamination. The seasonal effect remained highly significant, with wet-season concentrations consistently elevated ($p < 0.001$).

This land-use inference is based on lake-level LULC aggregation (n=3), which limits statistical robustness. The reported p-value should be interpreted as suggestive rather than definitive.

Incorporation of the PC1 variable into the model reduced the previously observed among-lake variance by approximately 27%, demonstrating that catchment-level land use explains a substantial portion of the overall spatial structure in microplastic distribution. Nevertheless, considerable residual site-level variance indicates that additional, highly localized factors continue to influence microplastic accumulation.

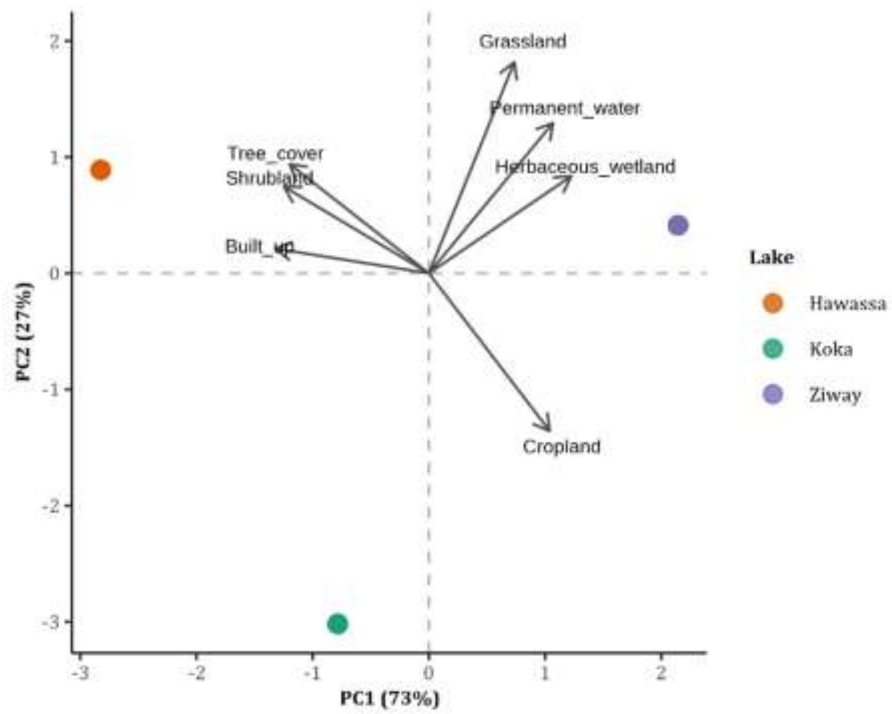

Figure 4 Biplot of principal components analysis showing LULC variable relationships and lake sample distributions. Arrows represent variable loadings scaled to indicate contribution strength to PC1 (73%) and PC2 (27%).

Method Agreement and Bias Assessment

Microplastic concentrations obtained from trawling and filtration showed limited agreement, indicating the methods are not interchangeable. Although significantly correlated ($r = 0.682$, $p < 0.001$), overall concordance was low (CCC = 0.384), and Bland-Altman analysis (Figure 5) revealed both systematic and proportional bias, with trawling consistently underestimating concentrations relative to filtration (mean difference = -287.5 particles m^{-3}; 95% CI: -350.2 to -224.7) and wide 95% limits of agreement (-965.0 to +390.1 particles m^{-3}).

These findings highlight a critical methodological constraint in active trawling approaches and support the use of filtration- or pump-based sampling as the preferred standard for quantitative assessments of microplastic abundance in freshwater environments. Where trawling is unavoidable, application-specific conversion factors and uncertainty bounds should be explicitly reported to account for systematic bias. Accordingly, all abundance estimates reported are based on filtration-derived measurements to ensure methodological consistency and minimize underestimation bias.

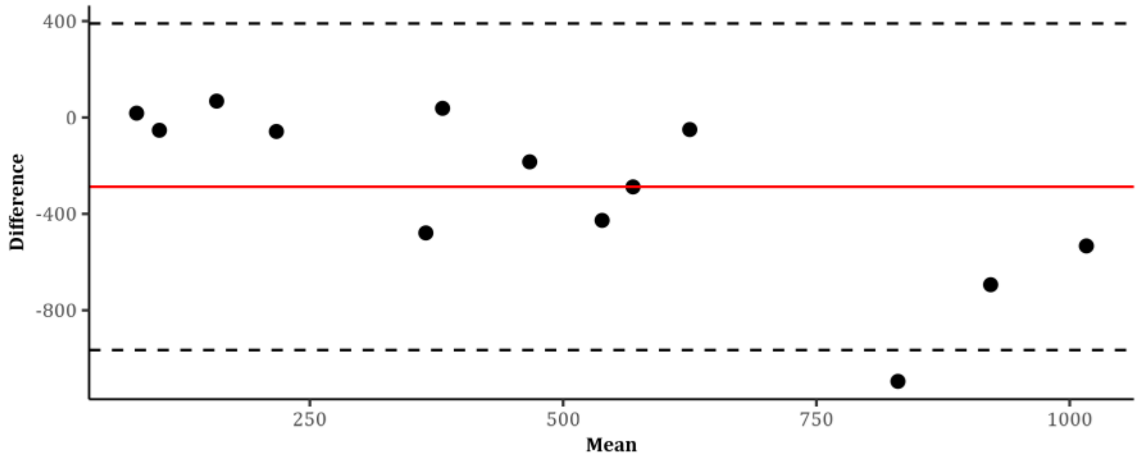

Figure 5 Bald-Altman plot for trawl and filtrattion based MP assesment

Microplastic Morphology, Size Distribution, Color, and Polymer Composition

Across the three lake systems, polymer composition exhibited clear spatial variability, with consistent dominance patterns across analytical approaches reflecting differing contamination sources. ATR-FTIR spectroscopy identified three primary polymer types overall: polyamide (PA) (48.2%), polypropylene (PP) (30.1%), and polyethylene (PE) (21.7%). Lake-specific patterns further revealed marked spatial differentiation. Lake Koka and Lake Ziway were both characterized by strong PA contributions, accounting for 53.3% and 48.6% of identified polymers, respectively, whereas Lake Hawassa exhibited a more balanced structure with PA, PP, and PE at 29.2%, 33.3%, and 33.3%, respectively. This PA-enriched signature across multiple lakes is consistent with substantial inputs from textile-derived microplastics, particularly fibers. In contrast, Lake Koka was additionally distinguished by a relatively higher contribution of polypropylene (33.3%), indicating a stronger influence of fragment-based sources, while polyethylene was generally less abundant but present across all systems. PE was most prominent in Lake Hawassa and the Ziway–Korokonch station (LZ_01), where it occurred primarily as fragments and filaments, suggesting localized inputs from packaging and secondary degradation pathways.

Microplastics size distributions also varied across the lakes, spanning a wide range from approximately 150 µm to nearly 5,000 µm. Mean particle sizes were broadly similar among systems, ranging from about 2,070 µm in Lake Koka to 2,420 µm in Lake Hawassa, with medians clustered between ~1,700 and 2,200 µm. Lake Koka and Lake Ziway were both dominated by the 1,000–2,000 µm fraction (40.6% and 35.5%, respectively), indicating a concentration of medium-sized particles. Lake Ziway additionally exhibited substantial proportions of 2,000–3,000 µm (25.0%) and >4,000 µm particles (17.1%), indicating a broader and more heterogeneous size structure. Lake Hawassa showed the greatest proportion of larger size microplastics, with particles >4,000 µm comprising 21.9%, alongside a relatively even distribution across intermediate classes, suggesting enhanced retention or aggregation of larger debris within this system.

Morphological characterization confirms that the microplastic assemblage across all lakes was overwhelmingly dominated by secondary forms, with fragments and fibers representing 51.2% and 44.0% of particles, respectively, while primary forms such as pellets and spheroids were absent. This dominance of secondary microplastics aligns with the observed polymer fragmentation patterns and supports the interpretation that textile-derived fibers and degraded plastic fragments are the principal pathways of contamination. Size structure further reflects this process, with particles <2,000 µm constituting 48.8% of the total assemblage, indicating progressive breakdown of larger debris. Spatially, Lake Hawassa was distinguished by a comparatively coarser assemblage with a higher proportion of particles exceeding 4,000 µm, whereas Lake Koka and the Ziway–Ketar (LZ_06) station exhibited greater contributions of finer microplastics below approximately 1,500–2,000 µm, reinforcing inter-lake differences in transport and retention dynamics. Chromatic composition was dominated by blue (33.7%) and translucent (33.7%) particles, followed by red (16.9%), suggesting shared sources such as textiles, packaging materials, and consumer plastics.

Collectively, the comparative assessment highlights pronounced inter-lake heterogeneity in polymeric composition, particle morphology, and size structure, reflecting differences in pollution sources, hydrodynamic conditions, and environmental processing. Lakes Koka and Ziway share a PA-dominated, fiber-rich profile strongly indicative of textile-related inputs, whereas Lake Hawassa represents a more diversified polymer environment with a balanced composition and a distinctly coarser size signature. Lake Koka additionally shows stronger PP fragment influence, while PE is comparatively enriched in Lake Hawassa and the Ziway–Korokonch (LZ_01) station, highlighting localized source inputs and degradation pathways. These consistent yet system-specific differences underscore the importance of lake-tailored microplastics management strategies that account for both source pathways and in-lake transport and transformation dynamics.

DISCUSSION

Hydrology, seasonal rainfall, and watershed activities govern the spatial and seasonal variability of chemical composition in Ethiopian Rift Valley lakes. Roughly half of basin precipitation becomes runoff and baseflow, sustaining inflows that create the dominant spatial gradient (PC1) of conductivity, sodium, and potassium (Truneh *et al*. 2023). Wet season pulses elevate nutrients and ions, while dry-season evaporation concentrates solutes (Zinabu 2002). Catchment erosion, agricultural runoff, and urban effluents strongly drive nutrient dynamics in Lake Ziway (Mechal *et al*. 2024), whereas Lake Koka shows contamination hotspots near the Awash River from upstream industrial and agricultural inputs (Kasahun *et al*. 2020). Together, these hydrological and watershed processes explain the pronounced spatial differentiation among lakes (PERMANOVA R^2 = 0.91) and seasonal shifts in SRP, turbidity, nitrate, and sulfate, reflecting combined climatic and land-use pressures.

A Dual Control System for Microplastic Pollution in Ethiopian Rift Valley Lakes

Our results indicate that microplastic pollution in the Ethiopian Rift Valley lakes is governed by a dual-control system: seasonal hydrology modulates transport, while catchment land use sets the baseline pollution potential. Microplastic densities were significantly higher during the wet season (EMM = 418 ± 34 particles m^{-3}) than the dry season (EMM = 311 ± 34 particles m^{-3}), consistent with global hydrological contaminant transport patterns (Windsor *et al*., 2019). The consistent seasonal pattern across all three lakes supported by a non-significant lake and season interaction ($F_{2,69}$ = 0.19, p = 0.827) suggests that regional hydrology, rather than lake-specific characteristics, primarily drives temporal variability.

Variance partitioning revealed a hierarchical spatial structure, with differences among lakes and sampling sites explaining 82% of total variance and a site-level ICC of 0.63, indicating strong small-scale clustering likely driven by tributaries, shoreline activities, and local hydrodynamics (Baldwin *et al*., 2016). Lake-specific differences were evident: Lake Koka (EMM = 485 ± 42 SE particles m^{-3}) and Lake Hawassa (EMM = 452 ± 42 SE particles m^{-3}) exhibited higher densities than Lake Ziway (EMM = 288 ± 42 SE particles m^{-3}), reflecting stronger anthropogenic pressures, proximity to urban centers, and intensive agriculture. Absolute concentrations surpass many global freshwater systems, approaching heavily polluted urban lakes in Asia (**Error! Reference source not found.**), positioning the Ethiopian Rift Valley as a critical pollution hotspot. These extreme loads likely result from rapid urbanization without adequate wastewater treatment, limited solid waste management, and lake-specific hydrology.

Principal component analysis (PCA) reduced multicollinearity among LULC predictors, with PC1 (76% variance) representing an urbanization gradient. PC1 showed a significant negative association with microplastic density (Estimate = -36.2, SE = 13.8, p = 0.014), confirming catchment land cover as a key regulator of pollution, likely via wastewater, stormwater, road runoff, and improper solid waste disposal (Siegfried *et al.*, 2017; Chen *et al.*, 2020). The absence of interactions with season indicates that land cover effects persist year-round, establishing a baseline pollution level subsequently modulated by hydrology (Truneh *et al*. 2023).

A key caveat is that our land-use inference is based on contrasts among only three lakes n=3 at the catchment level), which limits statistical robustness and may produce artificially p-values. Consequently, this specific landscape finding should be interpreted as suggestive rather than definitive; it requires broad validation across a larger set of regional lake systems incorporating high-resolution, site-level land-use metrics.

Compared to other African lakes, concentrations in the Ethiopian Rift Valley are substantially higher than those reported for Lake Naivasha (Kenya; 0-0.633 particles m^{-2}) and Lake Victoria (0.02-2.19 particles m^{-3}) (Migwi *et al.*, 2020; Egessa *et al.*, 2020). This suggests that the Ethiopian Rift Valley may represent a regional microplastic pollution hotspot, warranting prioritized management attention.

Table 2 Global Microplastics Concentrations in Freshwater Systems. Microplastics concentrations are presented as particles/m³ where available from literature

Lake / System	Region	Country	Particles/m³	Reference
Lake Neuchâtel	Europe	Switzerland	0.061	Negrete *et al*., 2020
Lake Bolsena	Europe	Italy	0.82 - 4.42	Fischer *et al*., 2016
Great Lakes	North America	USA	1.9 (median)	Baldwin *et al*., 2016
Lake Superior	North America	USA	830 - 1,400	Fox *et al*., 2022
Akmola Region Lakes	Asia	Kazakhstan	120 - 450	Salikova *et al*., 2024
Cherating River	Asia	Malaysia	1,660 - 8,925	Pariatamby *et al*., 2020
Wuhan Lakes	Asia	China	4,000 - 26,000	Salikova *et al*., 2017
Mountain Lakes	Asia	Kazakhstan	~34,000	Madibekov *et al*., 2023
Lake Koka	Africa	Ethiopia	340.6	This study
Lake Ziway	Africa	Ethiopia	622.4	This study
Lake Hawassa	Africa	Ethiopia	660.9	This study
Lake Naivasha	Africa	Kenya	Up to 0.633 (Areal: m ²)	Migwi *et al*., 2020
Lake Victoria	Africa	Uganda/Kenya	0.02 - 2.19	Egessa *et al*., 2020

Together, these findings illustrate a dual control system: catchment urbanization sets pollution potential, while seasonal hydrology governs temporal pulses. This framework has direct management implications, suggesting targeted interventions such as stormwater filtration in urbanized catchments and timing mitigation strategies to coincide with wet-season peaks.

Methodological Considerations for Microplastic Monitoring

Trawling consistently underestimating concentrations (mean difference = -287.5 particles m^{-3}; 95% limits of agreement = -965.0 to +390.1 particles m^{-3}) due to size selectivity (Bland & Altman, 1986; De la Torre *et al.*, 2022). Consequently, all results reported here rely on filtration, which captures smaller particles missed by trawls. While relative trends (seasonal contrasts, lake rankings, land use relationships) remain robust, absolute concentrations are conservative estimates of total microplastic loads. These findings highlight the importance of consistent, fine-scale sampling for future monitoring and ecotoxicological assessments in inland waters.

Source Attribution and Ecological Implications of Polymer Types

The dominance of Polyamide (PA) (48.2%) and Polypropylene (PP) (30.1%) across the studied lakes highlights distinct anthropogenic input sources. The high prevalence of PA, particularly in Lakes Ziway and Hawassa, strongly suggests inputs from multiple pathways. In addition to degradation of abandoned, lost, or discarded fishing gear (ALDFG), where nylon (polyamide) is widely used in gillnets and other fishing equipment, mechanical abrasion and UV exposure contribute to progressive fragmentation into secondary microplastics (Karl *et al*., 2025; Pagnotta, 2025). While fisheries-related ALDFG likely contributes substantially to PA loads, particularly in Lakes Ziway and Hawassa where gillnet fishing is intensive, domestic wastewater from laundering synthetic textiles represents an equally important and continuous source of PA fibers (Browne *et al*., 2011; Cesa *et al*., 2020). Distinguishing between these sources would require additional forensic analysis, such as polymer-specific marker compounds. Given the proximity of urban settlements and limited wastewater treatment infrastructure in the Ethiopian Rift Valley, particularly around Lakes Ziway and Hawassa, textile-derived fiber inputs likely represent a substantial and continuous source of PA contamination alongside fisheries-related inputs. Additionally, the significant proportion of fibers (44.0%) observed in this study is consistent with a composite signal of both fishing-related nylon degradation and domestic wastewater discharge, as PA and polyester fibers are heavily shed during the laundering of synthetic textiles (Cesa, *et al*., 2020).

In contrast, the elevated levels of PP and Polyethylene (PE) fragments, particularly in Lake Koka, mirror global trends associated with the breakdown of single use packaging and agricultural plastics. PP and PE are the most produced polymers globally for packaging materials (Real 2022). Their presence as fragments indicates that larger debris entered the lake system, likely via riverine runoff or direct littering and underwent physical fragmentation due to wave action and photo-oxidative weathering (Andrady 2022).

The prevalence of blue (33.7%) and translucent (33.7%) microplastics is consistent with the coloration of common fishing lines and beverage packaging (Martí *et al*. 2020). This coloration poses an ecological risk, as aquatic organisms frequently mistake blue and transparent particles for prey such as copepods or plankton, leading to ingestion and potential trophic transfer (Xiong *et al*. 2019). The absence of primary microplastics (pellets) further confirms that plastic pollution in these lakes is almost exclusively derived from the breakdown of secondary consumer products rather than industrial spillage.

Beyond the direct physical impacts of ingestion, the predominance of weathered secondary microplastics in these lakes raises concern over the "Trojan Horse" effect, whereby microplastics act as vectors for co-occurring chemical and biological contaminants. Owing to their large specific surface area, hydrophobicity, and progressive surface oxidation during environmental weathering, microplastics readily adsorb heavy metals, persistent organic pollutants, antibiotics, and pathogenic microorganisms from surrounding waters (Rochman *et al*., 2013; Holmes *et al*., 2012; Li *et al*., 2018). This mechanism is particularly relevant in the Ethiopian Rift Valley, where Lakes Koka and Ziway receive substantial industrial effluents, agricultural runoff, and untreated municipal wastewater, introducing elevated concentrations of metals and microbial contaminants (Kasahun *et al*., 2020; Mechal *et al*., 2024). Following ingestion by aquatic organisms, these contaminant-laden particles may enhance exposure through desorption within the gastrointestinal tract or by transporting microbial biofilms, thereby increasing toxicological and ecological risks beyond the physical effects of plastic ingestion alone. Such interactions may contribute to oxidative stress, impaired reproduction, altered feeding behavior, and facilitate the transfer of contaminants through aquatic food webs, highlighting that the ecological consequences of microplastic pollution depend not only on particle abundance but also on their role as mobile carriers of hazardous substances (Rochman *et al*., 20 13; Hartmann *et al*., 2019; Li *et al*., 2018).

CONCLUSION

Microplastic (MP) pollution in the Ethiopian Rift Valley is governed by a dual control system: catchment land use establishes baseline contamination, while seasonal hydrology modulates transport. Our tri lake comparison confirmed this framework, with higher MP densities in the riverine fed, industrial impacted Lake Koka and the urban, closed basin Lake Hawassa compared to agricultural Lake Ziway. Wet season rainfall acts as a key transport vector, delivering substantial pulses of MPs from surrounding catchments.

Resulting concentrations, among the highest recorded in African freshwater systems, position the Ethiopian Rift Valley as an emerging hotspot, posing significant ecological and socioeconomic risks. Management should focus on source reduction in urban and industrial catchments and transport mitigation (e.g., stormwater management) timed to intercept wet season peaks.

Methodologically, Manta trawling systematically underestimates total MP abundance, missing the numerically dominant small size fraction. Future monitoring and ecotoxicological studies must consider this dual control system and employ filtration or pump-based methods to accurately quantify environmental risk.

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