Trends in Ecological and Indoor Environmental Engineering

Emmanuel Akinseye et al. TEIEE 4(1) 2026

RESEARCH ARTICLE OPEN ACCESS
https://doi.org/10.62622/TEIEE.026.4.1.33-44 ISSN 2956-9761

LIMNOLOGY AND ALGAL BIOASSESSMENT OF ERIN-IJESHA (OLUMIRIN) WATERFALL, SOUTHWESTERN NIGERIA

Emmanuel Akinseye[1], Medina Kadiri*[1], Jeffrey Ogbebor[2]
[1]Department of Plant Biology and Biotechnology, University of Benin, Benin City, Nigeria
[2]Department of Environmental Management and Toxicology, Faculty of Life Sciences, University of Benin, Benin City, Nigeria
*Corresponding email: mokadiri@uniben.edu

Received: 04.01.2026; ***Accepted:*** 03.02.2026; ***Available online:*** 10.02.2026; ***Published:*** 30.03.2026

Cite this article: Akinseye, E., Kadiri, M., & Ogbebor, J. (2026). Limnology and Algal Bioassessment of Erin-Ijesha (Olumirin) Waterfall, Southwestern Nigeria. *Trends in Ecological and Indoor Environmental Engineering*, 4(1), 33–44.

Background: Waterfalls generate strong spatial heterogeneity in hydrological and physicochemical conditions, affecting oxygen dynamics, carbon fluxes, nutrients, and aquatic biota. Studies report pronounced gradients in water chemistry, microbial contamination, and biological assemblages, especially in tropical regions. In Nigeria, increasing anthropogenic pressures contrast with limited limnological data. Insufficient integration of water quality and algal indicators hampers understanding of ecosystem functioning and disturbance gradients, necessitating targeted limnological assessments to support biodiversity conservation and sustainable management of waterfall ecosystems. **Objectives:** This study aims to conduct a comprehensive limnological and algal assessment of Erin Ijesha Falls, Nigeria. It hypothesizes that spatial variations in physicochemical parameters create distinct water quality gradients that structure algal communities, and that the Palmer Index can reveal anthropogenic organic pollution not detected by conventional physicochemical indicators. **Methods:** Sampling was conducted during the dry season of 2024 across upper, middle, and lower sections of seven waterfall cascades. Integrated water and periphytic algal samples were collected in triplicate following ISO, APHA, and Nigerian standards. In situ measurements included temperature, pH, conductivity, and dissolved oxygen, while nutrients, major ions, and hardness were analysed in the laboratory. Algae were identified microscopically using standard taxonomic keys, and water quality was evaluated using the Palmer pollution index to assess organic contamination. **Results:** Air and water temperatures at Erin-Ijesha Waterfall showed clear diurnal warming, with air rising from 20 to 33°C and water from 19 to 26.5°C. Turbidity and colour were low to moderate (6–13 NTU; 1–4 PtCoU), while conductivity, TDS, pH, and alkalinity remained low and stable. Dissolved oxygen was high (8–10.5 mg L^{-1}), and nutrients and hardness were generally low, reflecting a well-oxygenated, soft, and minimally impacted freshwater system. The algal community at Erin-Ijesha Waterfall comprised 78 taxa across four divisions, dominated by Chlorophyta (42.3%) and Bacillariophyta (38.5%). Green algae and diatoms indicate generally good water quality, habitat heterogeneity, and moderate nutrient availability, while the Palmer Index (19) suggests slight organic enrichment without severe pollution. **Conclusion:** Spatial variation in physicochemical parameters at Erin Ijesha Falls defines a distinct water quality gradient. Algal communities, dominated by Chlorophyta and Bacillariophyta, effectively track hydrochemical conditions and reveal moderate organic enrichment undetected by physicochemical measures. Integrated indicators indicate moderate disturbance, ecological resilience, and the need for regular monitoring.

Keywords: waterfall ecosystems; limnological assessment; physicochemical water quality; periphytic algae; Palmer pollution index; spatial variability; anthropogenic impact; West Africa.

INTRODUCTION

A waterfall is defined as a section of a river flow characterized by a dramatic drop in water from a height due to steep terrain or geomorphic cliffs, resulting in intense turbulent mixing and aeration of the water column. Such elements of the river network not only represent important geomorphological structures but also function as dynamically developing freshwater ecosystems with complex physicochemical and biotic processes (Wetzel, 2001; Kalff, 2002).

From a hydrological and ecological perspective, waterfalls are characterized by high hydraulic gradients, which cause strong variations in the physicochemical parameters of water, influencing the spatial distribution of organisms, gas concentrations, and the transport of substances within the river network (Rust et al., 2025; Kalff, 2002). For example, studies have shown that dissolved oxygen (DO) concentrations in natural mountain streams (with fall sections) typically range from 8 to 11 mg L^{-1} (>8 mg L^{-1}), reflecting enhanced aeration due to turbulence and supporting aerobic communities (measured in seasonal water quality studies at waterfalls; DO increases during high flows) (Islam et al., 2022). Physicochemical parameters of waterfalls include high oxygen aeration values due to intensive mixing of water with atmospheric air, which contributes to increased dissolved oxygen concentrations, a key indicator of freshwater quality and a prerequisite for the existence of aerobic aquatic organisms (Rust et al., 2025). Several studies have observed that dissolved oxygen levels within waterfall zones can exceed values in quiescent river sections, providing favourable conditions for filter feeders, fish, and other organisms (Printarakul & Meeinkuirt, 2022).

Turbulent processes characteristic of waterfall fall zones also influence gas exchange and carbon balance: in one tropical study, the partial pressure of CO_2 after a waterfall fall was reduced by approximately 51% compared to upstream sites, indicating significant CO_2 degassing under intense mixing conditions (Leibowitz et al., 2017). Waterfalls are ecologically important because they support high levels of biodiversity and perform critical ecosystem services. Waterfalls host unique macrozoobenthic communities and other hydrophilic organisms: stable isotope analyses of $\delta^{15}N$ for waterfalls in tropical streams have yielded values ranging from approximately –1.9 to 5.5‰, corresponding to a wide range of trophic levels from herbivores to carnivores (Baker et al., 2017a). These ecosystems function as spatially discrete biotopes, where waterfalls themselves act as natural barriers limiting the upstream ascent of certain fish and other aquatic organisms, which influences the distribution of biota and the genetic isolation of populations within the river system (Rust et al., 2025). For example, empirical data from tropical waterfalls show significant differences in organism density: fish density downstream of a waterfall can be higher than upstream (0.24 fish m^{-2} versus 0.02 fish m^{-2}), while freshwater crustaceans exhibit the opposite trend (Baker et al., 2017b). These differences reflect complex ecosystem dynamics caused by a combination of hydrological, geomorphological, and biological factors. In tropical regions, waterfalls and adjacent streams form distinct habitats that serve as ecological transition zones between high-energy river sections and calmer lower reaches (Clayton & Pearson, 2016). They influence downstream water quality, biodiversity distribution, and organic matter decomposition processes (Wetzel, 2001; Baker et al., 2017b). The formation of such transition zones leads to structural heterogeneity in the river network, which is important for maintaining the functional diversity of ecosystems.

Waterfalls are important "ecological hotspots" that support high biological productivity and aquatic biota diversity, as well as provide significant ecosystem services. These services include maintaining high-quality water supplies, creating habitat, redistributing nutrients, and facilitating energy exchange within river networks (Baker et al., 2017b). Global freshwater ecosystems collectively provide services ranging from climate regulation to water supply worth trillions of dollars annually, underscoring their importance for the resilience of natural and human systems (Costanza et al., 2014).

Across Nigeria, waterfalls are common in diverse geomorphological and climatic conditions and are widely used for water supply, recreation, tourism, and cultural practices. Several studies have highlighted their socio-economic importance, particularly in the context of nature-based and community-based tourism development (Arabomen & Babalola, 2025; Bashiru et al., 2024). Some of the more well-known sites include Gurara Falls (Niger State), Erin Ijesha Waterfall (Osun State), Farin Ruwa Falls (Nasarawa), Agbokim Waterfalls, Kwa Falls, and Amanagwu Waterfall (Cross River State), Owu Falls (Kwara), Awhum Waterfall, and Ezeagu Waterfall (Enugu State), Arinta Waterfall and Ero-Omola Falls (Ekiti State), Matsirga Waterfalls (Kaduna State), Mayanka Falls, and Assop Falls (Plateau State), and Ogba Ukwu Caves & Waterfall (Anambra) (Rust et al., 2025).

Hydroecological studies of individual waterfalls, such as Erin-Ijesha and Ezeagu, reveal significant spatial variability in the physicochemical and microbiological parameters of water, as well as the presence of sensitive biological communities, indicating the important role of waterfalls in maintaining the ecological health of freshwater ecosystems (Adejuwon & George, 2024; Eneh et al., 2024). Similar findings for other freshwater systems in Nigeria confirm that the structural and biological characteristics of aquatic ecosystems are closely linked to water quality and the level of anthropogenic impact (Jonah et al., 2024).

Despite their socioecological and economic significance, comprehensive water studies aimed at an integrated assessment of the role of waterfalls in biodiversity conservation and sustainable water resource management remain relatively rare. This highlights the need for further empirical and interdisciplinary approaches to the study of waterfall ecosystems in Nigeria, especially in the context of increasing anthropogenic pressure and tourism development (Adejuwon & George, 2024; Bashiru et al., 2024).

Limnology provides an integrative scientific framework for assessing the physical, chemical, and biological characteristics of inland waters, as well as for understanding the functioning, resilience, and ecological health of aquatic ecosystems (Wetzel, 2001; Mahdzir et al., 2024). Key limnological variables, including water temperature, pH, dissolved oxygen, electrical conductivity, nutrient content, and suspended solids, play a critical role in shaping the structure and functioning of aquatic biota, particularly primary producers such as algae (Chapman, 2021; APHA, 2017; Li et al., 2025). In lotic ecosystems, flow-through streams can generate local heterogeneity in physical and chemical parameters through intense aeration, increased turbulence, sediment resuspension, and spatiotemporal variability in light conditions, which significantly influences the distribution, structure, and productivity of algal communities (Vannote et al., 1980; Biggs & Smith, 2002; Soeprobowati & Jumari, 2022; Li et al., 2025).

Algae are a fundamental component of freshwater ecosystems and play a central role in food webs, serving as major primary producers that mediate energy flow, nutrient cycling, and overall ecosystem metabolism (Reynolds, 2006; Lobus, 2022). Both phytoplanktonic and benthic or periphytic forms of algae are highly sensitive to changes in the chemical composition and hydrological regime of waters, making them reliable bioindicators of the ecological state and quality of water (Stevenson et al., 2012). In high-energy environments such as waterfalls, algal communities typically comprise stress-tolerant taxa, including diatoms and filamentous green algae adapted to strong currents and fluctuating nutrient availability (Round et al., 1990; Atazadeh, 2023; Wei et al., 2025).

Studies conducted in rivers and reservoirs in Nigeria have shown that the spatiotemporal dynamics of algae are largely regulated by limnological conditions, particularly nutrient availability, electrical conductivity, and dissolved oxygen concentration (Kadiri, 2006a; Kadiri, 2006b; Akhere & Kadiri, 2023; Essien et al., 2025). Nevertheless, the majority of limnological studies based on algal analysis in Nigeria have focused on rivers, lakes, and reservoirs, whereas waterfall ecosystems remain poorly investigated. This represents a significant knowledge gap, as waterfalls are capable of supporting distinctive algal communities due to enhanced aeration, reduced sedimentation rates, frequent physical disturbances, and localized nutrient inputs associated with anthropogenic activities, including bathing, washing, and tourism.

For Erin-Ijesha Waterfall (Olumirin), located in Osun State, southwestern Nigeria, significant spatial variations in water quality have been recorded between the upper, middle, and lower sections of the cascade. Concentrations of major ions (Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, NO_3^-, and PO_4^{3-}) and total water hardness increase downstream, indicating the accumulation of dissolved substances in the lower sections (Adejuwon & George, 2024). Moreover, bacteriological analyses revealed exceedances of safe levels of total bacterial counts and the presence of Escherichia coli, particularly in the lower sections of the waterfall, indicating microbiological contamination and potential health risks associated with recreational water use (Adejuwon & George, 2024; Odeyemi et al., 2023). These patterns are frequently attributed to anthropogenic pressures, including tourism, direct human-water contact, and surface runoff, highlighting the need for comprehensive limnological assessments of cascade water ecosystems under increasing recreational stress.

Numerous studies demonstrate that multicomponent stressors, including flow changes, excess nutrients, and anthropogenic impacts, influence the structure and species composition of algal communities, making them sensitive indicators of changes in aquatic ecosystem health (Taurozzi, 2025). Despite the ecological significance of waterfalls, integrated studies of their limnological characteristics and algal composition remain rare in Nigeria. This limits our understanding of the functioning of these ecosystems and their response to natural and anthropogenic impacts. Incorporating algal studies is particularly important, as their species composition and abundance are early indicators of nutrient levels, organic pollution, and ecosystem disturbances (Stevenson, 2014; Rojo et al., 2025). This integrated approach allows for a more comprehensive understanding of ecosystem health and provides valuable baseline data for its management and conservation.

The scientific objective of the current study is to conduct a comprehensive limnological and algal assessment of Erin Ijesha Falls, focusing on the spatial distribution of physicochemical water parameters, algal species composition, and the application of the Palmer Index to assess water quality and ecological status.

Scientific hypotheses suggest that spatial variations in the physicochemical parameters of the waterfall's waters create a characteristic water quality gradient. The study is expected to confirm that algal communities reflect these hydrochemical gradients and can serve as sensitive bioindicators of anthropogenic impact. The Palmer index is expected to reveal hidden signs of organic pollution that are not detectable by standard physicochemical measurements. Thus, the study aims to gain new knowledge about the limnological dynamics of cascading water systems in the tropics, identify key factors influencing water quality and biodiversity, and establish a basis for the effective management and conservation of these ecosystems.

MATERIALS AND METHODS

Study area

The study was conducted at Erin-Ijesha (Olumirin) Waterfall, located in Erin-Ijesha town, Osun State, southwestern Nigeria (7°30′N, 4°55′E) (Figures 1). The waterfall consists of multiple cascading levels with associated plunge pools and downstream channels.

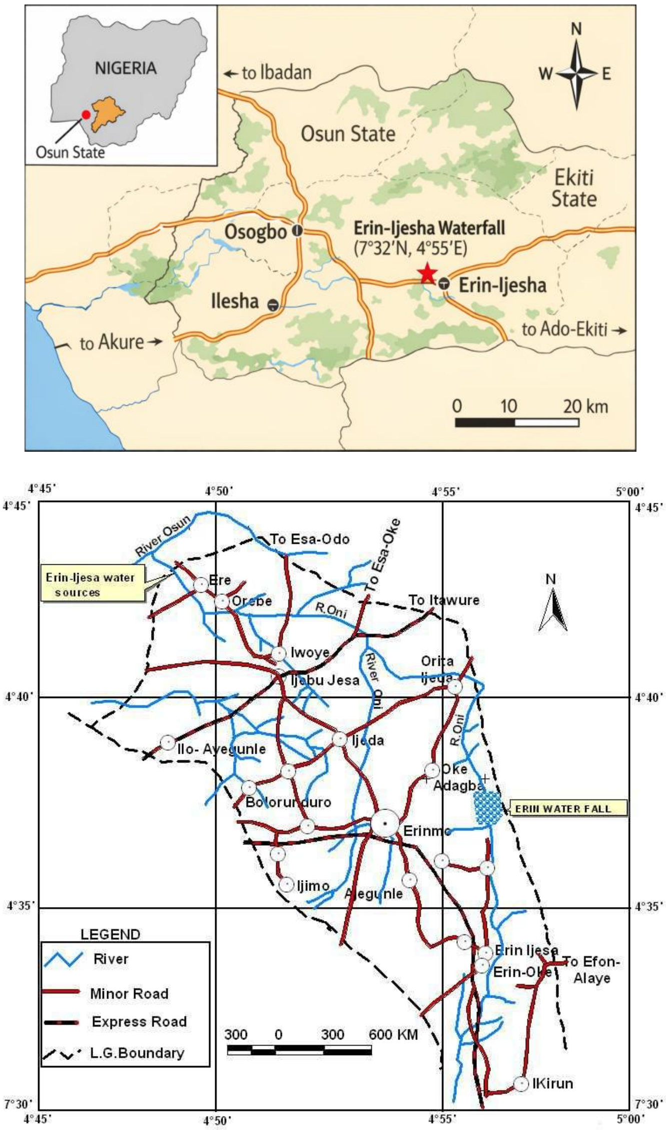

Figure 1. Map of Erin-Ijesha Waterfall

Sampling procedure

Sampling was conducted during the dry season of 2024 to minimize seasonal variability in hydrological and physicochemical parameters. Integrated water and algal samples were collected from the upper, middle, and lower sections of seven waterfall cascades, with three replicates per site to ensure representativeness.

Water samples were collected following ISO 5667-3:2024 and Nigerian standards (SON/NSQ 554:2016) using pre-rinsed, sterilized 1 L polyethylene or glass bottles at 0.3–0.5 m depth. Integrated samples were obtained by combining sub-samples from multiple points within each section to account for spatial heterogeneity.

Algal samples were collected via periphyton scraping from submerged substrates (rocks, roots, and sediments) using brushes and mesh sieves (20–50 µm) in accordance with APHA (2017) and Nigerian environmental monitoring guidelines (NESREA, 2018). Biological samples were preserved in Lugol's solution or 4% formalin for laboratory analysis.

Sampling was performed at hourly intervals between 08:00 and 16:00 to reduce the effects of diurnal fluctuations in temperature, light, and flow conditions. All equipment was rinsed with deionized water before use, and samples were transported in cooled containers at 4°C and analysed within 24 hours of collection.

Physico-chemical analysis

Surface water samples were collected in pre-cleaned, sterilized polyethylene bottles in accordance with international and Nigerian standards (ISO 5667-3:2024; SON/NSQ 554:2016). To minimize contamination, all bottles and sampling equipment were rinsed three times with the water to be sampled prior to collection. Integrated water samples were obtained from multiple points within each cascade section and combined to account for spatial variability, following ISO 5667-3:2024 guidelines.

In situ measurements of temperature, pH, electrical conductivity, and dissolved oxygen were conducted immediately after sample collection using a calibrated multiparameter probe (APHA, 2017). The probe was calibrated daily according to the manufacturer's instructions and international best practices to ensure accuracy. Measurements were taken at 0.3–0.5 m depth at multiple points within each sampling site, and average values were recorded for each replicate.

For laboratory analyses, water samples were transported in cooled containers (4 °C) and analysed within 24 hours. Concentrations of nutrients, including nitrates (NO_3^-) and orthophosphates (PO_4^{3-}), as well as other physicochemical parameters such as total dissolved solids (TDS), total hardness, and major ions (Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, Fe), were determined following the procedures described in APHA (2017). Analytical techniques included spectrophotometry for nutrient quantification, titrimetric methods for hardness, and ion-specific electrodes for major ions, in compliance with both international (ISO 5667-3:2024) and Nigerian (SON/NSQ 554:2016) water quality standards.

All results were reported in standard units and checked against Nigerian drinking water and surface water quality guidelines (NESREA, 2018) to assess compliance and potential ecological risks. Replicate measurements were performed to ensure precision and reliability, and quality control included the use of blanks, standards, and duplicates as recommended in APHA (2017) and ISO guidelines.

Algal sampling and identification

Periphytic algae were collected from the substrate by gently scraping the submerged rocks with a soft brush within predetermined study areas. The scraped material was washed with distilled water to remove impurities, after which it was preserved using 1% Lugol's iodine solution. For diatoms, acid digestion was used where necessary to remove organic matter and obtain purified cells. After concentration, no additional preservation procedures were required, as Lugol's iodine solution ensured long-term storage of the samples and stabilization of morphological features.

Algae were identified in the laboratory to the genus or species level using standard taxonomic keys and reference books (Round et al., 1990; Bellinger & Sigee, 2010). A compound light microscope was used for observations, allowing for a detailed examination of the morphological features of cells and structures characteristic of each taxon. The main identification criteria were cell shape and size, cell wall structure, colony organization (for colonial forms), and the presence of characteristic morphological features, including plastids, septa, and sclerophylls, where appropriate. All samples were documented, including the location and date of collection, as well as environmental conditions such as temperature, illumination, and water flow velocity, for further analysis of algal diversity and distribution.

Palmer Pollution Index Determination

To assess the degree of organic pollution in water bodies, the Palmer index was used. It is based on the presence and relative abundance of algal genera resistant to organic pollutants (Palmer, 1969). The Palmer index is used because it allows for a quantitative assessment of the impact of organic pollutants on the structure of aquatic flora, identifies both weak and significant anthropogenic impacts on the ecosystem, and provides a standardized basis for inter-station and inter-annual comparisons.

After identifying algae to the genus level, each genus was assigned a pollution resistance score according to the original Palmer scale.

The index for each study station was calculated as the sum of the resistance indices of all registered genera present in the sample, using the formula:

$$\text{Palmer index} = \sum P_i, \quad (1)$$

where P_i – pollution resistance indices of registered genera.

The following classification was used to interpret the obtained values (Labib et al., 2023; Okoye & Ogbebor, 2023):
– < 10 – no organic pollution;
– 11–14 – moderate organic pollution;
– > 15 – high organic pollution.

RESULTS

Physico-chemical parameters

Air and water temperatures (Figure 2) at Erin-Ijesha Waterfall exhibited clear diurnal warming trends, reflecting solar radiation patterns typical of tropical freshwater systems. Air temperature increased markedly from 20°C in the early morning (08:00–09:00) to a maximum of 33°C at 15:00, before a slight decline to 32.5°C by 16:00. In contrast, water temperature showed a more gradual increase, ranging from 19°C in the morning to a maximum of 26.5°C in the mid- to late afternoon.

Turbidity values at Erin-Ijesha Waterfall during the diurnal sampling period ranged from 6 to 13 nephelometric turbidity units (NTU) (Figure 3), indicating generally low to moderate suspended particulate load in the water column. The highest turbidity value was recorded in the early morning (13 NTU at 09:00), followed by a general decline and stabilization between 6 and 8 NTU for most of the day, with a secondary increase at 14:00 (11 NTU).

Colour values remained consistently low, ranging from 1 to 4 PtCoU (Figure 3). The lowest colour value was observed at 15:00 (PtCoU), coinciding with relatively low turbidity, and slightly elevated colour values at 10:00 and 14:00 (PtCoU).

The electrical conductivity and total dissolved solids (TDS) of Erin-Ijesha Waterfall exhibited consistently low values throughout the diurnal sampling period, ranging narrowly between 29 and 32 µS cm⁻¹, while TDS varied between 14 and 16 mg L⁻¹ (Figure 4).

The pH values of Erin-Ijesha Waterfall during the diurnal sampling period (08:00–16:00) ranged narrowly between 6.42 and 6.65 (Figure 5), reflecting a slightly acidic to near-neutral condition throughout the day. There was a gradual increase in pH from morning to late afternoon.

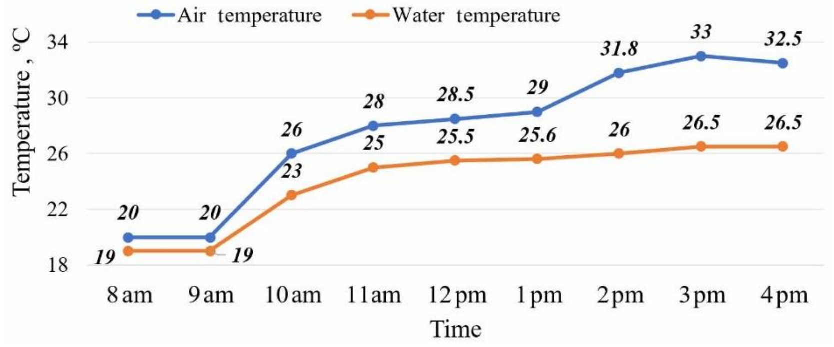

Figure 2. Temperature variation of Erin-Ijesha Waterfall

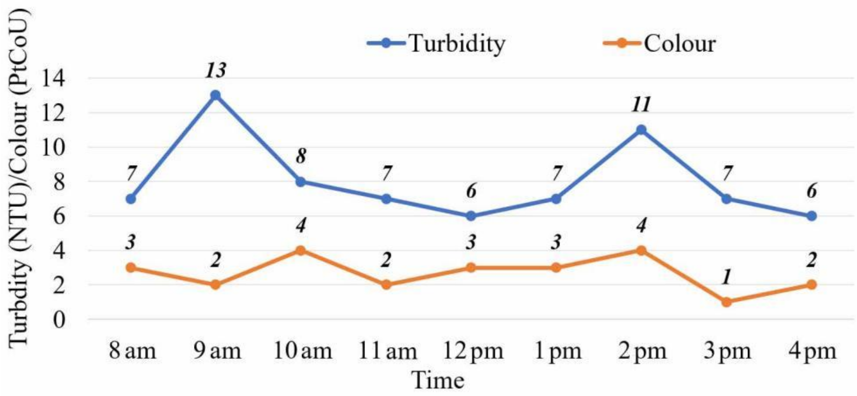

Figure 3. Turbidity and colour variation of Erin-Ijesha Waterfall

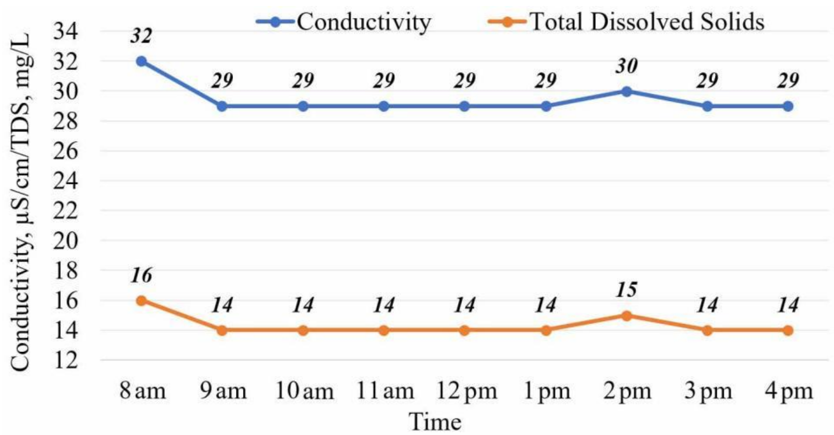

Figure 4. Electrical conductivity and total dissolved solids variation of Erin-Ijesha Waterfall

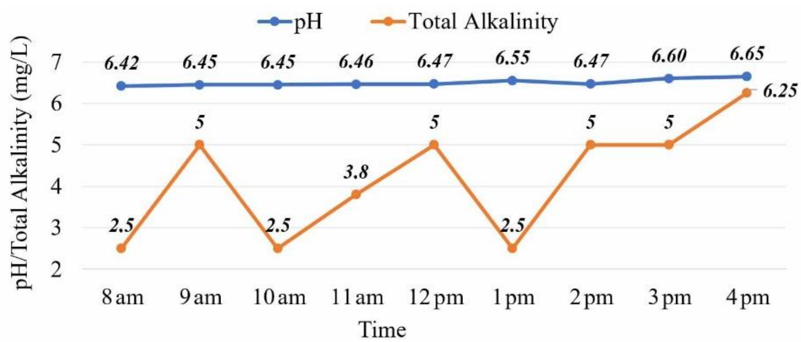

Figure 5. pH and Total alkalinity variation of Erin-Ijesha Waterfall

Total alkalinity values ranged from 2.5 to 6.25 mg L^{-1} (Figure 5), indicating low buffering capacity of the waterfall system. There was fluctuation in alkalinity during the day, particularly the higher values recorded at 09:00, 12:00, 14:00, 15:00, and 16:00.

Dissolved oxygen (DO) values during the diurnal monitoring period (08:00–16:00) ranged from 8.0 to 10.5 mg L^{-1}, indicating generally well-oxygenated conditions at the waterfall (Figure 6).

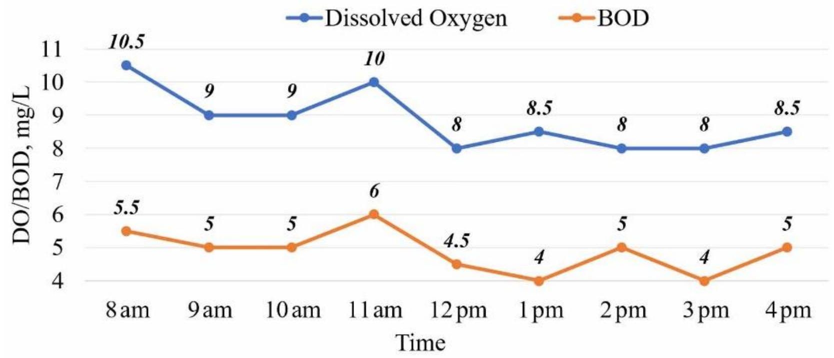

Figure 6. Dissolved Oxygen (DO) and Biological Oxygen Demand (BOD) variation of Erin-Ijesha Waterfall

The highest DO concentration was recorded in the early morning (10.5 mg L^{-1} at 08:00), followed by a gradual decline toward midday and afternoon, where values stabilized between 8.0 and 8.5 mg L^{-1}.

The concentrations of nutrients- sulphate (SO_4^{2-}), nitrate (NO_3^-), and phosphate (PO_4^{3-}) recorded at Erin-Ijesha Waterfall (Figure 7) exhibit low to moderate levels with pronounced diurnal variability, reflecting the dynamic nature of waterfall ecosystems and the influence of both natural processes and localized anthropogenic inputs. Sulphate concentrations ranged from 1 to 3 mg L^{-1}, with occasional midday and afternoon peaks (3 mg L^{-1} at 13:00 and 15:00). Nitrate concentrations remained relatively low, fluctuating between 0.2 and 0.7 mg L^{-1}, with slight mid-day elevations. Phosphate concentrations showed greater variability than nitrate, ranging from 0.09 to 0.49 mg L^{-1} (Figure 7), with short-term peak values recorded around late morning to midday (11:00–12:00).

Sulphate concentrations ranged from 1–3 mg L^{-1} (Figure 7) over the sampling period, showing minor temporal fluctuations with no pronounced accumulation, indicating limited anthropogenic sulphate input and stable geochemical conditions.

The results show consistently low to moderate water hardness, with total hardness values ranging from 5 to 15 mg L^{-1}, (Figure 8) indicating generally soft water conditions. Calcium concentrations varied narrowly between 2 and 4 mg L^{-1}, while magnesium ranged from 0.61 to 2.44 mg L^{-1} (Figure 8). In most samples, calcium contributed slightly more than magnesium to the total hardness, although magnesium showed greater variability.

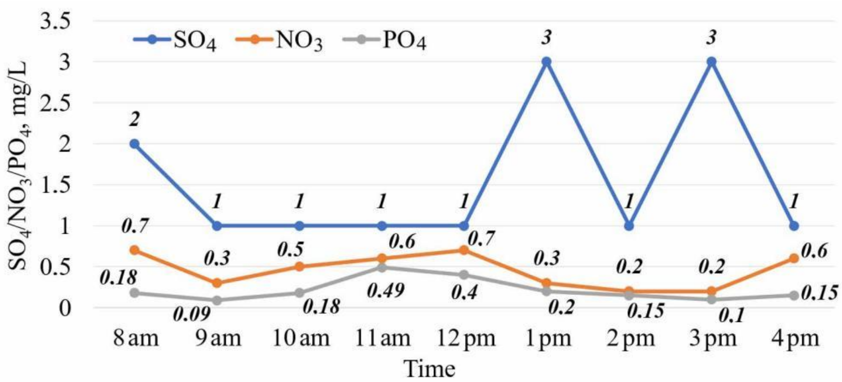

Figure 7. Variation of nutrients in Erin-Ijesha Waterfall

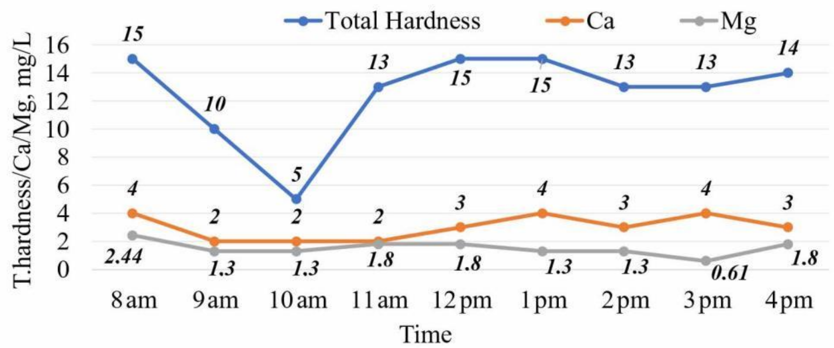

Figure 8. Variation of total hardness, Ca and Mg in Erin-Ijesha Waterfall

Algal composition of Erin-Ijesha Waterfall

Table 1 shows the composition of algae in the waterfall. The algal assemblage comprised 4 divisions, 5 Classes, 14 Orders, 26 Families, 35 genera, and 78 taxa. The divisions were notably Bacillariophyta (diatoms), Chlorophyta (green algae), Xanthophyta (yellow-green algae), and Cyanobacteria (blue-green algae). The bulk of the algae were members of the Chlorophyta division, comprising 42.3% of the total, and consisted of 7 Orders, 11 Families, 12 genera, and 33 taxa. The Order with maximum representation of taxa was *Zygnematales*, with 8 taxa of Desmidiaceae (Closterium (3 taxa), Spirogyra (4 taxa) and Mougeotia (1 taxon). Next in importance was the

Order Ulotrichales, with 6 taxa of *Microspora species* (4), *Monoraphidium graffithii*, and *Ulothrix acuminata*. Other Orders *Chaetophorales*, *Chlorococcales*, *Cladophorales* and *Oedogoniales* were represented by one or two species.

The division Bacillariophyta or diatoms comprised 38.5% composition of the total algae. These were made up of the conventional Orders of Centrales and Pennales. Centrales consisted of only two Families-Biddulphiaceae (*Terpsinoe musica*), and Coscinodiscaceae (*Melosira varians*). The majority of the diatoms were members of the Order Pennales. Of these, the Family with the largest number of taxa was Fragillariaceae-Synedra (12 species), *Asterionella formosa*, *Diatoma confervacea*, and *Tabellaria* sp. Naviculaceae was next with 9 taxa (*Navicula*-4 spp, and *Pinnularia*-5 spp). The division Xanthophyta was represented solely by *Vaucheria* sp, Cyanobacteria division was made up of mainly the Order Oscillatoriales with 6 taxa (*Lyngbya* sp, *Microcoleus* sp., *Oscillatoria princeps*, *Phormidium tenue*, *Phormidium calcicola*, and *Spirulina maxima*). The second Order Nostocales comprised only two taxa (*Nostoc commune*, and *Scytonema crispum*).

Palmer pollution index of Erin-Ijesha Waterfall

A Palmer Index score of 19 classifies Erin Ijesha Falls as likely to have high organic pollution. Detailed individual index values for each of the 20 algae studied are presented in Table 2.

Table 1. Algal composition of Erin-Ijesha Waterfall

Divisions	Classes	Orders	Families	Genera	Taxa	Composition, %
Bacillariophyta	Bacillariophyceae	3	10	14	30	38.5
Chlorophyta	Chlorophyceae	7	11	12	33	42.3
	Klebsormidiophyceae	1	1	1	1	1.3
Cyanophyta	Cyanophyceae	2	3	7	13	16.7
Xanthophyta	Xanthophyceae	1	1	1	1	1.3
Total 4	**5**	**14**	**26**	**35**	**78**	**100**

Table 2. Palmer Pollution Index scores at Erin-Ijesha Waterfall

Genus	P_i value	Erin-Ijesha Waterfall	Genus	P_i value	Erin-Ijesha Waterfall
Anacystis	1	–	*Micractinum*	1	–
Ankistrodesmus	2	–	*Navicula*	3	3
Chlamydomonas	4	–	*Nitzschia*	3	3
Chlorella	3	–	*Oscillatoria*	5	5
Closterium	1	1	*Pandorina*	1	–
Cyclotella	1	–	*Phacus*	2	–
Euglena	5	–	*Phormidium*	1	1
Gomphonema	1	1	*Scenedesmus*	4	–
Lepocinclis	1	–	*Stigeoclonium*	2	2
Melosira	1	1	*Synedra*	2	2
Total	**19**				

DISCUSSION

The discussion interpretation is supported by nutrient dynamics, oxygen balance, ionic composition, and biological indicators, particularly diatoms and pollution-tolerant algal taxa.

Physicochemical regime and diurnal variability

Water temperatures followed a predictable diurnal cycle, rising from 19°C in the early morning to around 26.5°C by mid-afternoon, closely tracking air temperature (Figure 3) but remained within the optimal range for tropical freshwater biota and algal metabolism. This modest thermal amplitude or dampened response of water temperature relative to air temperature is characteristic of lotic environments, where continuous flow, shading, effective heat exchange, and evaporative cooling moderate thermal fluctuations. This moderate thermal amplitude variation is considered characteristic of waterfall ecosystems and does not exceed ranges extreme enough to cause stress to most freshwater organisms (Jones et al., 2017).

The observed thermal regime emphasizes the limited buffering capacity of the waterfall system, as water temperature lagged behind increases in air temperature by approximately 6–7°C during periods of peak heating. This thermal stability is ecologically significant, given that abrupt fluctuations in temperature can impose physiological stress on aquatic biota. The relatively narrow diurnal range of water temperature recorded supports favourable metabolic conditions for algae, invertebrates, and microbial communities, and corresponds with the high concentrations of dissolved oxygen observed within the system. Cooler water temperatures in the morning likely enhanced oxygen solubility, whereas the modest warming observed in the afternoon did not reach levels associated with oxygen depletion or thermal stress for tropical freshwater organisms.

The low colour and turbidity of the water indicate high clarity and limited concentrations of dissolved coloured substances, including humic and fulvic acids. Slightly elevated colour values recorded at 10:00 and 14:00 (PtCoU) may be attributed to transient increases in suspended organic matter or fine particulate material. Crucially, the absence of persistently high colour values suggests minimal influence from decomposing organic debris or stained runoff originating from surrounding vegetation, which is consistent with a well-aerated, fast-flowing waterfall environment. From an ecological perspective, the combination of low turbidity and low colour enhances light penetration, thereby promoting photosynthetic activity of periphytic algae and submerged primary producers.

The pH ranged narrowly from 6.42 to 6.65, indicating slightly acidic conditions, consistent with forested and granite-derived catchments in southwestern Nigeria. These values fall within the acceptable limits established by the World Health Organization (WHO, 2017) (6.5–8.5) and the Nigerian Standard for Drinking Water Quality (SON/NSQ, 2015), and are favourable for diatoms and chlorophytes, which frequently dominate slightly acidic waters (Round et al., 1990). The observed gradual increase in pH from morning to late afternoon may be attributed to enhanced photosynthetic activity of algae and macrophytes, which removes dissolved CO_2 from the water column, thereby shifting the carbonate equilibrium toward higher pH values. Slightly acidic pH is characteristic of many tropical freshwater systems, particularly those draining crystalline basement rocks and forested catchments, where organic matter inputs and limited carbonate weathering exert a dominant influence on water chemistry.

Total alkalinity ranged from 2.5 to 6.25 mg L^{-1}, indicating a low buffering capacity of the waterfall system. Such low alkalinity is typical of upland streams and waterfalls, where rapid water turnover, limited residence time, and low bicarbonate concentrations prevail. The observed diurnal fluctuations in alkalinity, particularly the elevated values recorded at 09:00, 12:00, 14:00, 15:00, and 16:00, may reflect short-term variations in bicarbonate availability influenced by groundwater seepage, localized mineral dissolution, and biological processes. Nevertheless, the generally low alkalinity suggests that the system is potentially sensitive to acidification, as even minor acidic inputs could produce measurable shifts in pH.

Overall, the pH and total alkalinity data indicate that Erin-Ijesha Waterfall functions as a weakly buffered, oligotrophic to mildly mesotrophic freshwater system, predominantly regulated by natural geochemical processes and biological activity rather than anthropogenic disturbance. Low-alkalinity systems are particularly vulnerable to environmental changes, including increased nutrient loading, acid deposition, or alterations in land use within the catchment.

From an ecological perspective, the combination of slightly acidic pH and low alkalinity has significant implications for the algal community structure observed at Erin-Ijesha Waterfall. Many freshwater diatoms (e.g., *Navicula* Bory, *Pinnularia* Ehrenberg, *Synedra* Ehrenberg) and green algae (e.g., *Closterium* Ehrenberg, *Spirogyra* Link, *Mougeotia* Agardh) are well adapted to such conditions, which accounts for their dominance in the algal assemblage. Conversely, strongly alkaliphilic taxa are expected to be underrepresented.

The low absolute concentrations of both calcium and magnesium suggest minimal mineral enrichment, consistent with dilute freshwater systems influenced by limited geological weathering and/or high flushing rates. The Ca–Mg balance and low total hardness reflect a soft, weakly buffered water body with low ionic strength.

The waterfall maintained consistently high dissolved oxygen (DO) concentrations (8.0–10.5 mg L^{-1}) throughout the day, exceeding WHO and Nigerian minimum thresholds of 5 mg L^{-1} for aquatic life. These values indicate well-oxygenated conditions characteristic of turbulent waterfall systems and align with WHO (2017) and Nigerian Federal Ministry of Environment (FMEnv, 2011) guidelines for good-quality surface waters. This pattern is characteristic of lotic waterfall systems, where intense turbulence and aeration maintain high oxygen levels, while increasing temperature and biological activity during the day slightly reduce oxygen solubility (Wetzel, 2001; Kalff, 2002). The consistently high DO values suggest favourable conditions for aerobic aquatic organisms, including periphytic algae and invertebrates. The high DO values were accompanied by low biological oxygen demand (BOD: 4.0–6.0 mg L^{-1}). The highest BOD value (6.0 mg L^{-1}) was observed at 11:00, coinciding with increased human activity and possibly enhanced microbial decomposition of organic matter. Lower BOD values recorded in the early afternoon (4.0–4.5 mg L^{-1}) suggest periods of reduced organic loading or efficient oxygen replenishment through waterfall aeration. The generally moderate BOD levels indicate the presence of biodegradable organic matter, but not at concentrations sufficient to cause oxygen depletion, corroborating the Palmer Pollution Index value of 19, which reflects slight organic enrichment but not severe pollution.

This inverse but balanced DO–BOD relationship suggests limited organic loading and efficient re-aeration, and strong self-purification capacity typical of lotic, well-mixed environments (Chapman, 2021; WHO, 2017).

Electrical conductivity (29–32 µS cm^{-1}) and total dissolved solids (14–16 mg L^{-1}) were consistently very low, reflecting low ionic strength and limited mineral dissolution, and therefore, confirming the oligotrophic to low-mesotrophic ionic status of the waterfall and minimal mineral or wastewater inputs. These values are characteristic of waters draining crystalline basement rocks common in southwestern Nigeria and suggest minimal anthropogenic ion inputs (Kayode et al., 2024). These values are well below WHO and NSDWQ thresholds and align with pristine or lightly disturbed headwater systems.

Turbidity (6–13 NTU) and colour (1–4 Pt-Co units) showed modest diurnal fluctuations, with short-term peaks likely linked to visitor activity and sediment re-suspension rather than chronic pollution. The water clarity remained acceptable for algal photosynthesis and benthic colonization (Dodds et al., 2013).

Nutrients dynamics and ionic composition

The nutrients concentrations of sulphate (SO_4^{2-}), nitrate (NO_3^-), and phosphate (PO_4^{3-}) recorded at Erin-Ijesha Waterfall exhibit low to moderate levels with pronounced diurnal variability, reflecting the dynamic nature of waterfall ecosystems and the influence of both natural processes and localized anthropogenic inputs. Nitrate concentrations remained relatively low, fluctuating between 0.2 and 0.7 mg L^{-1}, with higher values observed during the morning and late afternoon. Such concentrations are characteristic of tropical freshwater systems receiving intermittent nutrient inputs from organic matter decomposition, surface runoff, and human activities such as bathing and tourism. The absence of sustained high nitrate levels suggests that the system is not subject to chronic nutrient loading, but rather experiences episodic enrichment followed by rapid dilution and biological uptake. This pattern is consistent with highly aerated lotic environments, where rapid water turnover and assimilation by primary producers limit nitrate accumulation.

Phosphate concentrations exhibited greater variability than nitrate, ranging from 0.09–0.49 mg L^{-1}, with peak values recorded around late morning to midday (11:00–12:00). The observed phosphate peaks during this period may reflect short-term inputs from surface runoff or enhanced mineralization under increasing temperature and light conditions. The transient midday increase in phosphate likely reflects localized inputs or internal recycling, but did not reach concentrations typically associated with nuisance algal blooms. Phosphate is often the limiting nutrient in freshwater ecosystems, and even moderate increases can stimulate algal growth. Elevated phosphate levels observed during these periods may be attributed to increased human activity, re-suspension of sediments, and localized inputs of organic matter. Although these values indicate moderate nutrient availability, they remain below thresholds commonly associated with severe eutrophication, particularly in systems with strong hydraulic flushing such as waterfalls. These concentrations are consistent with World Health Organization guidelines (WHO, 2017) and align with values reported for moderately productive tropical streams and relatively undisturbed lotic systems (Wetzel, 2001).

Sulphate concentrations ranged from 1–3 mg L^{-1}, with occasional midday and afternoon peaks (3 mg L^{-1} at 13:00 and 15:00). These low but stable concentrations are typical of unpolluted to mildly impacted freshwater systems and are likely derived from natural rock weathering, atmospheric deposition, and surface runoff rather than industrial sources. The absence of persistently elevated sulphate values suggests limited influence of sulphate-rich effluents and supports the classification of the waterfall as only moderately impacted.

The combined nutrient profile indicates that Erin-Ijesha Waterfall exhibits mesotrophic tendencies, characterized by sufficient nutrient availability to support diverse algal communities without inducing excessive biomass accumulation. This interpretation aligns with the observed algal assemblage, where green algae (Chlorophyta) and diatoms (Bacillariophyta) dominated, alongside moderate representation of cyanobacteria. The presence of filamentous green algae (*Spirogyra* Link, *Microspora* Kützing) and diatoms (*Navicula* Bory, *Synedra* Ehrenberg) is consistent with moderate nitrate and phosphate availability, whereas the occurrence of pollution-tolerant cyanobacteria (*Oscillatoria* Gomont, *Phormidium* Kützing) suggests episodic organic and nutrient enrichment rather than persistent eutrophic conditions.

Importantly, the nutrient dynamics corroborate the Palmer Pollution Index (PPI) value of 19, indicating moderate organic pollution. The absence of consistently elevated nitrate and phosphate concentrations explains the maintenance of relatively high algal diversity and the lack of observed oxygen depletion, despite moderate biological oxygen demand. Overall, the sulphate, nitrate, and phosphate data indicate that Erin-Ijesha Waterfall maintains a functional nutrient balance, although continued anthropogenic pressure could shift the system toward higher trophic status if nutrient inputs exceed the system's assimilative capacity.

Algae

The algal community structure of Erin-Ijesha Waterfall reflects the combined influence of flowing-water dynamics, substrate heterogeneity, and moderate nutrient availability typical of tropical waterfall systems. The assemblage recorded in this study—comprising 78 taxa distributed across four algal divisions—demonstrates relatively high algal richness for a lotic waterfall environment, where hydraulic disturbance often constrains algal diversity (Biggs & Smith, 2002; Wehr et al., 2015). The dominance of Chlorophyta (42.3%) and *Bacillariophyta* (38.5%) suggests a system that supports both attached periphytic communities and filamentous or loosely attached forms adapted to fluctuating flow regimes.

The predominance of Chlorophyta, particularly members of the order Zygnematales (e.g., *Spirogyra, Closterium, Mougeotia*), indicates favourable light conditions and relatively low turbidity, as these taxa are known to thrive in well-illuminated freshwater environments with moderate nutrient enrichment (Rathore et al., 2025; John et al., 2011, John et al., 2022). Zygnematalean desmids are often associated with slightly acidic to circumneutral waters and are sensitive to extreme pollution (Kadiri, 2002), suggesting that the waterfall maintains conditions that are not severely degraded. Similarly, the presence of Ulotrichales (e.g., *Microspora, Ulothrix*) points to good oxygenation and the availability of stable substrates, such as rocks and submerged surfaces typical of waterfall splash zones.

Diatoms (Bacillariophyta) constituted a substantial proportion of the algal flora, with pennate diatoms dominating over centric forms. The high representation of *Synedra*, *Navicula*, and *Pinnularia* species is characteristic of flowing freshwater systems and reflects their strong adaptive capacity to lotic habitats through efficient attachment mechanisms and tolerance to shear stress (Stevenson et al., 2012). The presence of *Asterionella formosa* and *Diatoma confervacea* further suggests mesotrophic tendencies, as these taxa are frequently reported in waters with moderate nutrient concentrations and good oxygen availability (Kumar & Nautiyal, 2024; Van Dam et al., 1994).

The relatively limited occurrence of Xanthophyta, represented solely by *Vaucheria* sp., is consistent with observations from many tropical freshwater systems, where this group typically forms a minor component of the algal flora. *Vaucheria* is often associated with shallow, well-oxygenated waters and may colonize moist rock surfaces around waterfalls, benefiting from constant spray and nutrient inputs (Wehr et al., 2015).

Cyanobacteria accounted for 16.7% of the total taxa and were dominated by filamentous Oscillatoriales, including *Oscillatoria, Lyngbya*, and *Phormidium*. These genera are ecologically significant because of their well-documented tolerance to organic enrichment and fluctuating environmental conditions (Palmer, 1969; Whitton & Potts, 2012). The presence of *Nostoc commune and Scytonema crispum* (Nostocales) further suggests episodic nutrient enrichment and the availability of stable substrates, as these taxa are capable of nitrogen fixation and often colonize rock surfaces in splash zones.

The PPI value of 19 places Erin-Ijesha Waterfall within the category of moderate organic pollution according to Palmer's classification (Palmer, 1969). This score reflects the occurrence of pollution-tolerant genera such as *Oscillatoria, Phormidium, Navicula, Nitzschia, Synedra,* and *Stigeoclonium*. Importantly, a PPI value of 19 does not indicate severe pollution but rather suggests moderate organic loading, potentially arising from tourism activities, surface runoff, or localized anthropogenic inputs upstream. This interpretation aligns with the coexistence of pollution-tolerant cyanobacteria alongside more sensitive green algae and diverse diatom assemblages.

Overall, the algal composition and Palmer Index together indicate that Erin-Ijesha Waterfall is ecologically productive but moderately impacted, maintaining relatively good water quality while showing early signs of organic enrichment. Such conditions are common in popular waterfall systems in southwestern Nigeria, where natural aeration and flow mitigate severe degradation but increasing human activity exerts measurable ecological pressure (Akachukwu et al., 2025, Olalere et al., 2020). The results underscore the value of algal bioindicators in assessing subtle changes in water quality that may not be immediately evident from physicochemical parameters alone.

Algal assemblage structure and bioindication

The algal community was taxonomically rich, comprising 78 taxa across four divisions, with dominance of Chlorophyta (42.3%) and Bacillariophyta (38.5%) (Table 1). The prevalence of green algae such as *Spirogyra*, *Closterium*, and *Mougeotia* is typical of clean to slightly enriched freshwater systems with adequate light and low to moderate nutrient availability. Their abundance supports the interpretation of generally good water quality, while their coexistence with diatoms indicates habitat heterogeneity and stable substrata.

Diatoms, particularly members of the Fragillariaceae (*Synedra spp., Asterionella formosa, Diatoma confervacea*) and Naviculaceae (*Navicula* spp., *Pinnularia* spp.), are central to widely used diatom indices, and provide more refined ecological signals. Many of these taxa are characteristic of oligotrophic to mesotrophic (*Synedra, Navicula,* and *Pinnularia* are generally associated with mesotrophic conditions), well-oxygenated waters and are widely used in standard diatom indices such as the Trophic Diatom Index (TDI) and the Specific Pollution Sensitivity Index (IPS) (Kelly et al., 2008). For example, *Asterionella formosa* and *Synedra* spp. are typically associated with low to moderate nutrient conditions, while several *Navicula* and *Pinnularia* species exhibit moderate tolerance to organic enrichment but still favour relatively clean waters.

The PPI score of 19 further corroborates this interpretation, placing Erin-Ijesha Waterfall in the moderate organic pollution category. The presence of Palmer-listed pollution-tolerant taxa cyanobacteria such as *Oscillatoria, Lyngbya, Phormidium,* and *Spirulina* further supports the interpretation of slight organic influence without severe degradation (Palmer, 1969). When viewed alongside the PPI score of 19, the algal assemblage suggests incipient organic enrichment rather than outright pollution, a pattern commonly reported for freshwater systems exposed to low-intensity human activities such as tourism and localized runoff (Palmer, 1969; Stevenson et al., 2012, Stevenson, 2014).

Integrated ecological assessment

The physicochemical characteristics and algal assemblages of Erin-Ijesha Waterfall collectively indicate a largely unpolluted, well-oxygenated freshwater system of generally good ecological quality, with limited anthropogenic disturbance. The ecosystem can be characterized as moderately disturbed yet ecologically resilient. The observed concordance between low conductivity and TDS, high DO, moderate nutrient concentrations, and the dominance of sensitive diatom and green algal taxa provides strong support for this assessment.

The integration of water chemistry, diurnal variation patterns, and biological indicators, including algal composition and the Palmer Pollution Index, offers a robust framework for evaluating the limnological status of the waterfall (Tables 1–2; Figures 3–8). Algal index scores serve as sensitive early-warning indicators that complement conventional water chemistry, highlighting the utility of integrated bio-limnological approaches. Importantly, this study underscores the value of combining classical limnological measurements with algal bioindicators for comprehensive assessment of freshwater quality in tropical waterfall ecosystems.

CONCLUSION

This study provided a comprehensive limnological and algal assessment of Erin Ijesha Falls (Olumirin), providing important baseline data on the condition of this freshwater ecotourism site in southwestern Nigeria. Analysis of the spatial distribution of physicochemical parameters revealed that the falls' waters are of generally good quality: pH ranges from slightly acidic to near-neutral, high dissolved oxygen, low BOD, low electrical conductivity and total mineralization, and relatively low nutrient concentrations. These characteristics indicate intense hydrodynamic mixing, effective aeration, and limited ion and organic matter input, characteristic of well-drained waterfall systems.

The structure of the algal communities also supports the physicochemical analysis. The prevalence of Chlorophyta and Bacillariophyta, particularly pennate diatoms (*Synedra*, *Navicula*, *Pinnularia*, *Asterionella*, and *Diatoma*), indicates well-aerated waters with oligotrophic and mesotrophic tendencies. The Palmer Pollution Index yielded a value of 19, indicating moderate organic enrichment but not significant pollution, consistent with low to moderate nutrient levels and relatively low BOD.

Thus, the study results support the hypotheses: spatial variations in physicochemical parameters form a characteristic water quality gradient, and algal communities adequately reflect these hydrochemical conditions, serving as sensitive bioindicators of anthropogenic impact. The integration of physicochemical measurements with algal indicators proved to be an effective tool for environmental assessment.

Overall, Erin Ijesha Falls can be characterized as a moderately disturbed but relatively healthy freshwater ecosystem. The study's findings provide a basis for regular monitoring and management of the waterfall system, helping to maintain its environmental sustainability in the face of growing tourism and environmental change.

Acknowledgement

The authors gratefully acknowledge the Limnology/Phycology Laboratory of the Department of Plant Biology and Biotechnology, University of Benin, Nigeria, where the work was carried out.

Author's statements

Contributions

Conceptualization: M.K.; Data curation: E.A.; Formal Analysis: E.A.; Investigation: E.A.; Methodology: J.O.; Project administration: J.O.; Resources: M.K.; Software: J.O.; Supervision: M.K.; Validation: M.K.; Visualization: J.O.; Writing – original draft: M.K.; Writing – review & editing: M.K.

Declaration of conflicting interest

The authors declare no competing interests.

Financial interests

The authors declare they have no financial interests.

Funding

Not applicable.

Data availability statement

Data used for the study would be made available on request.

AI Disclosure

The authors declare that generative AI was not used to assist in writing this manuscript.

Ethical approval declarations

Not applicable.

Additional information

Publisher's note

Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

REFERENCES

Adejuwon, J. O., & George, F. I. (2024). Qualitative and quantitative water investigation of Erin-Ijesha (Olumirin) Waterfall, Erin-Ijesha, Nigeria. *Heliyon*, 10(14), e34555. https://doi.org/10.1016/j.heliyon.2024.e34555

Akachukwu, E. N., Obi-Iyeke, G. E., Ajai, A. I., Mohammed, A. Z., & Arimoro, F. O. (2025). Phytoplankton as indicators of ecological changes in Afrotropical reservoirs. *Environmental Monitoring and Assessment*, 197(7), 777. https://doi.org/10.1007/s10661-025-14208-x.

Akhere, M. A., & Kadiri, M. O. (2023). Physicochemical Characteristics of a Tropical Seasonal Water Body: Ikoro Stream, Edo State, Nigeria. *Journal of Applied Sciences and Environmental Management*, 27(5), 911–918. https://doi.org/10.4314/jasem.v27i5.4.

American Public Health Association (APHA) (2017). Standard methods for the examination of water and wastewater (23rd ed.). *Washington, DC: APHA*. https://www.standardmethods.org/doi/book/10.2105/smww.2882.

Arabomen, O. J., & Babalola, F. D. (2025). Evaluation of the tourism potential of Erin-Ijesha (Olumirin) Waterfalls, Osun State, Nigeria. *FUDMA Journal of Sciences*, 9(11), 32–40. https://doi.org/10.33003/fjs-2025-0911-3971.

Atazadeh, E. (2023). Monitoring of rivers and streams conditions using biological indices with emphasis on algae: a comprehensive descriptive review toward river management. *River Basin Management-Under a Changing Climate*. https://doi.org/10.5772/intechopen.105749.

Baker, K., Chadwick, M. A., McGill, R. A., Wahab, R. A., & Kahar, R. (2017a). Macroinvertebrate trophic structure on waterfalls in Borneo. *Marine and Freshwater Research*, 68(11), 2061–2069. https://doi.org/10.1071/MF16373.

Baker, K., Chadwick, M. A., Wahab, R. A., & Kahar, R. (2017b). Benthic community structure and ecosystem functions in above-and below-waterfall pools in Borneo. *Hydrobiologia*, 787(1), 307–322. https://doi.org/10.1007/s10750-016-2975-4.

Bashiru, A. A., Adebusuyi, J., & Folorunso, O. S. (2024). Community-Based Tourism and Development of Waterfall Attractions in Southwest, Nigeria: Case of Erin Ijesha and Arinta Waterfalls. *International Journal of Contemporary Research in Humanities*, 2(1), 253–261. https://highgrace.org/injocorh/papers/30%20INJOCORH%20Community-Based%20Tourism%20and%20Development.pdf.

Bellinger, E. G., & Sigee, D. C. (2010). Freshwater algae: Identification and use as bioindicators. *Wiley-Blackwell*. https://www.wolterskluwer.com/en/solutions/ovid/freshwater-algae-identification-and-use-as-bioindicators-9771.

Biggs, B. J., & Smith, R. A. (2002). Taxonomic richness of stream benthic algae: effects of flood disturbance and nutrients. *Limnology and Oceanography*, 47(4), 1175–1186. https://doi.org/10.4319/lo.2002.47.4.1175.

Chapman, D. V. (2021). Water quality assessments: a guide to the use of biota, sediments and water in environmental monitoring. *CRC Press*. 656 p. https://doi.org/10.1201/9781003062103.

Clayton, P. D., & Pearson, R. G. (2016). Harsh habitats? Waterfalls and their faunal dynamics in tropical Australia. *Hydrobiologia*, 775(1), 123–137. https://doi.org/10.1007/s10750-016-2719-5.

Costanza, R., De Groot, R., Sutton, P., Van der Ploeg, S., Anderson, S. J., Kubiszewski, I., ... & Turner, R. K. (2014). Changes in the global value of ecosystem services. *Global Environmental Change*, 26, 152–158. https://doi.org/10.1016/j.gloenvcha.2014.04.002.

Dodds, W. K., Perkin, J. S., & Gerken, J. E. (2013). Human impact on freshwater ecosystem services: a global perspective. *Environmental Science & Technology*, 47(16), 9061–9068. https://doi.org/10.1021/es4021052.

Eneh, C. C., Aguzie, I. O., Odii, E. C., Nwankwo, N. J., Okoro, J. O., & Ezenwa, I. M. (2024). Water quality and biological characteristics of Ezeagu Waterfall. *Water Conservation and Management*, 8(4), 444–453. https://doi.org/10.26480/wcm.04.2024.444.453.

Essien, I. I., Udo, E. D., Asuquo, T. J., & Onyegbule, C. L. (2025). Limnological Determinants of Periphytic Algae Assemblage on Macrophyte in the Humic Freshwater Ecosystem of Eniong River, Itu Nigeria. *Asian Journal of Research in Biology*, 8(1), 98–108. https://doi.org/10.56557/ajrib/2025/v8i152.

FMEnv. (2011). National Environmental (Surface and Groundwater Quality Control) Regulations. *Federal Ministry of Environment, Nigeria*.

Islam, M. S., Chakma, N. B., Chakma, P., Kabir, M. H., Shammi, R. S., Hoque, M. M. M., & Iqubal, K. F. (2022). Seasonal Variation of Water Qualities in River, Lake and Waterfall in Rangamati and Khagrachhari Hill Tracts, Bangladesh. *Grassroots Journal of Natural Resources*, 5(2), 59–79. https://doi.org/10.33002/nr2581.6853.050205.

ISO. (2024). ISO 5667-3:2024 – Water quality — Sampling — Part 3: Preservation and handling of water samples. *International Organization for Standardization*. https://www.iso.org/standard/82273.html.

John, D. M., Guiry, M. D., Wilbraham, J., & Krokowski, J. (2022). The 2011 edition of "The Freshwater Algal Flora of the British Isles": additions, corrections, nomenclatural and taxonomic changes. *Applied Phycology*, 3(1), 36–71. https://doi.org/10.1080/26388081.2022.2031295.

John, D. M., Whitton, B. A., & Brook, A. J. (2011). The freshwater algal flora of the British Isles (2nd ed.). *Cambridge University Press*.

Jonah, U. E., Esenowo, I. K., & Enin, U. I. (2024). Water Quality and Macroinvertebrates Assessment of Eniong Creek, Akwa Ibom State, Niger Delta, Nigeria. *Journal of Bioresource Management*, 11(3), 19. https://corescholar.libraries.wright.edu/jbm/vol11/iss3/19/.

Jones, L. A., Muhlfeld, C. C. & Hauer, F. R. (2017). Temperature (Methods in stream ecology). In Methods in Stream Ecology, Third Edition (1). *Elsevier Inc, London*.

Kadiri, M. O. (1996). More desmids from the Ikpoba reservoir, Nigeria: Comparison with other African records. *Archiv für Hydrobiologie. Supplementband, Algological studies*, 112, 87–98.

Kadiri, M. O. (2002). A checklist of desmids in Nigeria. *Global Journal of Pure and Applied Sciences*, 8(2), 223–238. https://doi.org/10.4314/gjpas.v8i2.16036.

Kadiri, M. O. (2006b). Phytoplankton Flora and Physicochemical attributes of some waters in the Eastern Niger-Delta area of Nigeria. *Nigerian Journal of Botany*, 19(2), 188–200.

Kadiri, M. O. (2006a). Phytoplankton survey in the western Niger Delta, Nigeria. Afr. J. Env. Pollut. *Health*, 5, 48–58.

Kalff, J. (2002). Limnology: Inland water ecosystems (2nd ed.). *Prentice Hall*.

Kayode, M. O., Tomori, W. B., Okoronkwo, E. A., & Adiat, K. A. N. (2024). Seasonal variation of groundwater quality in a basement complex geology of Ado Ekiti Nigeria using water quality index model. *Journal of Umm Al-Qura University for Applied Sciences*, 1–26. https://doi.org/10.1007/s43994-024-00195-1.

Kelly, M. G., Bennion, H., Cox, E. J., Goldsmith, B., Jamieson, J., Juggins, S., Mann, D. G., Telford, R. J., & Ameziane, T. (2008). Common freshwater diatoms of Britain and Ireland. *Environment Agency*.

Kumar, S., & Nautiyal, P. (2024). Assessment of ecological state of serially impounded Himalayan River using diatoms-based matrices: Identification of critical stretches for management. *Ecological Frontiers*, 44(2), 321–326. https://doi.org/10.1016/j.chnaes.2023.07.009.

Labib, W., El-Dahhar, A. A., Shahin, S. A., Ismail, M. M., Hosny, S., & Diab, M. H. (2023). Water quality indices as tools for assessment of the Eastern Harbor's water status (Alexandria, Egypt). *SN Applied Sciences*, 5(3), 89. https://doi.org/10.1007/s42452-023-05304-z.

Leibowitz, Z. W., Brito, L. A. F., De Lima, P. V., Eskinazi-Sant'Anna, E. M., & Barros, N. O. (2017). Significant changes in water pCO2 caused by turbulence from waterfalls. *Limnologica*, 62, 1–4. https://doi.org/10.1016/j.limno.2016.09.008.

Li, D., Geng, M., & Xie, Y. (2025). Extreme Hydrological Shifts Trigger Water Quality Variations in Shallow Lake Ecosystems: Insights from Hydroclimatic Behaviors. *Sustainability*, 17(24), 11110. https://doi.org/10.3390/su172411110.

Lobus, N. V. (2022). Biogeochemical role of algae in aquatic ecosystems: Basic research and applied biotechnology. *Journal of Marine Science and Engineering*, 10(12), 1846. https://www.mdpi.com/2077-1312/10/12/1846.

Mahdzir, M. M., Yahaya, S. H., Fauadi, M. H. F. M., & Yeow, T. T. (2024). A comprehensive review of water quality control on lentic ecosystem through the water quality, IoT and aeration models. *Multidisciplinary Reviews*, 7(5), 2024098. https://doi.org/10.31893/multirev.2024098.

National Environmental Standards and Regulations Enforcement Agency (NESREA). (2011/2018). *National Environmental (Surface and Groundwater Quality) Regulations.* https://nesrea.gov.ng/wp-content/uploads/2025/05/Surface_and_Groundwater_Quality_Control_Regulation-2011.pdf.

Odeyemi, A., Fagbohun, E., & Akindolapo, O. (2011). The bacteriological and physico-chemical studies on Olumirin Waterfall, Erin-Ijesha, Osun State, Nigeria. *Journal of Microbiology, Biotechnology and Food Sciences*, 1(2), 83–97.

Okoye, G. U., & Ogbebor, J. U. (2023). Evaluation of the Organic Pollution Status of some Rivers in Edo State using Palmer's Pollution Index. *NIPES-Journal of Science and Technology Research*, 5(4). https://doi.org/10.5281/zenodo.10426140.

Olalere, O. J., Verma, D. K., Funmilayo, O. F., Adewumi, E., Oluwatobi, A. P., Blessing, O., & Dolapo, A. K. (2025). Ecological Drivers of Phytoplankton Community Structure in Egbe Reservoir, Southwestern Nigeria. *Thalassas: An International Journal of Marine Sciences*, 41(4), 244. https://doi.org/10.1007/s41208-025-00998-x.

Palmer, C. M. (1969). A composite rating of algae tolerating organic pollution. *Journal of Phycology*, 5(1), 78–82.

Printarakul, N., & Meeinkuirt, W. (2022). The bryophyte community as bioindicator of heavy metals in a waterfall outflow. *Scientific Reports*, 12(1), 6942. https://doi.org/10.1038/s41598-022-10980-9.

Rathore, P. K., Mehta, R., Jain, M., & Jatav, P. (2025). Seasonal Distribution of Zygnemataceae and Mesotaenaceae Families of Algae at Site Joga of the Narmada River, Harda, MP, India. *International Journal of Life Sciences*, 13(1), 99–107.

Reynolds, C. S. (2006). The ecology of phytoplankton. *Cambridge University Press*. https://doi.org/10.1017/CBO9780511542145.

Rojo, D., Alonso, A., Pérez, J., Agut, A., Hermosilla, B., Tiegs, S. D., & Boyero, L. (2025). Decomposition of different organic matter substrates and algal biomass accrual as early warning indicators of human impacts on stream ecosystems. *Ecological Indicators*, 178, 113998. https://doi.org/10.1016/j.ecolind.2025.113998.

Round, F. E., Crawford, R. M., & Mann, D. G. (1990). The diatoms: Biology and morphology of the genera. *Cambridge University Press*.

Rust, R. L., Frizzell, A., & Kessler, J. D. (2025). Waterfalls enhance regional methane emissions by enabling dissolved methane to bypass microbial oxidation. *Communications Earth & Environment*, 6(1), 140. https://doi.org/10.1038/s43247-025-02060-3.

Soeprobowati, T. R., & Jumari, J. (2022). The water quality index and phytoplankton communities of Kokoh Putih River, Sembalun, East Lombok, Indonesia. *Aquaculture, Aquarium, Conservation & Legislation*, 15(4), 2025–2040. https://bioflux.com.ro/docs/2022.2025-2040.pdf.

Standards Organisation of Nigeria (SON/NSQ). (2015). *Nigerian Standard for Drinking Water Quality* (NIS 554). https://africacheck.org/sites/default/files/Nigerian-Standard-for-Drinking-Water-Quality-NIS-554-2015.pdf.

Stevenson, J. (2014). Ecological assessments with algae: a review and synthesis. *Journal of Phycology*, 50(3), 437–461. https://doi.org/10.1111/jpy.12189.

Stevenson, R. J., Bennett, B. J., Jordan, D. N., & French, R. D. (2012). Phosphorus regulates stream injury by filamentous green algae, DO, and pH with thresholds in responses. *Hydrobiologia*, 695(1), 25–42. https://doi.org/10.1007/s10750-012-1118-9.

Taurozzi, D., Cesarini, G., di Santo, C., & Scalici, M. (2025). Beyond the flow: ecological insights from diatom communities of a Mediterranean intermittent river. *Environmental Research*, 122284. https://doi.org/10.1016/j.envres.2025.122284.

Van Van Dam, H., Mertens, A., & Sinkeldam, J. (1994). A coded checklist and ecological indicator values of freshwater diatoms from the Netherlands. *Netherland Journal of Aquatic Ecology*, 28(1), 117–133. https://doi.org/10.1007/BF02334251.

Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R., & Cushing, C. E. (1980). The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences*, 37(1), 130–137. https://doi.org/10.1139/f80-01.

Wehr, J. D., Sheath, R. G., & Kociolek, J. P. (2015). Freshwater algae of North America: Ecology and classification (2nd ed.). *Academic Press.*

Wei, W., Lv, H., Li, C., Guo, H., Ye, C., Wang, Y., & Hu, N. (2025). Distribution Characteristics of Epiphytic Algal Communities in the Third Largest River in China. *Water*, 17(17), 2508. https://doi.org/10.3390/w17172508.

Wetzel, R. G. (2001). Limnology: Lake and river ecosystems (3rd ed.). *Academic Press*.

Whitton, B. A., & Potts, M. (2012). The ecology of cyanobacteria II. *Springer*.

World Health Organization (WHO). (2017). Guidelines for drinking-water quality: fourth edition incorporating the first addendum, 4th ed. *World Health Organization*. https://iris.who.int/handle/10665/254637.