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Research Article

Effects of Microplastic Pollution on Microalgal Diversity and Community Structure in River Ginzo, Katsina State, Northwestern Nigeria

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ABSTRACT
Microplastic pollution is an emerging threat to freshwater systems, yet its effects on microalgal communities in northern Nigeria remain poorly understood. This study investigated microplastic occurrence, seasonal distribution, characteristics, polymer composition, and association with microalgal diversity and community structure in River Ginzo, Katsina State, Nigeria. Water samples were collected from nine stations at Kofar Marusa, Kofar Sauri, and Kofar Durbi during dry (March–May) and wet (June–August) seasons in 2025. Microplastics were extracted using sieving, peroxide digestion, density separation, filtration, and microscopy, with polymers confirmed by Fourier-transform infrared spectroscopy. Physicochemical parameters, microalgal abundance, diversity, and chlorophyll-a were determined using methods. Microplastic abundance ranged from 12.6 to 31.8 particles L^{-1} and was higher during the wet season, with Kofar Marusa as the contamination hotspot. Fibres predominated, followed by fragments and films, while polyethylene, polypropylene, and polyethylene terephthalate were dominant polymers. Wet-season increases in electrical conductivity, dissolved solids, turbidity, biochemical oxygen demand, oxygen demand, nitrate, and phosphate indicated enhanced runoff, organic loading, and contaminant transport. Twenty-five microalgal taxa from six divisions were identified, dominated by Bacillariophyta, Chlorophyta, and Cyanobacteria. Kofar Durbi recorded the highest microalgal abundance, chlorophyll-a, richness, diversity, and evenness, whereas Kofar Marusa showed reduced diversity and greater cyanobacterial and euglenophyte dominance. Principal Component Analysis showed seasonal environmental structuring, with the first two components explaining 92.0% of variance. The concurrence of elevated microplastic abundance and reduced microalgal diversity at Kofar Marusa suggests ecological stress, although nutrient enrichment, organic pollution, turbidity, and anthropogenic pressures may also influence responses.

Keywords: Biodiversity; Microalgae; Microplastics; Physicochemical parameters; River Ginzo

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INTRODUCTION

Plastic pollution has emerged as one of the most pressing environmental issues of the twenty-first century due to the exponential increase in global plastic production and the persistence of plastic materials in natural ecosystems (Jiao *et al*., 2024). Global plastic production has increased from approximately 2 million metric tonnes in the 1950s to over 400 million metric tonnes annually, with a substantial proportion eventually entering terrestrial and aquatic environments through improper waste disposal, industrial activities, wastewater discharge, agricultural runoff, and atmospheric deposition (Hossain & Engelhardt, 2025; Jiao *et al*., 2024). Unlike many conventional pollutants, plastics exhibit remarkable environmental persistence because of

their resistance to biological degradation, allowing them to accumulate and fragment into progressively smaller particles under the influence of ultraviolet radiation, mechanical abrasion, oxidation, and microbial activity (Ibrahim *et al*., 2025; Jolaosho *et al*., 2025). Microplastics, generally defined as plastic particles smaller than 5 mm in diameter, have attracted considerable scientific attention owing to their ubiquitous occurrence, persistence, and potential ecological risks (Yang *et al*., 2022). These particles originate either as primary microplastics intentionally manufactured for industrial or commercial applications or as secondary microplastics formed through the fragmentation of larger plastic debris in the environment (Zhang *et al*., 2020). Because of their small size, low density, and resistance to degradation, microplastics are readily transported through riverine systems, where they accumulate within the water column, sediments, and aquatic biota (Aib *et al*., 2025; Bhan *et al*., 2025).

Freshwater ecosystems have increasingly been recognized as major reservoirs and transport pathways for microplastics from terrestrial sources to marine environments (Zhao *et al*., 2024). Rivers receive substantial quantities of plastic debris through municipal wastewater, stormwater runoff, agricultural drainage, industrial discharges, landfill leachates, and atmospheric deposition (Emole *et al*., 2026; Zhao *et al*., 2024). Consequently, freshwater environments often contain complex mixtures of polymer types, particle sizes, and morphologies that vary according to land use, population density, hydrological conditions, and waste management practices (Range *et al*., 2023). The ecological concern extends beyond MP abundance because particles can interact with organisms and other contaminants. Their surfaces may adsorb metals, persistent organic pollutants, pharmaceuticals, while weathering and biofilm development can modify particle reactivity and biological interactions. African aquatic ecosystems increasingly contain MPs, including polyethylene, polypropylene, polyethylene terephthalate, fibres, and fragments (Nyaga *et al*., 2024). Evidence from Nigerian inland rivers confirms widespread microplastic (MP) contamination across aquatic compartments. Doherty et al. (2024) investigated fishes, sediment, and water from inland rivers spanning Nigeria's six geopolitical zones, including the Yauri, Benue, Argungu, Jamare, Ogun, Ethiope, and Orashi Rivers, and detected MPs in all examined matrices, with fibres particularly dominant in water and fish. Similarly, Ugosor et al. (2025) reviewed MP contamination across Nigerian aquatic ecosystems, highlighting evidence from rivers, lagoons, estuaries, sediments, seafood, and drinking-water systems. Recent studies have further documented MPs in River Benue, North-Central Nigeria, including both surface water and sediment, while Agbozu and Okorodo (2025) reported MPs in sediments of River Nun, Niger Delta, southern Nigeria. Collectively, these studies demonstrate that MP contamination is geographically widespread in Nigerian freshwater systems and occurs in water, sediment, and aquatic biota.

Microalgae are particularly important because they constitute major primary producers, contribute to oxygen production and carbon fixation, and support food webs. Their abundance, biomass, and diversity respond rapidly to environmental disturbance, making microalgal communities useful indicators of freshwater ecological change (Yong *et al*., 2016). Increasing evidence shows that MPs can inhibit algal growth and photosynthesis, induce oxidative stress, damage cells, and interfere with nutrient acquisition. Effects vary with particle size, concentration, polymer type, morphology, exposure duration, and algal taxon (Liu *et al*., 2021). A recent meta-analysis reported substantial inhibition of photosynthesis and growth in freshwater microalgae exposed to micro- and nanoplastics, with marked taxon-specific responses (Guo *et al*., 2024). Nevertheless, field-based evidence linking environmental MP contamination with natural microalgal community structure remains limited, particularly in tropical African freshwater systems.

River Ginzo in Katsina State, northwestern Nigeria, is used for domestic activities, irrigation, livestock watering, and other socioeconomic purposes. Existing studies demonstrate the presence and ecological relevance of microalgae in the River Ginzo system, including *Chlorella*, *Chlorogonium*, and *Microcystis* associated with municipal wastewater (Umar *et al*., 2021). However, the relationship between MP contamination, physicochemical water quality, and resident microalgal communities has not been adequately characterized. Therefore, this study investigated the seasonal distribution, abundance, characteristics, and polymer composition of MPs in River Ginzo and evaluated their relationships with physicochemical conditions, microalgal abundance, biomass, and community diversity. The study provides baseline evidence for assessing ecological risks, strengthening freshwater monitoring, and supporting pollution management in northern Nigeria.

MATERIALS AND METHODS

Study Area

The study was conducted along River Ginzo, an urban freshwater river in Katsina Metropolis, Katsina State, northwestern Nigeria. Katsina State extends approximately from 11°08′ to 13°22′ N and 6°52′ to 9°20′ E. The area has a tropical continental climate characterized by a prolonged dry season (October–May) and a shorter wet season (June–September). Annual rainfall is generally 600–800 mm, concentrated between July and August, while temperatures range from about 22°C to above 38°C. Three sections, Kofar Marusa, Kofar Sauri, and Kofar Durbi, were selected after reconnaissance surveys because of residential development, roadside commerce, drainage discharge, washing, irrigation, livestock activities, and waste disposal. These sections represented a gradient for assessing MP contamination and microalgal responses.

Study Design

A repeated seasonal field survey was conducted from March to August 2025. March–May represented the dry season, whereas June–August represented the wet season. Monthly sampling was performed at predetermined stations using a repeated-measures design, with triplicate samples collected independently at each station. The design enabled assessment of spatial and seasonal variation in MPs, water quality, and microalgal communities. Figure 1 presents the locations of the nine sampling stations.

Sampling Stations

Nine stations were established approximately 500 m apart according to accessibility, channel characteristics, surrounding land use, and proximity to potential pollution sources. Stations were grouped as Kofar Marusa (KM1–KM3), Kofar Sauri (KS1–KS3), and Kofar Durbi (KD1–KD3). At every monthly visit, three replicate surface-water samples were collected from each station, providing replication for laboratory analyses.

Surface-Water Collection

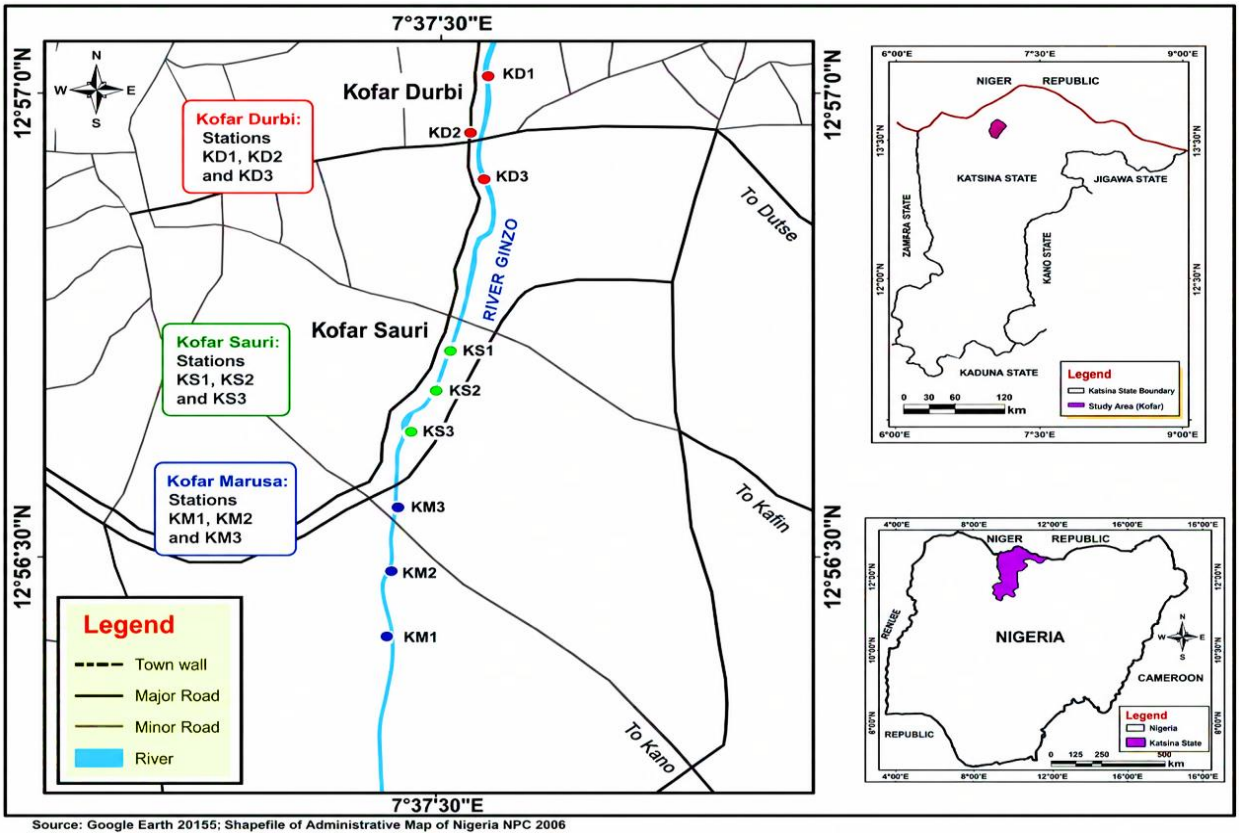
Sampling was undertaken between 08:00 and 10:00 h to reduce potential diurnal variation in water-quality. Glassware and sampling equipment were washed with laboratory detergent, rinsed with deionized water, and conditioned with site water before collection. 1 L of surface water was collected 20–30 cm below the water surface using cleaned 1-L amber borosilicate glass bottles with aluminium-foil-lined caps. Glass containers were used to minimize plastic contamination. Samples were stored at 4°C and transported promptly for analysis according to Standard Methods (Baird *et al*., 2017).

Physicochemical Analysis

Temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), and turbidity were measured in situ using a calibrated portable multiparameter meter following the manufacturer's instructions. Laboratory analyses were conducted immediately after sample arrival. Biochemical oxygen demand (BOD5) was determined using the five-day incubation procedure, while chemical oxygen demand (COD) was determined by the closed-reflux colorimetric method. Nitrate and phosphate were quantified spectrophotometrically according to the 24th edition of Standard Methods, which provides standardized procedures for water analyses (APHA, 2005; Baird *et al*., 2017).

Microplastic Extraction and Characterization

MP extraction followed Wootton *et al*. (2025), with modifications for river water. Each 1-L sample was passed through a 5-mm stainless-steel sieve to remove large debris. Organic matter was digested with approximately 50 mL of 30% H_2O_2, followed by incubation at 60°C for 24 h. Hydrogen-peroxide treatment is effective for removing natural organic matter while supporting subsequent polymer characterization (Maw *et al*., 2022). Density separation was then performed using saturated $ZnCl_2$ solution (approximately 1.6–1.7 g cm−3) to recover polymers across a broad density range. After 24 h settling, the supernatant was decanted and vacuum-filtered through pre-weighed Whatman GF/F glass-fibre filters (0.7 µm) using an all-glass filtration assembly. Filters were transferred to covered glass Petri dishes, protected with foil, and dried at room temperature. Suspected particles were examined at 10×–80× magnification and categorized as fibres, fragments, films, foams, or pellets. Polymer identity was confirmed using Fourier-transform infrared spectroscopy (FTIR) with an attenuated total reflectance (ATR) accessory. Spectra were acquired from 4000–400 cm−1 at 4 cm−1 resolution using 32 scans per particle. Spectral profiles were matched against commercial polymer libraries, and identifications were accepted when the similarity index was ≥70%. MP abundance was expressed as particles L−1, and polymer types and morphologies were reported as percentages.



Source: Google Earth 20155; Shapefile of Administrative Map of Nigeria NPC 2006

Figure 1. Map of River Ginzo, Katsina State, Nigeria, showing the nine selected microplastic sampling stations

Microalgal Sampling, Identification and Enumeration

Microalgal samples were collected concurrently with water samples. 1 L was collected at 20–30 cm depth using sterile amber glass bottles and immediately preserved with Lugol's iodine solution to a final concentration of 1%. Samples were refrigerated during transport. Identification and enumeration followed standard freshwater phytoplankton procedures (APHA, 2005 ; Odeh *et al*., 2023). Samples settled for 24 h before enumeration. Counts were performed using a Sedgwick–Rafter counting chamber under an Olympus BX53 compound microscope at 100×, 400×, and, where necessary, 1000× magnification. Taxa were identified using morphology, dimensions, pigmentation, colony organization, chloroplast characteristics, frustule features, and reproductive structures. Community structure was evaluated using Shannon–Wiener (H'), Simpson (1−D), Margalef richness (Dmg), and Pielou evenness (J') indices (Magurran, 2021).

Chlorophyll-a Determination

Chlorophyll-a was measured as an indicator of phytoplankton biomass following APHA (2005). A 500-mL aliquot was filtered through a Whatman GF/F filter under low vacuum. Pigments were extracted in 90% acetone in darkness at 4°C for 24 h. Extracts were centrifuged at 5000 rpm for 10 min, and absorbance was measured at 664, 647, 630, and 750 nm using a UV–visible spectrophotometer. Turbidity correction was applied using the 750-nm reading, and chlorophyll-a was expressed as µg L−1.

Quality Assurance and Contamination Control

Contamination-control procedures were applied throughout sampling and processing. Glass or metal equipment was preferentially used, and all working surfaces were cleaned before processing. Samples and filters were kept covered whenever possible. Laboratory personnel wore natural-fibre laboratory clothing, and synthetic materials were avoided during MP processing. Procedural blanks consisting of filtered deionized water were processed alongside samples to identify airborne or procedural contamination. Suspected particles observed in blanks were recorded and used to correct sample counts where necessary. Physicochemical instruments were calibrated before deployment, and analyses were performed in triplicate. These measures followed established recommendations for improving comparability and minimizing false-positive MP identification (Duis & Coors, 2016; L. Yang *et al*., 2021).

Data Analysis

All experimental data were expressed as mean ± standard deviation (SD) based on three replicates (n = 3). Descriptive statistics were used to summarize microplastic abundance, particle characteristics, physicochemical parameters, microalgal abundance, chlorophyll-a concentration, and diversity indices across sampling stations and seasons. Differences in microplastic abundance, environmental variables, and microalgal community attributes among sampling stations and between dry and wet seasons were evaluated using one-way analysis of variance (ANOVA), followed by Tukey's post-hoc test at a significance level of $p < 0.05$. Pearson correlation analysis was performed to assess relationships between microplastic abundance, physicochemical parameters, and microalgal characteristics. Principal Component Analysis (PCA) was applied to identify major environmental gradients and variables influencing spatial and seasonal patterns. Microalgal diversity was assessed using species richness, Shannon–Wiener diversity, Simpson diversity, and Pielou's evenness indices. Statistical analyses were performed using SPSS version 26.0, while graphical presentations were generated using OriginPro. All statistical tests were conducted at a 95% confidence level.

RESULTS

Physicochemical Characteristics of River Ginzo Water

The mean physicochemical characteristics of River Ginzo water during the dry and wet seasons are presented in Table 1. The results showed clear seasonal and spatial variations in most of the measured parameters. Water temperature was generally higher during the dry season, ranging from 31.88 ± 0.43 to 33.41 ± 0.62 °C, compared with 27.61 ± 0.42 to 29.26 ± 0.41 °C during the wet season. The highest temperature was recorded at KM during the dry season, while the lowest occurred at KD during the wet season. All temperature values differed significantly ($P < 0.05$). The pH values indicated slightly neutral to mildly alkaline conditions during the dry season (7.48–7.74) but decreased during the wet season (6.74–7.18). KM and KS showed no significant difference during the dry season, whereas the remaining values differed significantly ($P < 0.05$). Electrical conductivity (EC) and total dissolved solids (TDS) were consistently higher during the wet season. EC increased from 421.6–462.7 µS cm^{-1} in the dry season to 531.8–591.5 µS cm^{-1} in the wet season, while TDS increased from 269.2–293.4 mg L^{-1} to 341.5–374.7 mg L^{-1}, respectively. These parameters were highest at KM and lowest at KD in both seasons. Dissolved oxygen (DO) exhibited the opposite pattern, with lower values during the dry season (5.21–5.69 mg L^{-1}) than during the wet season (6.08–6.42 mg L^{-1}). The highest DO concentration was recorded at KM during the wet season, while the lowest was observed at KM during the dry season. Turbidity increased markedly during the wet season, from 15.8–18.5 NTU in the dry season to 38.7–49.3 NTU, with KM recording the highest values in both seasons. Similarly, BOD_5 and COD were considerably higher during the wet season. BOD_5 increased from 3.18–3.82 mg L^{-1} during the dry season to 4.48–5.26 mg L^{-1} during the wet season, whereas COD increased from 15.4–17.6 mg L^{-1} to 22.8–26.8 mg L^{-1}. Nutrient concentrations also showed pronounced seasonal variation. Nitrate concentrations increased from 2.97–3.42 mg L^{-1} in the dry season to 4.51–5.16 mg L^{-1} in the wet season, while phosphate increased from 0.48–0.61 mg L^{-1} to 0.77–0.92 mg L^{-1}.

Table 1: Mean physicochemical characteristics of River Ginzo water during the dry (March, April, and May) and wet (June, July, and August) seasons

Parameter	KM (Dry)	KS (Dry)	KD (Dry)	KM (Wet)	KS (Wet)	KD (Wet)
Temperature (°C)	33.41 ± 0.62^{a}	32.57 ± 0.51^{b}	31.88 ± 0.43^{c}	29.26 ± 0.41^{d}	28.47 ± 0.37^{e}	27.61 ± 0.42^{f}
pH	7.74 ± 0.10^{a}	7.62 ± 0.08^{a}	7.48 ± 0.09^{b}	7.18 ± 0.12^{c}	6.95 ± 0.10^{d}	6.74 ± 0.09^{e}
EC (µS cm^{-1})	462.7 ± 14.3^{c}	438.4 ± 12.5^{d}	421.6 ± 10.9^{e}	591.5 ± 18.6^{a}	564.2 ± 17.4^{b}	531.8 ± 15.8^{c}
TDS (mg L^{-1})	293.4 ± 8.5^{c}	281.6 ± 7.9^{d}	269.2 ± 8.1^{e}	374.7 ± 9.7^{a}	359.3 ± 9.2^{b}	341.5 ± 8.8^{c}
DO (mg L^{-1})	5.21 ± 0.28^{d}	5.47 ± 0.24^{c}	5.69 ± 0.21^{b}	6.42 ± 0.26^{a}	6.26 ± 0.23^{a}	6.08 ± 0.25^{a}
Turbidity (NTU)	18.5 ± 1.3^{d}	16.7 ± 1.2^{e}	15.8 ± 1.0^{e}	49.3 ± 2.6^{a}	43.8 ± 2.2^{b}	38.7 ± 1.9^{c}
BOD_5 (mg L^{-1})	3.82 ± 0.29^{c}	3.47 ± 0.26^{d}	3.18 ± 0.23^{e}	5.26 ± 0.34^{a}	4.91 ± 0.31^{b}	4.48 ± 0.28^{c}
COD (mg L^{-1})	17.6 ± 1.2^{c}	16.3 ± 1.1^{d}	15.4 ± 0.9^{e}	26.8 ± 1.4^{a}	24.9 ± 1.3^{b}	22.8 ± 1.2^{c}
Nitrate (mg L^{-1})	3.42 ± 0.18^{c}	3.18 ± 0.15^{c}	2.97 ± 0.14^{d}	5.16 ± 0.23^{a}	4.82 ± 0.21^{b}	4.51 ± 0.19^{b}
Phosphate (mg L^{-1})	0.61 ± 0.04^{c}	0.55 ± 0.03^{c}	0.48 ± 0.03^{d}	0.92 ± 0.05^{a}	0.84 ± 0.04^{b}	0.77 ± 0.04^{b}

Means within the same row bearing different superscript letters differ significantly according to Tukey's HSD test ($P < 0.05$). KM = Kofar Marusa; KS = Kofar Sauri; KD = Kofar Durbi.

Principal Component Analysis (PCA) revealed a clear separation of River Ginzo sampling stations according to season (Figure 2). PC1 and PC2 explained 73.6% and 18.4% of the total variance, respectively, accounting for 92.0% of the overall variation in the physicochemical dataset. All wet-season stations (KM, KS, and KD) were positioned on the positive side of PC1, whereas dry-season stations were predominantly associated with negative PC1 scores, indicating strong seasonal differentiation in water-quality characteristics. The positive PC1 axis was strongly associated with EC, TDS, turbidity, COD, BOD_5, nitrate, and phosphate, suggesting that these parameters contributed substantially to the physicochemical characteristics of the wet-season samples. In contrast, pH, temperature, and DO showed negative PC1 loadings, indicating their stronger association with the dry-season conditions. Along PC2, temperature and pH contributed positively, whereas DO showed a negative relationship. The clustering of KM, KS, and KD wet-season samples further indicates relatively similar physicochemical conditions during the rainy period, while the dispersion of dry-season stations suggests greater spatial heterogeneity. **Spatial and Seasonal Distribution of Microplastic Abundance**

The spatial and seasonal distribution of microplastics in River Ginzo is presented in Table 2. Microplastic abundance showed a clear seasonal and spatial variation across the sampling stations. During the dry season, concentrations ranged from 24.8 ± 1.6 to 32.8 ± 2.4 particles L^{-1}, with the highest values recorded at KM and the lowest at KD. Microplastic abundance increased progressively from March to May at all stations. During the wet season, considerably higher microplastic concentrations were recorded, ranging from 33.1 ± 2.3 to 45.6 ± 3.1 particles L^{-1}. The highest abundance occurred at KM in August (45.6 ± 3.1 particles L^{-1}), whereas the lowest was observed at KD in June (33.1 ± 2.3 particles L^{-1}). At each sampling month, the general spatial pattern was KM > KS > KD, with significant differences among stations ($P < 0.05$).

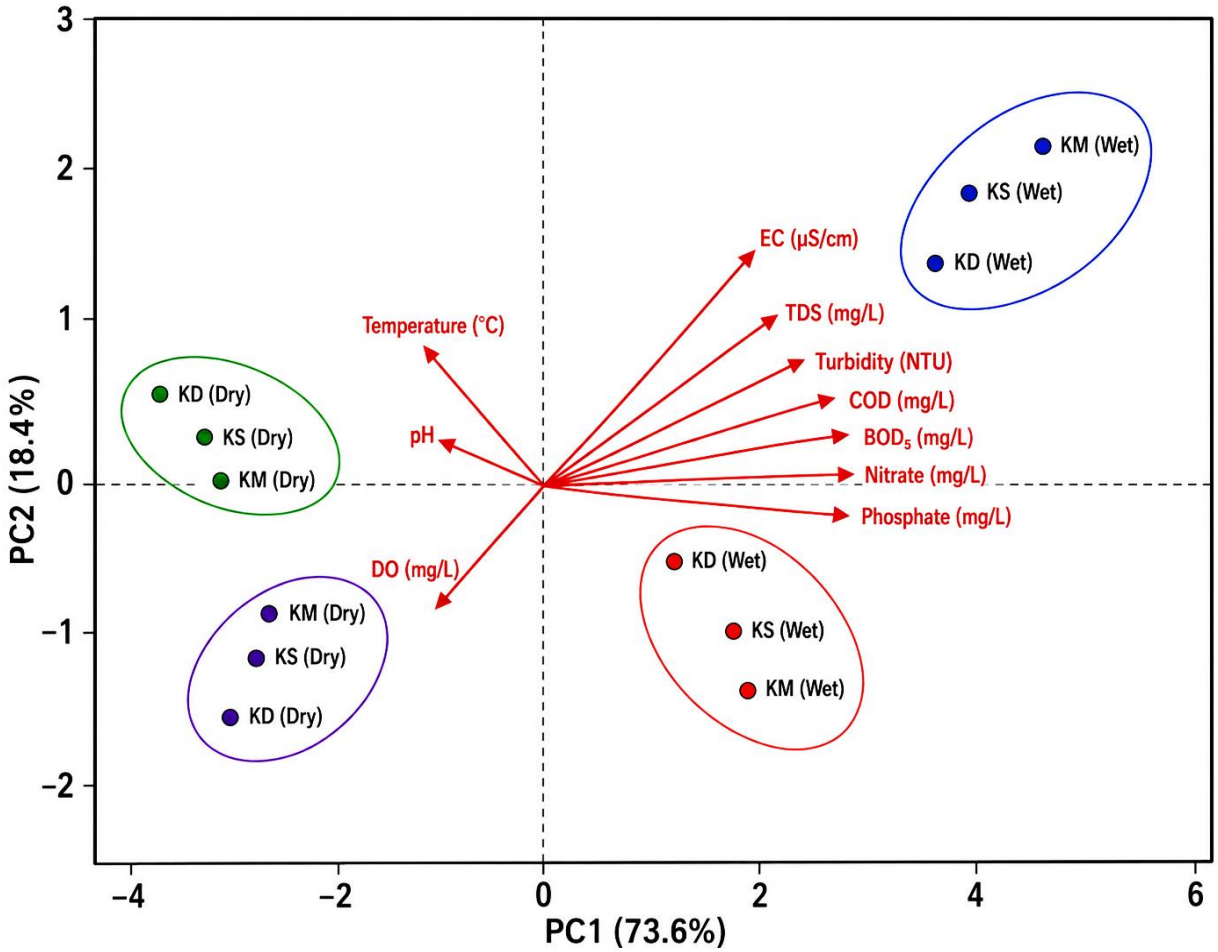


Figure 2: Principal Component Analysis (PCA) biplot showing the relationships between physicochemical parameters and sampling stations of River Ginzo water during the dry and wet seasons

Table 2. Spatial and seasonal distribution of microplastic abundance in River Ginzo, Katsina State, Nigeria

Season	Month	KM (particles L^{-1})	KS (particles L^{-1})	KD (particles L^{-1})
Dry	March	28.7 ± 2.1^{a}	26.4 ± 1.8^{b}	24.8 ± 1.6^{c}
	April	30.5 ± 2.3^{a}	28.1 ± 2.0^{b}	26.3 ± 1.8^{c}
	May	32.8 ± 2.4^{a}	30.2 ± 2.1^{b}	28.5 ± 1.9^{c}
Wet	June	37.6 ± 2.7^{a}	35.2 ± 2.5^{b}	33.1 ± 2.3^{c}
	July	41.8 ± 2.9^{a}	39.3 ± 2.7^{b}	36.7 ± 2.5^{c}
	August	45.6 ± 3.1^{a}	42.8 ± 2.9^{b}	40.2 ± 2.7^{c}

Monthly Distribution of Microplastic Shapes

The distribution of microplastic shapes varied both spatially and seasonally across the three sampling stations (Table 3). Fibres constituted the dominant microplastic shape throughout the study period, accounting for 35.8–49.3% of the total particles recovered. Fibre abundance increased progressively from the dry season (March–May) to the wet season (June–August), with the highest proportion recorded at Kofar Marusa (KM) in August (49.3 ± 2.9%), followed by KS (47.2 ± 2.7%) and KD (45.8 ± 2.5%). In contrast, fragments were the second most abundant category, contributing 24.2–32.8%, and generally exhibited a declining trend during the wet season. Films accounted for 13.7–17.0%, while foams (7.3–8.9%) and pellets (5.3–5.6%) were consistently the least represented particle types throughout the study. Significant differences ($P < 0.05$) were observed among the sampling stations for most particle categories within each month, with KM consistently recording higher fibre proportions than KS and KD. The seasonal increase in fibres during the rainy months indicates enhanced transport of textile fibres and degraded plastic materials into River Ginzo through stormwater runoff, municipal wastewater discharge, and surface drainage.

Table 3. Monthly distribution of microplastic shapes (%) across the sampling stations in River Ginzo, Katsina State, Nigeria

Month	Station	Fibres	Fragments	Films	Foams	Pellets
March	KM	38.7 ± 2.1^{a}	30.8 ± 1.8^{b}	16.4 ± 1.2^{c}	8.5 ± 0.7^{d}	5.6 ± 0.5^{e}
	KS	36.9 ± 1.9^{a}	31.9 ± 1.7^{b}	16.8 ± 1.1^{c}	8.8 ± 0.6^{d}	5.6 ± 0.4^{e}
	KD	35.8 ± 1.8^{b}	32.8 ± 1.6^{a}	17.0 ± 1.1^{c}	8.9 ± 0.7^{d}	5.5 ± 0.4^{e}
April	KM	40.4 ± 2.2^{a}	29.6 ± 1.7^{b}	16.1 ± 1.1^{c}	8.3 ± 0.7^{d}	5.6 ± 0.5^{e}
	KS	38.5 ± 2.0^{a}	30.7 ± 1.7^{b}	16.6 ± 1.1^{c}	8.7 ± 0.7^{d}	5.5 ± 0.4^{e}
	KD	37.6 ± 1.9^{b}	31.5 ± 1.6^{a}	16.8 ± 1.0^{c}	8.7 ± 0.7^{d}	5.4 ± 0.4^{e}
May	KM	42.6 ± 2.3^{a}	28.2 ± 1.7^{b}	15.8 ± 1.0^{c}	8.0 ± 0.6^{d}	5.4 ± 0.4^{e}
	KS	40.7 ± 2.1^{a}	29.5 ± 1.6^{b}	16.0 ± 1.0^{c}	8.4 ± 0.7^{d}	5.4 ± 0.4^{e}
	KD	39.5 ± 2.0^{b}	30.3 ± 1.6^{a}	16.2 ± 1.0^{c}	8.6 ± 0.7^{d}	5.4 ± 0.4^{e}
June	KM	45.1 ± 2.6^{a}	26.8 ± 1.9^{b}	14.9 ± 1.2^{c}	7.8 ± 0.7^{d}	5.4 ± 0.5^{e}
	KS	43.2 ± 2.4^{a}	27.9 ± 1.8^{b}	15.3 ± 1.1^{c}	8.2 ± 0.7^{d}	5.4 ± 0.5^{e}
	KD	42.0 ± 2.3^{b}	28.8 ± 1.7^{a}	15.5 ± 1.1^{c}	8.3 ± 0.7^{d}	5.4 ± 0.5^{e}
July	KM	47.6 ± 2.8^{a}	25.5 ± 1.9^{b}	14.1 ± 1.1^{c}	7.4 ± 0.6^{d}	5.4 ± 0.5^{e}
	KS	45.5 ± 2.5^{a}	26.7 ± 1.8^{b}	14.8 ± 1.1^{c}	7.7 ± 0.6^{d}	5.3 ± 0.5^{e}
	KD	44.2 ± 2.4^{b}	27.6 ± 1.8^{a}	15.0 ± 1.0^{c}	7.9 ± 0.7^{d}	5.3 ± 0.4^{e}
August	KM	49.3 ± 2.9^{a}	24.2 ± 1.8^{b}	13.7 ± 1.0^{c}	7.3 ± 0.6^{d}	5.5 ± 0.5^{e}
	KS	47.2 ± 2.7^{a}	25.5 ± 1.8^{b}	14.2 ± 1.0^{c}	7.8 ± 0.7^{d}	5.3 ± 0.4^{e}
	KD	45.8 ± 2.5^{b}	26.6 ± 1.7^{a}	14.5 ± 1.0^{c}	7.8 ± 0.7^{d}	5.3 ± 0.4^{e}

*Means within the same month and microplastic category followed by different superscript letters are significantly different among sampling stations according to Tukey's HSD test (**$P < 0.05$**). KM = Kofar Marusa; KS = Kofar Sauri; KD = Kofar Durbi*

Monthly Distribution of Microplastic Colours

The colour composition of microplastics also exhibited clear spatial and seasonal variations (Table 4). Transparent particles were the predominant colour category, representing 26.8–36.8% of the recovered particles across all stations and months. Their proportion increased steadily from March to August, reaching a maximum at KM (36.8 ± 2.2%) during August. Blue particles were the second most abundant colour, accounting for 24.1–26.5%,

followed by black particles (16.5–20.8%). White particles contributed between 9.8% and 13.5%, whereas green particles represented 5.2–8.2% of the total microplastics. Red and yellow particles occurred at relatively lower frequencies, contributing less than 4.2% and 2.5%, respectively. The proportion of transparent particles increased during the wet season, while black, white, green and yellow particles showed slight reductions across the sampling period. Significant spatial differences ($P < 0.05$) were evident among the sampling stations, with KM consistently exhibiting higher proportions of transparent and blue particles than KS and KD. These findings suggest that weathered packaging materials, polyethylene films, sachet-water plastics, and domestic plastic wastes constitute the primary sources of coloured microplastics entering River Ginzo.

Monthly Distribution of Microplastic Polymer Types

The polymer composition of microplastics identified by FTIR analysis is presented in Table 5. Polyethylene (PE) was the most dominant polymer throughout the study, accounting for 31.8–40.3% of all identified particles. PE abundance increased markedly from the dry season to the wet season, reaching its highest value at KM (40.3 ± 2.4%) in August. Polypropylene (PP) was the second most abundant polymer, contributing 22.1–25.6%, followed by polyethylene terephthalate (PET) with 17.4–19.5%. Lower proportions were recorded for polyvinyl chloride (PVC) (7.8–9.8%), polystyrene (PS) (5.8–6.9%), polyamide (PA) (3.2–5.2%), and polyurethane (PU) (1.7–3.7%). Significant differences ($P < 0.05$) were observed among sampling stations for all major polymer types, with KM consistently recording the highest PE concentrations throughout the monitoring period. The increasing dominance of PE during the wet season reflects enhanced mobilisation of plastic bags, sachet-water wrappers, food packaging materials, and other household plastic wastes into the river via rainfall-induced runoff. The polymer profile (PE > PP > PET > PVC > PS > PA > PU) indicates that domestic and municipal plastic wastes constitute the principal sources of microplastic contamination in River Ginzo during both the dry and wet seasons.

Pearson Correlation Analysis

Pearson correlation analysis revealed strong and consistent relationships among the microplastic morphological, polymer, and colour characteristics in River Ginzo (Figure 3). Morphological characteristics showed a strong negative correlation between fibres and the other morphological categories ($r = -0.95$ to -0.99), whereas fragments, films, foams, and pellets were strongly positively correlated with one another ($r = 0.96–0.99$). This indicates that increasing fibre abundance was associated with a corresponding reduction in the relative contribution of the other morphological forms. Similarly, the polymer composition exhibited predominantly strong positive correlations among PP, PET, PVC, PS, PA, and PU ($r = 0.95–1.00$), while PE was strongly negatively correlated with the remaining polymer types ($r = -0.97$ to -0.99). The exceptionally high correlations among several polymer categories indicate that their distributions varied in a highly coordinated manner across the sampling observations. The colour characteristics also demonstrated strong relationships. Transparent microplastics showed strong negative correlations with all other colour categories ($r = -0.97$ to -0.99), whereas blue, black, white, green, red, and yellow particles were strongly positively correlated ($r = 0.96–0.99$).

Hierarchical Cluster Analysis of Microplastics

Hierarchical cluster analysis (HCA) based on Euclidean distance and Ward's method revealed five distinct clusters among the River Ginzo sampling observations when microplastic morphological, colour, and polymer characteristics were considered jointly (Figure 4). The clustering showed a clear temporal pattern, with samples from the later sampling months generally separating from those collected during the earlier months. Cluster 1 comprised the KM samples from July to August and was characterized by the highest relative abundance of microplastic fibres and polyethylene (PE). Cluster 2 included KM–June and KS/KD samples from July to August, also exhibiting relatively high fibre and PE contributions. Cluster 3 consisted predominantly of KS and KD samples from March–April, together with KD–May, and was associated with comparatively lower fibre and PE proportions. Cluster 4, represented mainly by KM samples from March–April, showed lower-to-intermediate levels of fibres and PE. Cluster 5 comprised KM/KS–May and KS/KD–June, displaying an intermediate microplastic compositional profile.

Table 4. Mean monthly distribution of microplastic colours (%) across the sampling stations in River Ginzo, Katsina State

Month	Station	Transparent	Blue	Black	White	Green	Red	Yellow
March	KM	28.9 ± 1.7^{b}	25.4 ± 1.5^{a}	19.8 ± 1.2^{a}	12.6 ± 0.9^{b}	7.3 ± 0.6^{c}	3.8 ± 0.3^{d}	2.2 ± 0.2^{e}
	KS	27.6 ± 1.6^{c}	24.8 ± 1.4^{a}	20.2 ± 1.1^{a}	13.1 ± 0.9^{a}	7.8 ± 0.6^{b}	4.0 ± 0.3^{d}	2.5 ± 0.2^{e}
	KD	26.8 ± 1.5^{c}	24.1 ± 1.4^{b}	20.8 ± 1.2^{a}	13.5 ± 0.8^{a}	8.2 ± 0.6^{a}	4.2 ± 0.3^{c}	2.4 ± 0.2^{e}
April	KM	29.7 ± 1.8^{b}	25.7 ± 1.5^{a}	19.3 ± 1.1^{a}	12.1 ± 0.8^{b}	7.0 ± 0.5^{c}	3.9 ± 0.3^{d}	2.3 ± 0.2^{e}
	KS	28.4 ± 1.7^{c}	25.2 ± 1.4^{a}	19.8 ± 1.1^{a}	12.8 ± 0.9^{a}	7.5 ± 0.6^{b}	4.0 ± 0.3^{d}	2.3 ± 0.2^{e}
	KD	27.5 ± 1.6^{c}	24.6 ± 1.4^{b}	20.3 ± 1.2^{a}	13.2 ± 0.8^{a}	8.0 ± 0.6^{a}	4.1 ± 0.3^{c}	2.3 ± 0.2^{e}
May	KM	31.2 ± 1.9^{a}	25.5 ± 1.4^{b}	18.7 ± 1.1^{b}	11.5 ± 0.8^{c}	6.8 ± 0.5^{c}	4.0 ± 0.3^{d}	2.3 ± 0.2^{e}
	KS	29.8 ± 1.8^{b}	25.1 ± 1.4^{b}	19.3 ± 1.1^{b}	12.2 ± 0.8^{b}	7.2 ± 0.5^{b}	4.1 ± 0.3^{c}	2.3 ± 0.2^{e}
	KD	28.9 ± 1.7^{c}	24.5 ± 1.4^{c}	19.8 ± 1.1^{a}	12.8 ± 0.8^{a}	7.7 ± 0.6^{a}	4.0 ± 0.3^{c}	2.3 ± 0.2^{e}
June	KM	33.4 ± 2.0^{a}	25.8 ± 1.5^{b}	17.9 ± 1.1^{c}	10.9 ± 0.8^{c}	6.3 ± 0.5^{c}	3.8 ± 0.3^{d}	1.9 ± 0.2^{e}
	KS	32.1 ± 1.9^{b}	25.3 ± 1.5^{b}	18.4 ± 1.1^{b}	11.6 ± 0.8^{b}	6.8 ± 0.5^{b}	3.9 ± 0.3^{c}	1.9 ± 0.2^{e}
	KD	31.0 ± 1.8^{c}	24.8 ± 1.4^{c}	19.1 ± 1.1^{a}	12.1 ± 0.8^{a}	7.2 ± 0.5^{a}	3.9 ± 0.3^{c}	1.9 ± 0.2^{e}
July	KM	35.1 ± 2.1^{a}	26.2 ± 1.6^{b}	17.2 ± 1.0^{c}	10.2 ± 0.7^{c}	5.8 ± 0.5^{c}	3.6 ± 0.3^{d}	1.9 ± 0.2^{e}
	KS	33.8 ± 2.0^{b}	25.8 ± 1.5^{b}	17.8 ± 1.1^{b}	10.9 ± 0.7^{b}	6.3 ± 0.5^{b}	3.7 ± 0.3^{c}	1.7 ± 0.2^{e}
	KD	32.6 ± 1.9^{c}	25.1 ± 1.4^{c}	18.5 ± 1.1^{a}	11.5 ± 0.8^{a}	6.8 ± 0.5^{a}	3.8 ± 0.3^{c}	1.7 ± 0.2^{e}
August	KM	36.8 ± 2.2^{a}	26.5 ± 1.6^{b}	16.5 ± 1.0^{c}	9.8 ± 0.7^{c}	5.2 ± 0.4^{c}	3.4 ± 0.3^{d}	1.8 ± 0.2^{e}
	KS	35.3 ± 2.1^{b}	26.0 ± 1.5^{b}	17.3 ± 1.0^{b}	10.6 ± 0.7^{b}	5.8 ± 0.5^{b}	3.4 ± 0.3^{c}	1.6 ± 0.2^{e}
	KD	34.0 ± 2.0^{c}	25.4 ± 1.5^{c}	18.0 ± 1.1^{a}	11.2 ± 0.8^{a}	6.4 ± 0.5^{a}	3.4 ± 0.3^{c}	1.6 ± 0.2^{e}

Table 5. Mean monthly distribution of microplastic polymer types (%) across the sampling stations in River Ginzo, Katsina State

Month	Station	PE	PP	PET	PVC	PS	PA	PU
March	KM	33.8 ± 1.9^{a}	25.6 ± 1.6^{a}	17.4 ± 1.2^{b}	9.2 ± 0.8^{c}	6.4 ± 0.5^{d}	4.5 ± 0.4^{e}	3.1 ± 0.3^{f}
	KS	32.7 ± 1.8^{b}	24.9 ± 1.5^{b}	17.9 ± 1.2^{a}	9.5 ± 0.8^{c}	6.7 ± 0.5^{d}	4.8 ± 0.4^{e}	3.5 ± 0.3^{f}
	KD	31.8 ± 1.7^{c}	24.3 ± 1.4^{c}	18.3 ± 1.1^{a}	9.8 ± 0.8^{b}	6.9 ± 0.5^{c}	5.2 ± 0.4^{d}	3.7 ± 0.3^{e}
April	KM	34.5 ± 2.0^{a}	25.2 ± 1.5^{a}	17.6 ± 1.2^{b}	9.0 ± 0.8^{c}	6.3 ± 0.5^{d}	4.4 ± 0.4^{e}	3.0 ± 0.3^{f}
	KS	33.6 ± 1.9^{b}	24.6 ± 1.5^{b}	18.0 ± 1.2^{a}	9.3 ± 0.8^{c}	6.5 ± 0.5^{d}	4.8 ± 0.4^{e}	3.2 ± 0.3^{f}
	KD	32.8 ± 1.8^{c}	24.0 ± 1.4^{c}	18.4 ± 1.2^{a}	9.6 ± 0.8^{b}	6.8 ± 0.5^{c}	5.0 ± 0.4^{d}	3.4 ± 0.3^{e}
May	KM	35.8 ± 2.1^{a}	24.7 ± 1.5^{b}	17.8 ± 1.2^{b}	8.8 ± 0.7^{c}	6.2 ± 0.5^{d}	4.1 ± 0.3^{e}	2.6 ± 0.2^{f}
	KS	34.9 ± 2.0^{b}	24.3 ± 1.4^{b}	18.2 ± 1.2^{a}	9.1 ± 0.8^{c}	6.4 ± 0.5^{d}	4.4 ± 0.4^{e}	2.7 ± 0.2^{f}
	KD	34.0 ± 1.9^{c}	23.8 ± 1.4^{c}	18.7 ± 1.2^{a}	9.4 ± 0.8^{b}	6.7 ± 0.5^{c}	4.6 ± 0.4^{d}	2.8 ± 0.2^{e}
June	KM	37.4 ± 2.2^{a}	23.9 ± 1.4^{b}	18.1 ± 1.3^{b}	8.5 ± 0.7^{c}	6.1 ± 0.5^{d}	3.8 ± 0.3^{e}	2.2 ± 0.2^{f}
	KS	36.3 ± 2.1^{b}	23.5 ± 1.4^{b}	18.6 ± 1.2^{a}	8.8 ± 0.7^{c}	6.3 ± 0.5^{d}	4.1 ± 0.3^{e}	2.4 ± 0.2^{f}
	KD	35.5 ± 2.0^{c}	23.1 ± 1.4^{c}	19.0 ± 1.2^{a}	9.0 ± 0.8^{b}	6.5 ± 0.5^{c}	4.4 ± 0.4^{d}	2.5 ± 0.2^{e}
July	KM	39.1 ± 2.3^{a}	23.2 ± 1.4^{b}	18.2 ± 1.3^{b}	8.1 ± 0.7^{c}	5.9 ± 0.5^{d}	3.5 ± 0.3^{e}	2.0 ± 0.2^{f}
	KS	37.9 ± 2.2^{b}	22.9 ± 1.3^{b}	18.8 ± 1.3^{a}	8.5 ± 0.7^{c}	6.2 ± 0.5^{d}	3.8 ± 0.3^{e}	1.9 ± 0.2^{f}
	KD	36.8 ± 2.1^{c}	22.5 ± 1.3^{c}	19.3 ± 1.3^{a}	8.8 ± 0.7^{b}	6.4 ± 0.5^{c}	4.1 ± 0.3^{d}	2.1 ± 0.2^{e}
August	KM	40.3 ± 2.4^{a}	22.8 ± 1.3^{b}	18.4 ± 1.3^{b}	7.8 ± 0.7^{c}	5.8 ± 0.5^{d}	3.2 ± 0.3^{e}	1.7 ± 0.2^{f}
	KS	39.0 ± 2.3^{b}	22.4 ± 1.3^{b}	18.9 ± 1.3^{a}	8.2 ± 0.7^{c}	6.0 ± 0.5^{d}	3.6 ± 0.3^{e}	1.9 ± 0.2^{f}
	KD	37.8 ± 2.2^{c}	22.1 ± 1.3^{c}	19.5 ± 1.3^{a}	8.5 ± 0.7^{b}	6.3 ± 0.5^{c}	3.9 ± 0.3^{d}	1.9 ± 0.2^{e}

Means within the same month and polymer type followed by different superscript letters differ significantly among sampling stations according to Tukey's HSD test (P < 0.05). KM = Kofar Marusa; KS = Kofar Sauri; KD = Kofar Durbi; PE = Polyethylene; PP = Polypropylene; PET = Polyethylene terephthalate; PVC = Polyvinyl chloride; PS = Polystyrene; PA = Polyamide; PU = Polyurethane

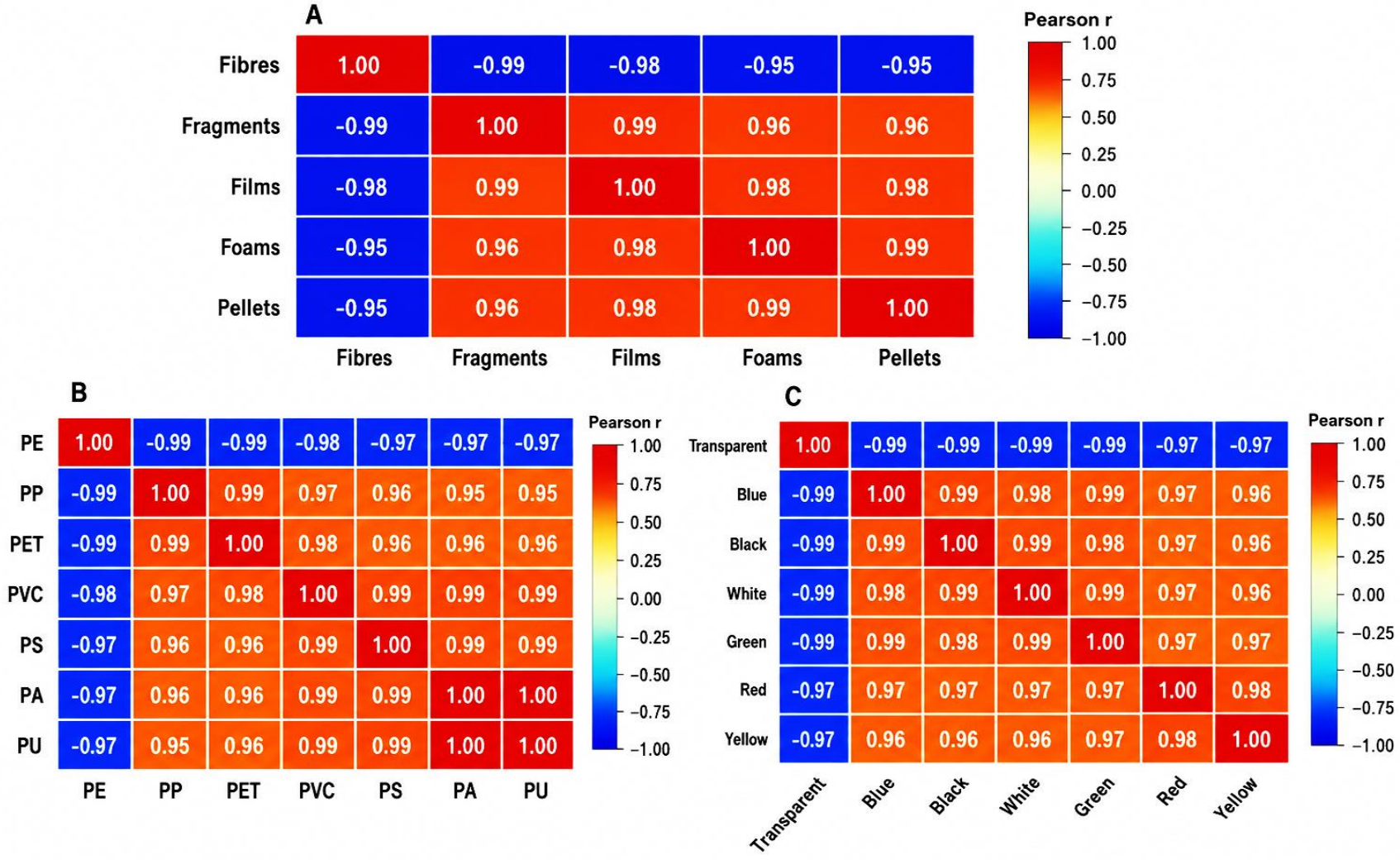


Figure 3. Pearson Correlation Heatmaps Showing Relationships among Microplastic Morphological Characteristics, Polymer Composition, and Colour Categories in River Ginzo Samples

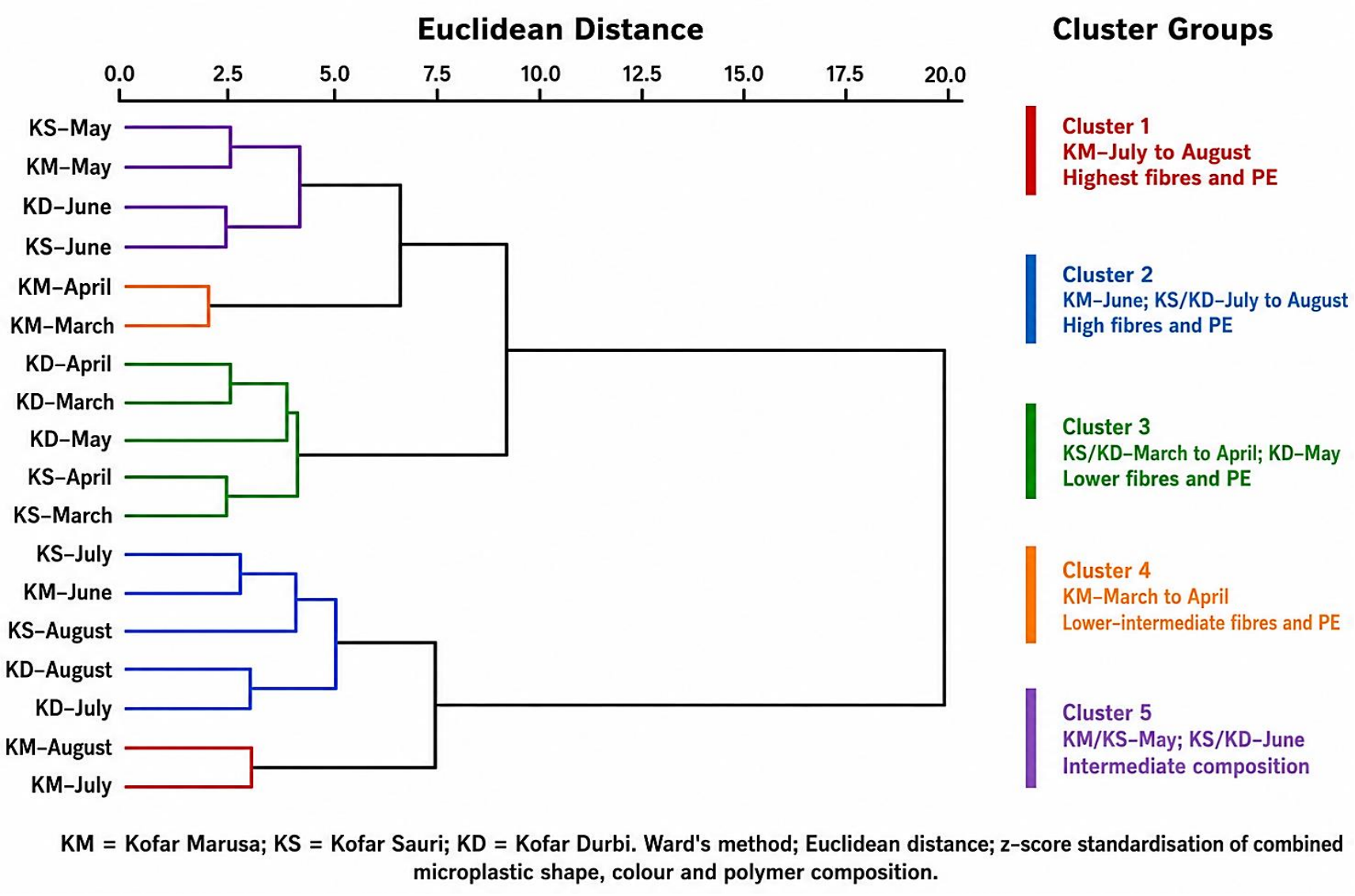


Figure 4. Hierarchical Cluster Analysis (HCA) of Microplastic Characteristics Across Sampling Stations and Months in River Ginzo, Katsina State

Microalgal Taxa, Abundance, Biomass and Relative Abundance

Table 6 presents the composition, abundance, biomass, and relative abundance of microalgal taxa recorded across the three sampling locations in River Ginzo. A total of 25 microalgal taxa belonging to six major taxonomic divisions were identified, comprising Bacillariophyta (9 taxa), Chlorophyta (7 taxa), Cyanobacteria (4 taxa), Euglenophyta (2 taxa), Chrysophyta (2 taxa), and Dinophyta (1 taxon). Among the diatoms, *Navicula* spp. recorded the highest abundance, increasing significantly ($P < 0.05$) from $0.86 \pm 0.07 \times 10^4$ cells mL^{-1} at Kofar Marusa (KM) to $1.46 \pm 0.11 \times 10^4$ cells mL^{-1} at Kofar Durbi (KD), with the highest chlorophyll-*a* biomass (3.24 ± 0.22 µg L^{-1}) and relative abundance (10.8 ± 0.8%). Other dominant diatoms, including *Nitzschia* spp., *Cyclotella* spp., *Fragilaria* spp., *Synedra ulna*, and *Pinnularia* spp., similarly exhibited significantly greater abundances at KD than at KM ($P < 0.05$). Green algae, particularly *Scenedesmus* spp., *Chlorella vulgaris*, *Pediastrum duplex*, and *Ankistrodesmus* spp., also showed increasing abundance from KM to KD, indicating more favourable environmental conditions at the relatively less disturbed site. Conversely, cyanobacterial taxa, including *Microcystis* spp., *Oscillatoria* spp., *Anabaena* spp., and *Lyngbya* spp., were significantly more abundant at KM than at KS and KD ($P < 0.05$). For example, *Microcystis aeruginosa* decreased from $0.78 \pm 0.06 \times 10^4$ cells mL^{-1} at KM to $0.46 \pm 0.04 \times 10^4$ cells mL^{-1} at KD, suggesting that the more polluted Kofar Marusa favoured the proliferation of pollution-tolerant cyanobacteria. Similarly, members of Euglenophyta, particularly *Euglena viridis* and *Phacus* spp., were more abundant at KM, reflecting their tolerance to organically enriched environments. Species belonging to Chrysophyta and Dinophyta occurred at comparatively lower abundances across all sampling locations. *Dinobryon* spp. and *Mallomonas* spp. showed slightly higher abundances at KD, whereas *Peridinium* spp., the only dinoflagellate recorded, exhibited the lowest overall abundance ($0.11–0.17 \times 10^4$ cells mL^{-1}) and biomass (0.42 ± 0.04 µg Chl-*a* L^{-1}).

Community Diversity Indices of Microalgae

Table 7 summarizes the community diversity indices of microalgae across the three sampling locations in River Ginzo. Although 25 microalgal taxa were identified throughout the study, the average number of species recorded per sampling event differed significantly ($P < 0.05$) among the sampling locations, increasing from 18 ± 1 species at Kofar Marusa (KM) to 22 ± 1 species at Kofar Sauri (KS) and 25 ± 0 species at Kofar Durbi (KD). Similarly, total microalgal cell abundance increased significantly from $9.45 \pm 0.64 \times 10^4$ cells mL^{-1} at KM to $14.05 \pm 0.82 \times 10^4$ cells mL^{-1} at KD, while chlorophyll-*a* biomass increased from 31.4 ± 1.8 µg L^{-1} to 46.1 ± 2.3 µg L^{-1}, indicating greater primary productivity at the relatively less disturbed site. The Shannon–Wiener diversity index (H′) showed a significant increase from 2.48 ± 0.07 at KM to 3.18 ± 0.09 at KD ($P < 0.05$), reflecting improved species diversity downstream. Likewise, Simpson's diversity index (1 − D) increased significantly from 0.83 ± 0.02 at KM to 0.94 ± 0.01 at KD, indicating a more even distribution of species at the less impacted sampling location. Margalef richness and Menhinick richness indices also increased significantly from KM to KD, demonstrating higher species richness at Kofar Durbi. Conversely, the dominance index (D) was highest at KM (0.17 ± 0.02) and lowest at KD (0.06 ± 0.01), indicating that a few pollution-tolerant species dominated the microalgal community at the more urbanized Kofar Marusa. Pielou's evenness index similarly increased from 0.77 ± 0.03 at KM to 0.91 ± 0.02 at KD, suggesting a more balanced community structure at the less disturbed site.

Ecological Risk Indices and Contamination Levels

To evaluate the potential ecological consequences of microplastic contamination, the Microplastic Pollution Load Index (MPPLI), Microplastic Contamination Factor (MCF), Potential Ecological Risk Index (PERI), and Risk Classification Index (RCI) were estimated for each sampling location during the dry and wet seasons (Table 8). All assessed indices, MPPLI, MCF, PERI and RCI were higher during the wet season than during the dry season at all three sampling locations. Kofar Marusa recorded the highest contamination levels, with MPPLI increasing from 2.84 ± 0.18 in the dry season to 4.31 ± 0.24 in the wet season, while PERI increased from 126.4 ± 8.7 to 187.3 ± 10.5. Kofar Sauri showed intermediate values, whereas Kofar Durbi consistently recorded the lowest values. The highest MCF and RCI values were also observed at Kofar Marusa during the wet season (4.86 ± 0.28 and 3.84 ± 0.19, respectively), while the lowest values occurred at Kofar Durbi during the dry season (1.81 ± 0.13 and 1.63 ± 0.11, respectively). The ecological risk classification consequently ranged from low at KD (dry season) to high at KM (wet season). Kofar Sauri was classified as moderate during the dry season and moderate–high during the wet season.

Comparison of Microplastic Abundance with Previous Studies

Table 9 compares the microplastic abundance and characteristics observed in River Ginzo with those reported in selected freshwater ecosystems in Nigeria, Africa, and other parts of the world. The abundance of microplastics recorded in the present study (12.6–31.8 particles L^{-1}) was generally lower than those reported for heavily urbanized Nigerian water bodies such as the Lagos Lagoon (139–303 particles L^{-1}) and rivers in southwestern Nigeria (28.5–114 particles L^{-1}) but was comparable to concentrations reported for Lake Ziway, Ethiopia (0.05–36.2 particles L^{-1}). Similarly, sediment-associated microplastic abundances reported for the Ogun River, Odo-Ona River, Vaal River, Wei River, and River Kelvin were substantially higher than those observed in River Ginzo, reflecting differences in environmental matrices, urbanization intensity, hydrological conditions, and waste management practices. Across most studies, fibres were the dominant particle morphology, while polyethylene (PE) and polypropylene (PP) consistently represented the most abundant polymer types, indicating that domestic waste, plastic packaging materials, synthetic textiles, and municipal runoff are the principal sources of microplastic contamination. The predominance of PE and PP in River Ginzo therefore agrees with regional and global trends, suggesting similar anthropogenic origins despite variations in contamination levels.

Table 6. Microalgal taxa, abundance, biomass and diversity indices across the sampling locations in River Ginzo

Taxonomic Division	Microalgal Species	KM (×10⁴ cells mL⁻¹)	KS (×10⁴ cells mL⁻¹)	KD (×10⁴ cells mL⁻¹)	Biomass (µg Chl-*a* L⁻¹)	Relative Abundance (%)
Bacillariophyta	*Navicula* spp.	0.86 ± 0.07^{c}	1.12 ± 0.09^{b}	1.46 ± 0.11^{a}	3.24 ± 0.22^{a}	10.8 ± 0.8^{a}
	Nitzschia spp.	0.74 ± 0.06^{c}	0.98 ± 0.08^{b}	1.28 ± 0.10^{a}	2.88 ± 0.20^{a}	9.4 ± 0.7^{b}
	Cyclotella spp.	0.51 ± 0.05^{c}	0.68 ± 0.06^{b}	0.87 ± 0.07^{a}	2.07 ± 0.18^{b}	6.2 ± 0.5^{c}
	Synedra ulna	0.39 ± 0.04^{c}	0.55 ± 0.05^{b}	0.71 ± 0.06^{a}	1.73 ± 0.14^{b}	5.1 ± 0.4^{d}
	Fragilaria spp.	0.43 ± 0.04^{c}	0.61 ± 0.05^{b}	0.82 ± 0.06^{a}	1.96 ± 0.16^{b}	5.9 ± 0.5^{c}
	Pinnularia spp.	0.34 ± 0.03^{c}	0.46 ± 0.04^{b}	0.63 ± 0.05^{a}	1.48 ± 0.13^{c}	4.3 ± 0.3^{d}
	Gomphonema spp.	0.28 ± 0.03^{c}	0.39 ± 0.04^{b}	0.55 ± 0.05^{a}	1.31 ± 0.12^{c}	3.8 ± 0.3^{e}
	Asterionella formosa	0.22 ± 0.02^{c}	0.33 ± 0.03^{b}	0.47 ± 0.04^{a}	1.08 ± 0.09^{c}	3.1 ± 0.2^{f}
	Melosira varians	0.19 ± 0.02^{c}	0.29 ± 0.03^{b}	0.41 ± 0.04^{a}	0.94 ± 0.08^{c}	2.7 ± 0.2^{f}
Chlorophyta	*Scenedesmus* spp.	0.66 ± 0.05^{c}	0.84 ± 0.07^{b}	1.03 ± 0.08^{a}	2.46 ± 0.17^{a}	7.6 ± 0.6^{b}
	Chlorella vulgaris	0.61 ± 0.05^{c}	0.81 ± 0.06^{b}	0.98 ± 0.08^{a}	2.31 ± 0.18^{a}	7.1 ± 0.5^{b}
	Pediastrum duplex	0.44 ± 0.04^{c}	0.59 ± 0.05^{b}	0.73 ± 0.06^{a}	1.81 ± 0.15^{b}	5.3 ± 0.4^{c}
	Ankistrodesmus spp.	0.33 ± 0.03^{c}	0.47 ± 0.04^{b}	0.62 ± 0.05^{a}	1.54 ± 0.13^{b}	4.4 ± 0.3^{d}
	Spirogyra spp.	0.31 ± 0.03^{c}	0.45 ± 0.04^{b}	0.58 ± 0.05^{a}	1.42 ± 0.12^{b}	4.1 ± 0.3^{d}
	Closterium spp.	0.26 ± 0.02^{c}	0.37 ± 0.03^{b}	0.49 ± 0.04^{a}	1.18 ± 0.10^{c}	3.5 ± 0.3^{e}
	Cosmarium spp.	0.21 ± 0.02^{c}	0.31 ± 0.03^{b}	0.43 ± 0.04^{a}	1.01 ± 0.09^{c}	2.9 ± 0.2^{f}
Cyanobacteria	*Microcystis* spp.	0.78 ± 0.06^{a}	0.63 ± 0.05^{b}	0.46 ± 0.04^{c}	2.02 ± 0.16^{b}	6.3 ± 0.5^{c}
	Oscillatoria spp.	0.69 ± 0.06^{a}	0.55 ± 0.05^{b}	0.39 ± 0.04^{c}	1.74 ± 0.14^{c}	5.6 ± 0.4^{d}
	Anabaena spp.	0.47 ± 0.04^{a}	0.36 ± 0.03^{b}	0.24 ± 0.02^{c}	1.16 ± 0.10^{c}	3.8 ± 0.3^{e}
	Lyngbya spp.	0.35 ± 0.03^{a}	0.27 ± 0.03^{b}	0.18 ± 0.02^{c}	0.91 ± 0.08^{c}	2.8 ± 0.2^{f}
Euglenophyta	*Euglena viridis*	0.29 ± 0.03^{a}	0.23 ± 0.02^{b}	0.16 ± 0.02^{c}	0.86 ± 0.08^{c}	2.2 ± 0.2^{f}
	Phacus spp.	0.17 ± 0.02^{a}	0.14 ± 0.01^{b}	0.10 ± 0.01^{c}	0.52 ± 0.05^{c}	1.3 ± 0.1^{g}
Chrysophyta	*Dinobryon* spp.	0.18 ± 0.02^{b}	0.22 ± 0.02^{a}	0.24 ± 0.02^{a}	0.63 ± 0.06^{c}	1.8 ± 0.1^{f}
	Mallomonas spp.	0.13 ± 0.01^{c}	0.17 ± 0.02^{b}	0.22 ± 0.02^{a}	0.48 ± 0.04^{c}	1.2 ± 0.1^{g}
Dinophyta	*Peridinium* spp.	0.11 ± 0.01^{b}	0.13 ± 0.01^{b}	0.17 ± 0.02^{a}	0.42 ± 0.04^{c}	0.9 ± 0.1^{g}

Means within the same row having different superscript letters are significantly different according to Tukey's HSD test ($P < 0.05$).
KM = Kofar Marusa; KS = Kofar Sauri; KD = Kofar Durbi.

Table 7. Community diversity indices of microalgae across the sampling locations (Mean ± SD)

Ecological Index	KM (Kofar Marusa)	KS (Kofar Sauri)	KD (Kofar Durbi)
Total Species Richness (S)	25 ± 0^{a}	25 ± 0^{a}	25 ± 0^{a}
Observed Species*	18 ± 1^{c}	22 ± 1^{b}	25 ± 0^{a}
Total Cell Abundance (×10^{4} cells mL^{-1})	9.45 ± 0.64^{c}	11.55 ± 0.73^{b}	14.05 ± 0.82^{a}
Chlorophyll-*a* Biomass (µg L^{-1})	31.4 ± 1.8^{c}	38.2 ± 2.0^{b}	46.1 ± 2.3^{a}
Shannon–Wiener Diversity Index (H′)	2.48 ± 0.07^{c}	2.86 ± 0.08^{b}	3.18 ± 0.09^{a}
Simpson Diversity Index (1 − D)	0.83 ± 0.02^{c}	0.89 ± 0.02^{b}	0.94 ± 0.01^{a}
Margalef Richness Index (d)	3.84 ± 0.26^{c}	4.67 ± 0.29^{b}	5.52 ± 0.31^{a}
Pielou Evenness Index (J′)	0.77 ± 0.03^{c}	0.84 ± 0.02^{b}	0.91 ± 0.02^{a}
Dominance Index (D)	0.17 ± 0.02^{a}	0.11 ± 0.01^{b}	0.06 ± 0.01^{c}
Menhinick Richness Index	2.41 ± 0.15^{c}	2.86 ± 0.17^{b}	3.31 ± 0.18^{a}

* Mean occurrence per sampling event

Table 8. Ecological risk indices and contamination levels of microplastics in River Ginzo Katsina

Sampling location	MPPLI	MCF	PERI	RCI	Ecological risk category
KM (Dry)	2.84 ± 0.18^{b}	3.16 ± 0.22^{b}	126.4 ± 8.7^{b}	2.71 ± 0.16^{b}	Moderate
KM (Wet)	4.31 ± 0.24^{a}	4.86 ± 0.28^{a}	187.3 ± 10.5^{a}	3.84 ± 0.19^{a}	High
KS (Dry)	2.21 ± 0.15^{c}	2.58 ± 0.17^{c}	101.6 ± 6.4^{c}	2.18 ± 0.13^{c}	Moderate
KS (Wet)	3.48 ± 0.21^{b}	3.92 ± 0.24^{b}	152.7 ± 9.3^{b}	3.07 ± 0.17^{b}	Moderate–High
KD (Dry)	1.54 ± 0.11^{e}	1.81 ± 0.13^{e}	71.8 ± 5.6^{e}	1.63 ± 0.11^{e}	Low
KD (Wet)	2.47 ± 0.16^{d}	2.86 ± 0.18^{d}	109.5 ± 7.1^{d}	2.39 ± 0.14^{d}	Moderate

Means within the same column bearing different superscripts differ significantly according to Tukey's HSD test ($P < 0.05$). MPPLI = Microplastic Pollution Load Index; MCF = Microplastic Contamination Factor; PERI = Potential Ecological Risk Index; RCI = Risk Classification Index.

Table 9. Comparison of the present study with published studies on freshwater microplastics from Nigeria, Africa, and other regions of the world

Study Area	Country	Water Body	Reported Microplastic Abundance	Dominant Particle Shape	Most Dominant Polymer(s)	Reference
River Ginzo	Nigeria	River	12.6–31.8 particles L^{-1}	Fibres	PE > PP > PET	Present study
Lagos Lagoon	Nigeria	Lagoon	139–303 particles L^{-1}	Fibres	PP, PE	(Olarinmoye *et al*., 2020)
Ogun River	Nigeria	River	66.7 ± 12.2–311 ± 20.8 particles kg^{-1}	Fibres, fragments	PE, PP, PA	(Shokunbi, *et al*., 2024)
Odo-Ona River	Nigeria	River	133 ± 30–433 ± 100 particles kg^{-1}	Fibres, fragments	PE, PP	(Shokunbi, *et al*., 2024)
Lake Ziway	Ethiopia	Lake	0.05–36.2 particles L^{-1}	Fragments, fibres	PET, PP, PE	(Merga *et al*., 2020)
Vaal River	South Africa	River	463 ± 284 particles kg^{-1} (sediment)	Fragments	PP, PE, PEVA	(Saad *et al*., 2022)
Qinghai–Tibet Rivers	China	Rivers	41.5 ± 22.3 particles L^{-1}	Fibres, fragments	PP, PE, PS, PET, PA, PVC	(Feng *et al*., 2021)
Wei River	China	River	360–1320 particles kg^{-1} (sediment)	Fibres	PVC, PS, PE	(Ding *et al*., 2019)
River Kelvin	United Kingdom	River	50–244 particles kg^{-1} (sediment)	Fibres, fragments	PP, PE	(Shokunbi, *et al*., 2024b)

PE = polyethylene; PP = polypropylene; PET = polyethylene terephthalate; PVC = polyvinyl chloride; PS = polystyrene; PA = polyamide (nylon); PEVA = polyethylene-vinyl acetate.

DISCUSSION

The physicochemical results demonstrate that River Ginzo is strongly influenced by seasonal hydrological processes and spatial differences in anthropogenic pressure. Water temperature was consistently higher during the dry season (31.88–33.41 °C) than during the wet season (27.61–29.26 °C), reflecting the expected influence of solar radiation, atmospheric temperature, cloud cover and rainfall dilution. The decrease in temperature during the wet season is particularly relevant because temperature influences microbial activity, oxygen solubility, algal metabolism and the physical behaviour of suspended particles (Luo *et al*., 2024). The slightly neutral to mildly alkaline dry-season pH (7.48–7.74) declined to 6.74–7.18 during the wet season, probably because rainfall introduced relatively dilute and slightly acidic surface runoff and organic matter into the river. Such seasonal shifts are important because pH can influence polymer surface charge, contaminant sorption and the physiological performance of freshwater microorganisms (Oktaviani *et al*., 2025). The pronounced wet-season increases in EC and TDS indicate increased inputs of dissolved ions and particulate-associated materials during rainfall. EC increased from 421.6–462.7 µS cm^{-1} during the dry season to 531.8–591.5 µS cm^{-1} during the wet season, while TDS increased from 269.2–293.4 to 341.5–374.7 mg L^{-1}. These changes are consistent with mobilization of dissolved and particulate materials from surrounding residential areas, roads, drainage channels and cultivated land (Bello Hussain, 2024). Importantly, the same wet-season period also showed substantial increases in turbidity, BOD_5, COD, nitrate and phosphate, suggesting that rainfall was not simply diluting the river but was actively transporting terrestrial materials and anthropogenic wastes into the channel. The highest values generally occurred at Kofar Marusa (KM), whereas Kofar Durbi (KD) exhibited comparatively lower values, supporting a spatial gradient in anthropogenic influence.

The increase in BOD_5 from 3.18–3.82 mg L^{-1} during the dry season to 4.48–5.26 mg L^{-1} during the wet season, together with the increase in COD from 15.4–17.6 to 22.8–26.8 mg L^{-1}, indicates increased organic loading during rainfall. Similarly, nitrate increased to 4.51–5.16 mg L^{-1} and phosphate to 0.77–0.92 mg L^{-1} during the wet season. This nutrient enrichment is ecologically important because it can stimulate phytoplankton growth while simultaneously favouring opportunistic and pollution-tolerant taxa (Essa *et al*., 2024). The apparent increase in DO during the wet season (6.08–6.42 mg L^{-1} compared with 5.21–5.69 mg L^{-1} during the dry season) may reflect enhanced atmospheric reaeration, increased turbulence and rainfall-driven mixing. Thus, the higher BOD_5 and COD during the wet season did not translate into lower measured DO, probably because physical reaeration temporarily compensated for increased oxygen demand. This illustrates why individual physicochemical parameters should not be interpreted independently.

The occurrence of microplastics throughout all sampling stations and months confirms that River Ginzo is continuously exposed to plastic contamination. FTIR is widely used for polymer identification (Cowger *et al*., 2024; Kozloski *et al*., 2024; Primpke *et al*., 2020). Microplastic abundance increased systematically from March to August. During the dry season, concentrations ranged from 24.8 ± 1.6 to 32.8 ± 2.4 particles L^{-1}, whereas wet-season concentrations increased to 33.1 ± 2.3–45.6 ± 3.1 particles L^{-1}. KM consistently recorded the highest abundance, followed by KS and KD, demonstrating a persistent spatial gradient. The approximately 40% increase from the lowest recorded concentration at KD in March to the highest concentration at KM in August is consistent with rainfall-mediated mobilization of land-derived plastic debris. During the rainy season, stormwater can transport discarded packaging, sachet-water materials, synthetic fibres, fragments of household plastics and other debris from streets and drainage channels into rivers. Contemporary reviews emphasize that rainfall, discharge, turbulence, sediment interactions, particle density, shape and weathering collectively determine microplastic transport in freshwater systems (Sugiura *et al*., 2021). The spatial sequence KM > KS > KD is also consistent with the distribution of anthropogenic activities along River Ginzo. Kofar Marusa is characterized by greater urban activity, residential development, trading, washing and drainage inputs, providing multiple pathways for plastic entry. The consistently lower abundance at KD suggests either lower direct inputs, greater downstream retention, enhanced deposition, or a combination of these processes. Therefore, the spatial pattern should not be interpreted simply as a reduction in pollution downstream; rather, it indicates differences in the balance between source input, transport, dilution and retention (Shi *et al*., 2024).

The magnitude of contamination is comparable with, and in some cases higher than, concentrations reported from several freshwater systems. Shokunbi

et al. (2024), for example, documented substantial seasonal variability in microplastic contamination in southwestern Nigerian rivers, demonstrating the importance of rainfall and local anthropogenic activities in controlling microplastic abundance. The River Ginzo concentrations are also within the broad range reported for some African freshwater systems, although direct comparison should be undertaken cautiously because sampling methods, filtration volumes, size limits and reporting units differ substantially among studies. Such methodological differences are a major source of uncertainty in global microplastic comparisons.

The dominance of fibres is ecologically significant because fibres are readily transported by water and can originate from multiple diffuse sources, including synthetic clothing, domestic wastewater, laundry discharge and degraded textile materials. Their prevalence may therefore reflect the cumulative influence of household wastewater and urban drainage rather than a single industrial source (Ibrahim *et al*., 2025). The increase in fibres during the wet season further suggests that previously deposited fibres may be remobilized by rainfall and runoff. Fragments were the second most abundant morphology and are generally associated with the progressive breakdown of larger plastic objects. Their occurrence alongside films is consistent with degradation of bags, packaging materials, wrappers and other consumer plastics. The presence of foams and pellets at lower frequencies indicates additional, although comparatively smaller, contributions from packaging, insulation materials and industrial or commercial plastic handling (Dahms & Greenfield, 2025). The strong negative correlation between fibres and the other morphological categories (r = −0.95 to −0.99), together with the strong positive correlations among fragments, films, foams and pellets (r = 0.96–0.99), suggests that particle morphology was structured by distinct source or transport processes rather than being randomly distributed. This interpretation is consistent with current understanding that particle shape strongly influences transport, settling, aggregation and biological interactions in rivers (Rodríguez-Seijo & Pereira, 2017).

The predominance of transparent particles is consistent with the weathering and fragmentation of clear packaging materials, polyethylene films and sachet-water plastics. Colour loss may also occur during environmental weathering, meaning that originally coloured plastics can become less visually distinctive after prolonged exposure to sunlight, abrasion and chemical oxidation. Blue and black particles may reflect consumer packaging, synthetic textiles and household materials (Rocha-Santos & Duarte, 2015). The strong negative correlation between transparent particles and the remaining colour categories (r = −0.97 to −0.99), coupled with strong positive correlations among blue, black, white, green, red and yellow particles, indicates coordinated changes in colour composition across sampling events. This pattern reinforces the conclusion that seasonal hydrology selectively mobilized particular groups of plastic debris (Shi *et al*., 2024).

The predominance of PE and PP is consistent with their extensive use in disposable bags, sachets, food packaging, household containers and other consumer products. Their dominance has also been observed in Nigerian freshwater systems. Shokunbi *et al*. (2024) reported PE and PP among the principal polymers in southwestern Nigerian rivers, while Olarinmoye *et al*., (2020) documented substantial microplastic contamination in Lagos Lagoon. The relatively high contribution of PET is noteworthy because PET is widely used in beverage bottles and synthetic textiles. Its occurrence alongside fibre dominance suggests that both household plastic waste and textile-derived materials may contribute to River Ginzo contamination. The presence of PVC and PS further indicates heterogeneous plastic inputs rather than contamination from a single polymer source. The polymer pattern also agrees with studies from other river systems. In the Wei River, China, fibres were dominant and PE, PVC and PS were among the principal polymers identified (Ding *et al*., 2019). In the Vaal River, South Africa, fragments and fibres constituted most recovered MPs, again illustrating the importance of mixed urban sources (Saad *et al*., 2022). Thus, the PE > PP > PET profile observed in River Ginzo appears characteristic of a freshwater system receiving substantial domestic and municipal plastic inputs.

The exceptionally strong correlations among PP, PET, PVC, PS, PA and PU (r = 0.95–1.00) indicate that these polymers varied in a coordinated manner across sampling conditions. In contrast, PE was strongly negatively correlated with the other polymers (r = −0.97 to −0.99). This suggests that PE may have had a somewhat different temporal or source signature from the other polymer groups. The HCA further supported temporal and spatial structuring. Five clusters were identified, with later wet-season observations generally separating from earlier dry-season samples. KM samples from July–August formed the cluster characterized by the highest fibre

and PE contributions, whereas KS and KD samples from March–April were associated with lower fibre and PE proportions. This pattern is particularly informative because it independently supports the univariate results. Rather than merely showing higher particle counts during the wet season, HCA indicates that the composition itself changed seasonally. The wet-season signal therefore appears to represent a shift toward greater contributions from fibre-rich and PE-dominated materials. This provides stronger evidence for rainfall-driven mobilization of specific urban plastic sources (Sharma *et al*., 2025).

The spatial differences in microalgal community structure can be interpreted in relation to the distribution and characteristics of microplastics along River Ginzo. The comparatively lower diversity and evenness at Kofar Marusa, where microplastic contamination was greatest, suggest that intense plastic pollution may contribute to environmental filtering and community restructuring. Microplastics can influence phytoplankton through physical attachment, aggregation, shading, oxidative stress, and interference with nutrient exchange, potentially disadvantaging sensitive taxa while favouring more tolerant organisms (Li *et al*., 2023; Prata *et al*., 2019). The predominance of fibres and the high occurrence of PE and PP are particularly relevant to this interpretation. Fibres may originate from domestic wastewater, synthetic textiles, and urban activities, whereas PE and PP are widely associated with packaging materials and household plastic waste. Recent research identifies freshwater microplastics as important substrates for plastisphere communities, which can modify microbial interactions and potentially influence surrounding planktonic communities (Bocci *et al*., 2024; Prata *et al*., 2019). Thus, the ecological significance of River Ginzo microplastics may extend beyond particle abundance to include their role as persistent habitats within the water column.

The greater representation of cyanobacteria and euglenophytes at the more contaminated location may indicate selection for taxa capable of tolerating multiple environmental stressors. Microplastic exposure can produce species-specific responses and may alter competitive relationships among algae; however, these responses depend on polymer type, particle characteristics, exposure concentration, and environmental conditions (Prata *et al*., 2019). Therefore, the observed community pattern may not be attributed exclusively to microplastics. Nutrient enrichment, organic pollution, turbidity, dissolved oxygen, and seasonal hydrological changes may act simultaneously and either amplify or mask microplastic effects (Moraes *et al*., 2021). The comparatively greater diversity and evenness at Kofar Durbi may reflect reduced anthropogenic pressure and lower microplastic exposure, allowing coexistence of a broader range of taxa. The association between lower microplastic contamination and a more diverse community therefore supports the use of microalgal assemblages as sensitive indicators of cumulative freshwater disturbance.A recent meta-analysis of freshwater microalgal studies found that micro/nanoplastics can significantly inhibit photosynthesis and chlorophyll-*a* and that responses are strongly taxon- and polymer-dependent (Guo *et al*., 2024).

The coexistence of substantial microplastic contamination and altered microalgal community structure is ecologically important because microalgae form the base of aquatic food webs. Experimental evidence indicates that microplastics can interfere with algal photosynthesis, increase oxidative stress and reduce growth, although responses depend strongly on particle concentration, size, polymer composition and algal species (Leffingwell *et al*., 2026). The present River Ginzo results provide an important field context for these experimental observations. The site with the highest microplastic burden, KM, had lower total algal abundance, lower chlorophyll-*a*, lower Shannon diversity and higher dominance by cyanobacteria and euglenophytes. However, the wet season simultaneously introduced higher nutrients and suspended matter, which could produce both stimulatory and inhibitory effects on phytoplankton. Consequently, the observed community structure probably represents the combined outcome of microplastic exposure, nutrient enrichment, organic pollution and seasonal hydrology. An additional ecological pathway involves the plastisphere. Microplastics provide surfaces for microbial colonization, potentially creating distinct microbial communities that interact with plankton and nutrient cycling. Bocci *et al*. (2024) emphasized that freshwater microplastics support diverse microbial biofilms and may influence ecosystem processes, although the ecological magnitude of these effects remains incompletely understood (Bocci *et al*., 2024). Moreover, recent experimental work demonstrated that biofouled plastics can alter phytoplankton community assembly and nutrient availability, indicating that the ecological effects of plastics may extend beyond direct particle toxicity (Nava *et al*., 2024).

CONCLUSION

This study provides an integrated assessment of microplastic contamination, physicochemical water quality, and microalgal community structure in River Ginzo, Katsina State, northwestern Nigeria. Microplastics were widely distributed, with pronounced spatial and seasonal variability. Kofar Marusa recorded the highest contamination, followed by Kofar Sauri and Kofar Durbi, likely reflecting rainfall-driven runoff, drainage discharge, remobilization, and urban inputs. Fibres predominated, followed by fragments and films, with transparent, blue, and black as major colours. Polyethylene (PE) was the dominant polymer, followed by polypropylene (PP) and polyethylene terephthalate (PET), and smaller contributions from PVC, PS, PA, and PU. The prevalence of fibres and PE/PP suggests important contributions from domestic wastewater, synthetic textiles, packaging materials, household plastics, and surface runoff. Correlation and hierarchical cluster analyses indicate changing hydrological conditions and diverse pollution sources. Water-quality parameters also varied seasonally. Wet-season increases in EC, TDS, turbidity, BOD_5, COD, nitrate, and phosphate indicate enhanced inputs of dissolved substances, suspended solids, organic matter, and nutrients. PCA separated seasonal conditions, with the first two components explaining 92.0% of total variance, confirming hydrological control of water-quality variability and contaminant transport. The microalgal community comprised 25 taxa across six major divisions, particularly Bacillariophyta, Chlorophyta, and Cyanobacteria. Kofar Durbi had the highest abundance, biomass, richness, diversity, and evenness, whereas Kofar Marusa showed lower diversity and greater cyanobacterial and euglenophyte dominance. The association between high microplastic abundance and reduced microalgal diversity suggests ecological stress, although nutrients, organic pollution, and turbidity may also contribute. Kofar Marusa represents a priority pollution hotspot. The study establishes a baseline for northern Nigeria and supports routine monitoring, improved waste management, drainage maintenance, and wet-season interventions. Future research should integrate sediment and biota assessments, source apportionment, hydrological monitoring, and controlled ecotoxicological experiments to clarify causal relationships and guide sustainable freshwater management, to strengthen ecological protection and sustainable freshwater management across northern Nigeria.

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