Blueprint Academic Publishers

Journal of Aquatic and Terrestrial Ecosystems
Journal ISSN: 2960-1118
4(2)
Received: June 02, 2026
Accepted: July 04, 2026
Published: July 09, 2026

Influence of Agricultural and Agro-Industrial Activities on Nutrient Dynamics and Water Quality in River Keyian, Kenya

Sankei Rael, Khanzenzi Judith and Simiyu Gelas

Department Of Environmental Science, School of Environmental Studies and Natural Resource Management, University of Eldoret,
P.O. Box 1125-30100, Eldoret, Kenya

Abstract

Freshwater ecosystems adjacent to agro-industrial developments are increasingly threatened by nutrient enrichment, yet the effects on water quality remain uncharacterized. This study evaluated the spatial distribution of nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), soluble reactive phosphorus (SRP), and total phosphorus (TP) in River Keyian, Narok County, Kenya, and assessed nutrient stoichiometry and eutrophication potential downstream of a treated sugar industry effluent discharge point. A total of 112 Water samples were collected bi-monthly from seven river stations and one effluent outlet between January and April 2024 using standard methods. Spatial variation and nutrient relationships were evaluated using one-way analysis of variance (ANOVA), Tukey's Honestly Significant Difference (HSD) test, Pearson correlation analysis, and the dissolved inorganic nitrogen to soluble reactive phosphorus (DIN: SRP) ratio. Nitrate, ammonium, SRP, and TP varied significantly among sampling stations ($p < 0.05$), whereas nitrite showed no significant spatial variation ($p = 0.115$). Nitrate increased approximately 1.8-fold, from 9.345 ± 6.073 mg/L upstream to 17.020 ± 3.626 mg/L downstream, while SRP and TP increased approximately 4.1-fold (0.216–0.893 mg/L) and 4.5-fold (0.670–3.009 mg/L), respectively. Total phosphorus exhibited the strongest spatial response ($\eta^2 = 0.582$) and was positively correlated with nitrate and ammonium ($p < 0.01$), indicating common nutrient sources. The DIN:SRP ratio declined from 37.779 upstream to 8.788 downstream, demonstrating increasing phosphorus availability relative to dissolved inorganic nitrogen and an elevated potential for eutrophication in the lower reaches of the river. The findings indicate that nutrient enrichment in River Keyian is driven by the combined effects of treated sugar industry effluent and diffuse agricultural activities rather than industrial discharge alone. These results provide evidence to support integrated watershed management, improved nutrient removal

technologies, and routine water quality monitoring to protect the ecological integrity of River Keyian.

Keywords: Dissolved inorganic nitrogen, soluble reactive phosphorus, sugar industry effluent, eutrophication, River Keyian, Kenya

Correspondence: rleepy1997@gmail.com

Copyright © 2026 Sankei et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY).

Funding: The author received no financial support for the research, authorship and/or publication of this article.

Data Availability: The authors confirm that the supporting findings of this study are available within the article and/ or its supplementary material or upon request.

Conflict of interest: The authors declare that there is no potential conflict of interest with respect to the research authorship and /or publication of this article.

Competing interests: The authors declare no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Introduction

Freshwater ecosystems provide indispensable ecological, economic, and social services by (van Vliet et al., 2023)supplying water for domestic use, agriculture, livestock production, industry, and the maintenance of aquatic biodiversity. However, these ecosystems are increasingly threatened by nutrient enrichment resulting from expanding agricultural activities and agro-industrial development. Across many developing countries, rapid agricultural intensification, increased fertilizer application, livestock production, and inadequate wastewater management have accelerated the deterioration of river water quality, compromising ecosystem integrity and human well-being (van Vliet et al., 2023). Excessive inputs of nitrogen and phosphorus into freshwater ecosystems stimulate eutrophication, harmful algal blooms, oxygen depletion, and biodiversity loss, making nutrient pollution one of the most pervasive threats to freshwater ecosystems worldwide(Wurtsbaugh et al., 2019). Among the various forms of freshwater pollution, nutrient enrichment remains one of the principal causes of freshwater degradation because it fundamentally alters nutrient cycling and ecological functioning in aquatic ecosystems.

Agriculture and agro-industrial activities constitute two of the principal anthropogenic pathways through which nutrients are introduced into freshwater ecosystems. Agricultural runoff transports fertilizer residues, livestock waste, and nutrient-enriched sediments into adjacent rivers, particularly during rainfall events, thereby increasing nitrogen and phosphorus loading in surface waters(Madjar et al., 2024; Wang et al., 2023). At the same time, agro-industrial facilities generate wastewater containing varying concentrations of nitrogen, phosphorus, and organic matter that may reach receiving water bodies despite wastewater treatment processes(van Vliet et al., 2023). The combined influence of

these diffuse and point pollution sources creates complex nutrient dynamics that regulate nutrient availability, alter biogeochemical cycling, and increase the likelihood of eutrophication and ecological degradation (Wurtsbaugh et al., 2019). Consequently, understanding the relative contributions of agricultural runoff and industrial effluent has become increasingly important for developing effective nutrient management strategies and protecting freshwater resources.

In Kenya, nutrient pollution has become an increasing environmental concern as many river systems traverse rapidly expanding agricultural and industrial landscapes. Within the Mara River Basin, agricultural land use, catchment disturbance, and seasonal hydrological variability have been shown to influence nutrient transport, physicochemical water quality, and ecological processes throughout the basin(Kilonzo et al., 2014).(Nyairo et al., 2015) demonstrated that anthropogenic activities and seasonal variation significantly influenced water quality in the Amala and Nyangores tributaries of the Mara River, with disturbed catchments exhibiting higher nutrient and microbial pollution than upstream reference sites. More recently, (Mwanake et al., 2019)demonstrated that land use exerts a stronger influence on nutrient-related biogeochemical processes than stream size, emphasizing the importance of agricultural activities in regulating nutrient dynamics within the Upper Mara River Basin. Collectively, these studies have substantially improved understanding of nutrient pollution in the Mara River Basin. However, they have primarily emphasized physicochemical water quality, microbial contamination, catchment processes, and ecosystem functioning, with comparatively limited attention given to the spatial distribution of dissolved inorganic nitrogen species, phosphorus fractions, and nutrient stoichiometry in river systems simultaneously influenced by agricultural activities and agro-industrial effluent.

River Keyian, located in Transmara West Sub-County of Narok County, forms part of the Mara River Basin and serves as an important freshwater resource supporting domestic water supply, livestock production, irrigation, and aquatic ecosystems. The surrounding catchment is characterized by extensive sugarcane cultivation, mixed crop farming, and livestock production, all of which contribute to nutrient loading through surface runoff. In addition, the river receives treated wastewater discharged from the Transmara Sugar Company through its wastewater treatment system. Although wastewater treatment is intended to reduce pollutant loads before discharge, limited published scientific evidence exists regarding the effectiveness of nutrient removal by the treatment process or its influence on downstream nutrient dynamics within River Keyian. Consequently, the combined effects of treated industrial effluent and diffuse agricultural runoff on nutrient enrichment, nutrient limitation, and eutrophication potential remain insufficiently understood.

This knowledge gap has important implications for environmental management because nutrient enrichment threatens both ecosystem health and water security. Elevated concentrations of dissolved inorganic nitrogen and phosphorus can stimulate excessive primary productivity, alter nutrient limitation patterns, promote harmful algal blooms, accelerate eutrophication, and ultimately impair the ecological integrity of freshwater ecosystems (Schindler et al., 2016)These changes may also compromise the suitability of river water for domestic use and livestock production by communities

that depend directly on the river. Recognizing these risks, the Government of Kenya established the Environmental Management and Coordination (Water Quality) Regulations, 2006, which provide national standards for protecting surface water quality and controlling pollution from industrial and agricultural sources (Government of Kenya, 2006). Effective implementation of these regulations, however, requires site-specific scientific evidence capable of distinguishing the relative influence of multiple pollution sources on river water quality.

The present study therefore investigated the influence of agricultural and agro-industrial activities on nutrient dynamics in River Keyian, Kenya. Specifically, the study quantified spatial variations in nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), soluble reactive phosphorus (SRP), and total phosphorus (TP) concentrations across upstream, effluent discharge-point, and downstream sampling stations. In addition, dissolved inorganic nitrogen to soluble reactive phosphorus (DIN:SRP) ratios were determined to evaluate nutrient stoichiometry and potential eutrophication risk, while Pearson correlation analysis was used to examine relationships among nutrient species. By integrating nutrient fractionation, nutrient stoichiometry, and spatial statistical analyses, this study provides a more comprehensive understanding of nutrient behaviour in an agro-industrial river system than has previously been available for River Keyian. The findings contribute scientific evidence to support nutrient pollution control, integrated catchment management, and implementation of national water quality protection strategies within the Mara River Basin and other agricultural river systems in Kenya.

Materials and Methods

Description of the Study Area

This study was conducted along River Keyian in Transmara West Sub-County, Narok County, Kenya (Figure 1). River Keyian forms part of the Mara River Basin and serves as an important freshwater resource for domestic use, livestock watering, irrigation, and industrial activities within the catchment. The river originates from the Mau Forest complex. It flows through a predominantly agricultural landscape characterized by sugarcane cultivation, mixed crop farming, free-range livestock production, and agro-industrial activities associated with the nearby Transmara Sugar Company.

Climate of the Study Area

Kilgoris sub-County area lies between approximately 1.0454° S and 35.1363° E at elevations ranging from 1,500 to 2,300 m above sea level. The region experiences a bimodal rainfall pattern, with long rains occurring between March and May and short rains between October and December. Average annual rainfall ranges from 1,200 to 1,800 mm, while temperatures range from 15°C to 28°C. During the study period (January-April 2024), river flow conditions were influenced by the onset of the long rainy season, which potentially affected nutrient transport and dilution processes.

Potential sources of nutrient pollution within the catchment include agricultural runoff from sugarcane farms, the application of inorganic fertilizers, livestock waste, domestic activities in nearby settlements, and treated industrial

effluent discharged by Transmara Sugar Company into the river.

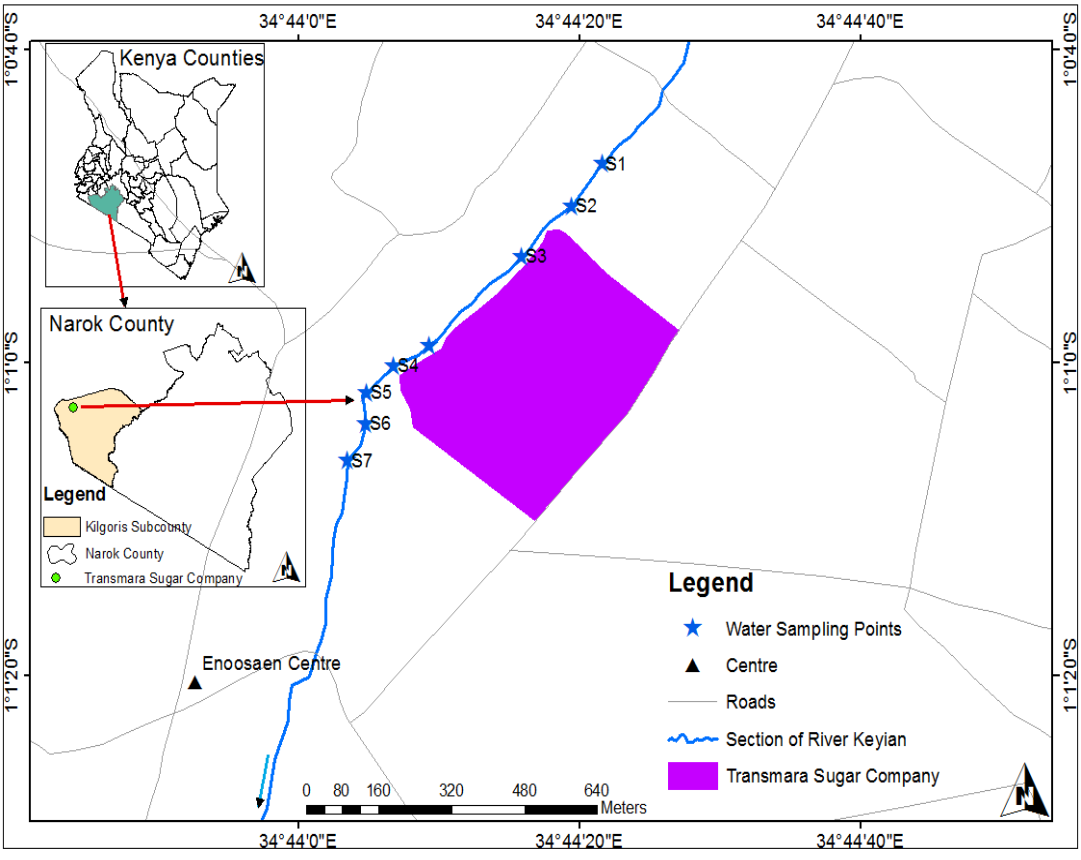


Figure 1: Map of the Study Area, Narok County, Kenya

Hydrology of the Study Area

The Mara River originates from the Mau Escarpment and flows through southwestern Kenya before discharging into Lake Victoria. River Keyian forms part of this basin as a tributary contributing to surface water flow within the catchment. A perennial flow regime generally characterizes the river system, although discharge varies seasonally in response to rainfall patterns. Higher flows are typically observed during the long and short rainy seasons, while reduced discharge occurs during dry periods, reflecting the influence of climatic variability on hydrological conditions within the basin.

Data collection

A purposive sampling approach was employed to select sampling locations along River Keyian. Based on their proximity to potential sources of nutrient pollution, including agro-industrial effluent discharge, agricultural activities, and livestock access points. The sampling design was intended to assess spatial variations in nutrient concentrations and water quality along a gradient of anthropogenic influence. Physicochemical parameters, including pH, temperature, total dissolved solids (TDS), and electrical conductivity (EC), were measured in situ using a calibrated portable multi-parameter meter equipped with the corresponding probes.

A total of seven sampling sites, 100m apart (S1-S7), were established along the river. Sites S1 and S2 were located upstream of major agricultural and agro-industrial activities and served as reference sites representing baseline water quality conditions. Site S3 was situated at the point where treated effluent from the sugar processing facility enters the river. Sites S4, S5, S6, and S7 were located downstream at 100m intervals from the discharge point to evaluate the cumulative effects of effluent inputs, agricultural runoff, and livestock-related activities on nutrient dynamics and water quality.

The selected sampling sites enabled comparison of upstream, discharge-point, and downstream conditions, thereby facilitating assessment of the influence of agricultural and agro-industrial activities on River Keyian. A total of 112 water samples were collected twice per month from January to April 2024. The bi-monthly sampling frequency was adopted to obtain replicate observations at each sampling station, thereby improving the reliability and statistical robustness of the dataset. Repeated sampling also helped account for short-term temporal variability in nutrient concentrations associated with fluctuations in environmental conditions and anthropogenic activities during the study period. In addition, treated effluent samples were collected from the factory discharge outlet during each sampling event to provide supporting information on the physicochemical characteristics of the discharged wastewater.

Immediately after collection, all samples were preserved using two drops of concentrated nitric acid and stored in pre-cleaned polyethylene bottles, placed in a cool box maintained at approximately 4 °C, and transported to the Biotechnology Laboratory at the University of Eldoret for nutrient analysis within 24 hours. All the tests were carried out using standard methods for examination of water and wastewater (American Public Health Association, 2022).

Laboratory Analysis and Sample Treatment

Water samples were analysed at the Biotechnology Laboratory, University of Eldoret, following procedures described in the *Standard Methods for the Examination of Water and Wastewater* (American Public Health Association et al., 2022). Samples designated for soluble reactive phosphorus (SRP) analysis were filtered through a 0.45 µm membrane filter before analysis to determine the dissolved reactive phosphorus fraction. Nitrate (NO_3^-) was determined using the Brucine colorimetric method (APHA Method 4500-NO_3^- C). Nitrite (NO_2^-) was determined using the diazotization colorimetric method, in which nitrite reacts with sulfanilamide and N-(1-naphthyl)ethylenediamine dihydrochloride (NEDD) to form a pink azo dye measured spectrophotometrically (APHA Method 4500-NO_2^- B). Ammonium (NH_4^+) was determined by the phenate method (APHA Method 4500-NH_3 F), soluble reactive phosphorus (SRP) using the ascorbic acid method (APHA Method 4500-P E), and total phosphorus (TP) by persulfate digestion followed by the ascorbic acid method (APHA Method 4500-P B & E).

To minimize analytical contamination, all glassware was soaked in 10% nitric acid, rinsed thoroughly with deionized water, and air-dried before use. Fresh calibration standards were prepared for each analytical batch, and calibration curves were generated for nitrate, nitrite, ammonium, soluble reactive phosphorus, and total phosphorus before sample analysis. Blanks were analysed alongside each batch to detect background contamination and verify the absence of

analytical interference. All samples were analysed in duplicate.

Data Analysis

Data were analysed using R version 4.4.0. Descriptive statistics, including the mean, standard deviation (SD), minimum, and maximum values, were computed to summarize nutrient concentrations at each sampling station. Data normality was assessed using the Shapiro-Wilk test. One-way analysis of variance (ANOVA) was then used to compare mean nutrient concentrations among the seven sampling stations. Significant ANOVA results were followed by Tukey's Honestly Significant Difference (HSD) test for pairwise comparisons. Tukey's. Pearson correlation analysis was used to assess relationships among NO_3^-, NO_2^-, NH_4^+, TP, and SRP. Statistical significance was assessed at the 95% confidence level ($\alpha = 0.05$). Dissolved inorganic nitrogen to soluble reactive phosphorus (DIN:SRP) ratios were calculated for each sampling station to characterize nutrient stoichiometry and support the interpretation of potential nutrient limitation. Dissolved inorganic nitrogen (DIN) was calculated as the sum of nitrate (NO_3^-), nitrite (NO_2^-), and ammonium (NH_4^+) concentrations, while soluble reactive phosphorus (SRP) represented the readily bioavailable phosphorus fraction.

Results

Table 1 presents the mean (± SD) nutrient concentrations and the corresponding Tukey HSD groupings across the sampling stations. Means sharing the same superscript letter within a column were not significantly different ($p < 0.05$). Tukey's HSD post hoc test identified a significant difference in nitrate concentrations only between S1 and S7, whereas no significant differences were detected for nitrite. Ammonium differed significantly between S7 and the upstream stations (S1 and S2). Total phosphorus showed the highest number of significant differences among sampling stations, while soluble reactive phosphorus differed significantly mainly between S7 and the upstream stations. Effluent values are presented for comparison only and were excluded from the statistical analysis.

.

Table 1. Showing mean (± SD) concentrations (mg/L) of ammonium (NH_4^+), soluble reactive phosphorus (SRP), and total phosphorus (TP) across sampling stations.

Site	NO_3^-(mg/L)	NO_2^-(mg/L)	NH_4^+ (mg/L)	SRP (mg/L)	TP (mg/L)
S1	9.345 ± 6.073^{a}	$2.167^{a} \pm 1.889$	$0.486^{a} \pm 0.339$	$0.216^{a} \pm 0.076$	$0.670^{a} \pm 0.760$
S2	$10.612^{ab} \pm 5.260$	$2.937^{a} \pm 2.314$	$0.638^{a} \pm 0.488$	$0.256^{a} \pm 0.099$	$0.727^{ab} \pm 0.814$
S3	$11.666^{ab} \pm 6.081$	$4.166^{a} \pm 3.043$	$0.990^{ab} \pm 0.478$	$0.458^{ab} \pm 0.201$	$1.287^{b} \pm 1.277$
S4	$14.548^{ab} \pm 7.006$	$4.583^{a} \pm 3.541$	$0.940^{ab} \pm 0.414$	$0.535^{ab} \pm 0.276$	$1.150^{b} \pm 0.917$
S5	$15.585^{ab} \pm 4.447$	$5.282^{a} \pm 4.669$	$1.059^{ab} \pm 0.510$	$0.582^{ab} \pm 0.282$	$1.321^{b} \pm 0.986$
S6	$15.941^{ab} \pm 3.451$	$5.520^{a} \pm 4.801$	$1.108^{ab} \pm 0.585$	$0.763^{b} \pm 0.20^{b}6$	$2.341^{c} \pm 1.751$
S7	$17.020^{b} \pm 3.626$	$6.508^{a} \pm 5.676$	$1.353^{b} \pm 0.980$	$0.893^{b} \pm 0.186$	$3.009^{d} \pm 2.060$
Effluent	28.500 ± 3.937	0.562 ± 0.403	2.055 ± 0.051	1.250 ± 0.052	2.670 ± 1.297

Table 2: Showing One-way ANOVA Results for Nutrient Concentrations Among Sampling Stations

Parameter	df (Between, Within)	F	p-value	η^2
NO_3^-	6, 77	3.495	0.004	0.214
NO_2^-	6, 77	1.776	0.115	0.122
NH_4^+	6, 77	3.105	0.009	0.195
TP	6, 77	17.847	<0.001	0.582
SRP	6, 77	5.218	<0.001	0.289

One-way ANOVA was performed to determine whether nutrient concentrations differed significantly among sampling stations. The results are presented in Table 2. One-way ANOVA indicated significant spatial variation in nitrate (NO_3^-), ammonium (NH_4^+), total phosphorus (TP), and soluble reactive phosphorus (SRP) concentrations among the sampling stations (Table 2). Nitrate differed significantly among stations ($F = 3.495$, $p = 0.004$), as did ammonium ($F = 3.105$, $p = 0.009$), total phosphorus ($F = 17.847$, $p < 0.001$), and soluble reactive phosphorus ($F = 5.218$, $p < 0.001$). In contrast, nitrite (NO_2^-) showed no significant variation among stations ($F = 1.776$, $p = 0.115$). The largest effect size was observed for TP ($\eta^2 = 0.582$), followed by SRP ($\eta^2 = 0.289$), NO_3^- ($\eta^2 = 0.214$), NH_4^+ ($\eta^2 = 0.195$), and NO_2^- ($\eta^2 = 0.122$).

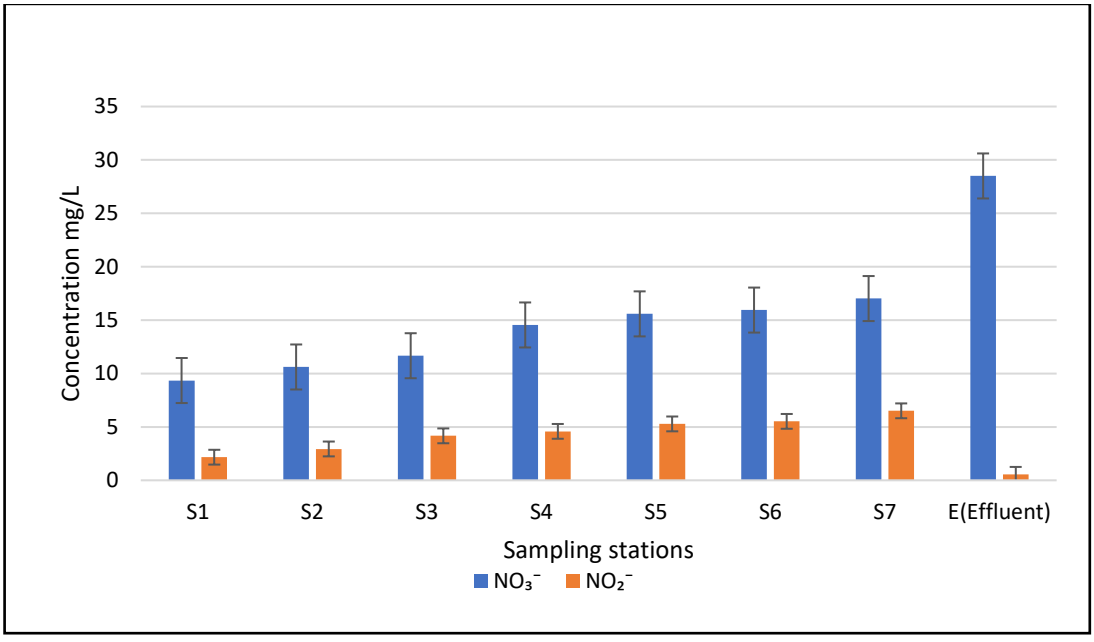


Figure 2: Mean(±SD)nitrate and nitrite concentrations across sampling stations

Figure 2 presents the mean (± SD) concentrations of nitrate (NO_3^-) and nitrite (NO_2^-) across the sampling stations. Nitrate concentrations increased from 9.345 ± 6.073 mg/L at S1 to 17.020 ± 3.626 mg/L at S7, with the highest concentration recorded in the effluent (28.500 ± 3.937 mg/L). Nitrite concentrations also increased across the river stations, ranging from 2.167 ± 1.889 mg/L at S1 to 6.508 ± 5.676 mg/L at S7, whereas the effluent recorded the lowest concentration (0.562 ± 0.403 mg/L). Error bars represent one standard deviation from the mean.

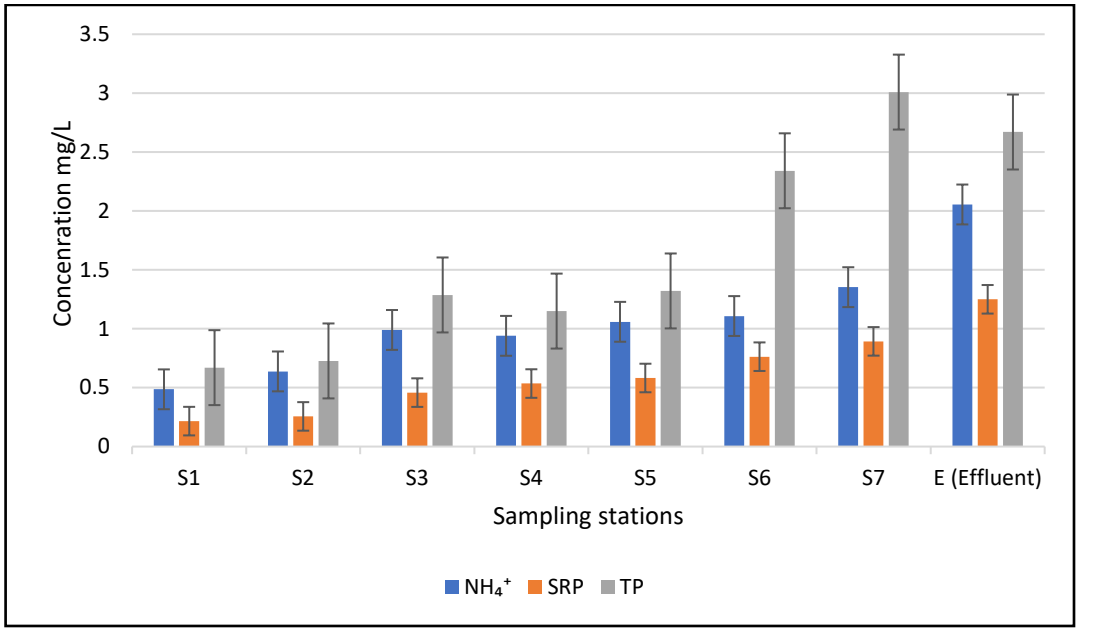


Figure 3: Mean(±SD) of ammonium(NH_4^+), soluble reactive phosphorus(SRP), and total phosphorus(TP) across sampling stations.

As shown in Figure 3, NH_4^+, SRP, and TP exhibited distinct spatial patterns among the sampling stations. NH_4^+ concentrations ranged from 0.486 ± 0.339 mg/L at S1 to 1.353 ± 0.980 mg/L at S7, whereas the effluent recorded the highest NH_4^+ concentration (2.055 ± 0.051 mg/L). Mean SRP concentrations increased from 0.216 ± 0.076 mg/L at S1 to 0.893 ± 0.186 mg/L at S7, with the effluent recording 1.250 ± 0.052 mg/L. Total phosphorus increased from 0.670 ± 0.760 mg/L at S1 to 3.009 ± 2.060 mg/L at S7, while the effluent contained 2.670 ± 1.297 mg/L.

Table 3: Showing Pearson Correlation Matrix for Nutrient Parameters

Parameter	NO_3^-	NO_2^-	NH_4^+	TP	SRP
NO_3^-	1.000	0.191	0.152	0.390**	0.192
$3NO_2^-$	0.191	1.000	-0.173	0.204	0.427**
NH_4^+	0.152	-0.173	1.000	0.474**	0.080
TP	0.390**	0.204	0.474**	1.000	0.306**
SRP	0.192	0.427**	0.080	0.306**	1.000

Table 3 presents the Pearson correlation coefficients among NO_3^-, NO_2^-, NH_4^+, TP, and SRP across the sampling stations. As shown in Table 3, NH_4^+ was positively correlated with TP ($r = 0.474$, $p < 0.01$), while NO_2^- showed a positive correlation with SRP ($r = 0.427$, $p < 0.01$). NO_3^- was moderately correlated with TP ($r = 0.390$, $p < 0.01$), and TP was positively associated with SRP ($r = 0.306$, $p < 0.01$). No significant correlations were observed among the remaining nutrient pairs.

Table 4: Showing mean (± SD) molar DIN: SRP ratio across sampling stations

Station	Mean ± SD
S1	37.779^{a} ± 43.621
S2	34.931^{ab} ± 29.611
S3	12.745^{b} ± 7.700
S4	15.71^{b} ± 11.721
S5	14.220^{b} ± 9.517
S6	9.996^{b} ± 7.577
S7	8.788^{b}± 6.894

Table 4 shows the mean (± SD) molar DIN: SRP ratio across the sampling

stations. Mean ratios ranged from 8.788 ± 6.894 at S7 to 37.779 ± 43.621 at S1.

Discussion

The spatial distribution of dissolved inorganic nitrogen (DIN) indicates progressive nitrogen enrichment downstream of the treated sugar industry effluent discharge, although responses differed among nitrate, nitrite and ammonium (Table 1; Figure 2). Nitrate was the dominant DIN species, increasing significantly from 9.35 ± 6.07 mg/L at S1 to 17.02 ± 3.63 mg/L at S7 ($F = 3.495$, $p = 0.004$; $\eta^2 = 0.214$), with significant differences occurring only between S1 and S7. This gradual increase suggests that diffuse agricultural runoff, livestock waste, and in-stream nitrogen transformation contributed more to downstream nitrate enrichment than the treated effluent alone, consistent with observations in other agricultural catchments (Kilonzo et al., 2014; Lubanga et al., 2021)and other tropical river systems undergoing agricultural intensification. Similar patterns have been reported in Kenya's Nyando River Basin, where fertilizer application and diffuse agricultural activities were identified as the dominant sources of nitrate entering surface waters (Nyilitya et al., 2021). Although nitrate concentrations remained below the World Health Organization (WHO) drinking-water guideline of 50 mg/L as NO_3^- (WHO), 2022) the observed downstream increase indicates continuous nitrogen enrichment that may accelerate eutrophication where phosphorus is also sufficiently available to support algal growth (Dodds & Smith, 2016). Nitrite concentrations increased from 2.17 ± 1.89 mg/L at S1 to 6.51 ± 5.68 mg/L at S7 but did not differ significantly among stations ($F = 1.776$, $p = 0.115$), reflecting substantial temporal variability. The high variability is consistent with the transient nature of nitrite, which is rapidly transformed through nitrification and denitrification in response to changes in dissolved oxygen and microbial activity (Camargo & Alonso, 2006). Nevertheless, downstream nitrite concentrations exceeded the WHO guideline value of 3 mg/L as NO_2^-, demonstrating that nitrogen enrichment in the lower reaches of River Keyian periodically reaches levels of concern for water quality management despite the absence of statistically significant spatial differences((WHO), 2022).

Ammonium also increased significantly downstream, from 0.49 ± 0.34 mg/L at S1 to 1.35 ± 0.98 mg/L at S7 ($F = 3.105$, $p = 0.009$), with significant differences between S1 and S7 and between S2 and S7(Table 2 and Figure 3). This pattern suggests cumulative inputs from treated wastewater, livestock waste and agricultural runoff, similar to findings in other East African agricultural watersheds (Kilonzo et al., 2014; Lubanga et al., 2021). Elevated ammonium may also contribute indirectly to ecological stress through nitrification, which increases oxygen demand, and through the formation of toxic unionised ammonia under favourable pH and temperature conditions(Randall et al., 2002).

Phosphorus exhibited the strongest spatial response among all nutrients, with total phosphorus accounting for 58.2% of the observed variation among sampling stations. The progressive downstream increase in both TP and SRP indicates cumulative phosphorus loading from multiple sources rather than a single point discharge. Similar observations have been reported in river systems where agricultural runoff, livestock waste, and treated wastewater collectively contribute to phosphorus enrichment (Jarvie et al., 2006).Although the treated effluent contained elevated phosphorus concentrations, continued downstream increases suggest additional

inputs from diffuse agricultural sources and remobilization of phosphorus within the river system. Long-term studies have shown that reductions in point-source phosphorus alone are often insufficient to eliminate eutrophication because phosphorus stored within catchments and river sediments continues to sustain downstream algal productivity (Jarvie et al., 2025). Consequently, effective phosphorus management requires integrated catchment-scale interventions rather than exclusive reliance on improvements in industrial wastewater treatment. The progressive increase in total phosphorus from 0.670 mg/L at the upstream reference station to 3.009 mg/L at the most downstream site demonstrates that phosphorus accumulated substantially as River Keyian flowed through the agricultural landscape (Table 1 and Figure 3). Even the lowest concentration measured exceeded the 0.035 mg/L threshold commonly associated with eutrophic freshwater systems (Organisation for Economic Co-operation and Development, 1982), indicating that phosphorus enrichment was evident throughout the study reach rather than being restricted to areas immediately downstream of the effluent discharge

The elevated nutrient concentrations observed in treated effluent indicate that wastewater treatment substantially reduced, but did not eliminate, nutrient inputs before discharge into River Keyian. Similar findings have been reported for sugar processing industries elsewhere, where conventional treatment systems effectively reduce organic loads but often achieve lower nutrient removal efficiencies, particularly for nitrogen and phosphorus (Ur Rehman et al., 2024). These observations suggest that upgrading existing treatment facilities with enhanced biological nutrient removal or constructed wetland systems could further reduce nutrient discharge and improve compliance with environmental protection objectives.

Pearson correlation analysis revealed clear linkages among nutrient species, demonstrating that nutrient enrichment in River Keyian reflects the combined influence of anthropogenic inputs and in-stream biogeochemical processes (Table 4). Total phosphorus (TP) was positively correlated with ammonium ($r = 0.474$, $p < 0.01$), nitrate ($r = 0.390$, $p < 0.01$) and soluble reactive phosphorus (SRP) ($r = 0.306$, $p < 0.01$), indicating that phosphorus accumulation occurred alongside increasing inorganic nitrogen. These relationships point to common nutrient sources, including treated sugar industry effluent, agricultural runoff, livestock waste and organic matter mineralisation, which collectively regulate nutrient dynamics in agricultural river systems (Jarvie et al., 2018; Withers et al., 2008). In contrast, nitrite was significantly correlated only with SRP ($r = 0.427$, $p < 0.01$). This pattern reflects the highly reactive nature of nitrite, which is rapidly transformed through nitrification and denitrification in response to changes in dissolved oxygen, organic matter availability and microbial activity(Camargo et al., 2006). The absence of significant correlations among nitrate, nitrite and ammonium further demonstrates the continuous transformation of inorganic nitrogen within the river rather than the simultaneous accumulation of individual nitrogen species(Kuypers et al., 2018). By contrast, the stronger and more consistent associations involving phosphorus indicate that phosphorus enrichment was primarily driven by cumulative catchment loading, reflecting the relatively conservative behaviour of phosphorus compared with inorganic nitrogen (Jarvie et al., 2018). Interpreted together, the ANOVA and Pearson

correlation analyses suggest that the observed nutrient patterns reflect cumulative catchment processes rather than a single pollution source. Although treated effluent contributed nutrients to the river, the continued downstream increase in nitrogen and phosphorus indicates that additional inputs from agricultural runoff and livestock activities substantially influenced water quality. This explains why the strongest nutrient enrichment occurred downstream instead of immediately at the discharge point. The results therefore support a watershed-scale approach to nutrient management that complements improvements in industrial wastewater treatment with measures to reduce diffuse nutrient losses from surrounding agricultural land(Dodds et al., 2016; McDowell et al., 2025).

Study Limitation

This study was based on four months of monitoring and did not include measurements of chlorophyll-*a*, phytoplankton biomass, sediment phosphorus, hydrological nutrient loading, or stable isotope tracers for source apportionment. Consequently, the study could not quantify internal phosphorus release from sediments, distinguish nutrient contributions from individual sources, or directly link nutrient enrichment to biological responses. Nevertheless, the observed spatial patterns and statistical relationships provide robust evidence of continuous downstream nutrient enrichment.

Conclusion

This study achieved its objectives by characterising the spatial distribution of dissolved inorganic nitrogen and phosphorus in River Keyian, evaluating nutrient stoichiometry using the DIN: SRP ratio, and determining spatial differences in nutrient concentrations among sampling stations. The findings demonstrated progressive downstream nutrient enrichment, with nitrate increasing by approximately 1.8-fold, soluble reactive phosphorus by 4.1-fold, and total phosphorus by 4.5-fold, while the DIN: SRP ratio declined from 37.779 upstream to 8.788 downstream, indicating increasing phosphorus availability relative to dissolved inorganic nitrogen.

Total phosphorus exhibited the strongest spatial response among the measured nutrients, with sampling station explaining 58.2% of the observed variation ($\eta^2 = 0.582$). ANOVA and Tukey's HSD further identified significant differences among multiple sampling stations. Positive correlations among nitrate, ammonium, and phosphorus fractions indicate that nutrient enrichment reflects the combined influence of multiple nutrient sources operating throughout the catchment rather than treated sugar industry effluent alone. These findings demonstrate that both point-source and diffuse anthropogenic inputs contribute to the nutrient dynamics of River Keyian and increase the risk of eutrophication.

Recommendation

The findings indicate that improving water quality in River Keyian will require management measures that address nutrient inputs across the entire catchment rather than focusing solely on industrial effluent. Regular compliance monitoring of treated wastewater should be complemented by measures that reduce nutrient losses from agricultural land, including nutrient management planning, protection of riparian corridors, restoration of vegetated buffer strips, and controlled livestock access to the river. Because phosphorus showed the highest downstream accumulation, management interventions should prioritise reducing phosphorus inputs while maintaining effective control of nitrogen sources. Such

measures would strengthen implementation of Kenya's Water Act (2016), the Environmental Management and Coordination (Water Quality) Regulations, 2006, and contribute to the achievement of Sustainable Development Goal 6.

Future Research

The downstream accumulation of phosphorus despite treated effluent meeting discharge requirements suggests that important nutrient sources remain unresolved. Future research should therefore quantify the relative contributions of sugar industry effluent, agricultural runoff, livestock waste, and natural background inputs using source apportionment techniques such as nutrient fingerprinting or stable isotope analysis. Investigating nutrient retention within river sediments and riparian zones would also improve understanding of why phosphorus accumulated more rapidly than dissolved inorganic nitrogen. Extending monitoring to include complete hydrological cycles would further establish how rainfall, river discharge, and sugarcane production influence nutrient transport and recovery along River Keyian.

References

American Public Health Association. (2022). Standard Methods for the Examination of Water and Wastewater Method 4500-O B. *American Public Health Association*

American Public Health Association, American Water Works Association, & Water Environment Federation. (2022). *Standard Methods for the Examination of Water and Wastewater* (24 ed.). Washington,DC: American Public Health Association.

Camargo, J. A., & Alonso, Á. (2006). Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: A global assessment. *Environment International, 32*(6), 831-849.https://doi.org/https://doi.org/10.1016/j.envint.2006.05.002

Dodds, W. K., & Smith, V. H. J. I. W. (2016). Nitrogen, phosphorus, and eutrophication in streams. *6*(2), 155-164

Government of Kenya. (2006). *The Environmental Management and Co-ordination (Water Quality) Regulations, 2006 (Legal Notice No. 120)*. Nairobi,Kenya: Kenya Law Retrieved from https://new.kenyalaw.org/akn/ke/act/ln/2006/120/eng%402022-12-31

Jarvie, H. P., Neal, C., & Withers, P. J. A. (2006). Sewage-effluent phosphorus: A greater risk to river eutrophication than agricultural phosphorus? *Science of The Total Environment, 360*(1), 246-253.https://doi.org/https://doi.org/10.1016/j.scitotenv.2005.08.038

Jarvie, H. P., Sharpley, A. N., Kresse, T., Hays, P. D., Williams, R. J., King, S. M., & Berry, L. G. (2018). Coupling High-Frequency Stream Metabolism and Nutrient Monitoring to Explore Biogeochemical Controls on Downstream Nitrate Delivery. *Environmental Science & Technology, 52*(23), 13708-13717.https://doi.org/10.1021/acs.est.8b03074

Jarvie, H. P., Worrall, F., Burt, T. P., & Howden, N. J. K. (2025). A 150-year river water quality record shows reductions in phosphorus loads but not in algal growth potential. *Communications Earth & Environment, 6*(1), 62.https://doi.org/10.1038/s43247-024-01978-4

Kilonzo, F., Masese, F. O., Van Griensven, A., Bauwens, W., Obando, J., & Lens, P. N. L. (2014). Spatial–temporal variability in water quality and macro-invertebrate assemblages in the Upper Mara River basin, Kenya.

Physics and Chemistry of the Earth, Parts A/B/C, 67-69, 93-104.https://doi.org/https://doi.org/10.1016/j.pce.2013.10.006

Kuypers, M. M. M., Marchant, H. K., & Kartal, B. (2018). The microbial nitrogen-cycling network. *Nature Reviews Microbiology, 16*(5), 263-276.https://doi.org/10.1038/nrmicro.2018.9

Lubanga, H. L., Manyala, J. O., Sitati, A., Yegon, M. J., & Masese, F. O. (2021). Spatial variability in water quality and macroinvertebrate assemblages across a disturbance gradient in the Mara River Basin, Kenya. *Ecohydrology & Hydrobiology, 21*(4), 718-730.https://doi.org/https://doi.org/10.1016/j.ecohyd.2021.03.001

Madjar, R. M., Vasile Scăețeanu, G., & Sandu, M. A. (2024). Nutrient Water Pollution from Unsustainable Patterns of Agricultural Systems, Effects and Measures of Integrated Farming. *Water, 16*(21), 3146. doi:10.3390/w16213146

McDowell, R. W., Luo, D., Pletnyakov, P., Upsdell, M., & Dodds, W. K. (2025). Anthropogenic nutrient inputs cause excessive algal growth for nearly half the world's population. *Nature Communications, 16*(1), 1830.https://doi.org/10.1038/s41467-025-57054-8

Mwanake, R. M., Gettel, G. M., Aho, K. S., Namwaya, D. W., Masese, F. O., Butterbach-Bahl, K., & Raymond, P. A. (2019). Land Use, Not Stream Order, Controls N2O Concentration and Flux in the Upper Mara River Basin, Kenya. *Journal of Geophysical Research: Biogeosciences, 124*(11), 3491-3506.https://doi.org/https://doi.org/10.1029/2019JG005063

Nyairo, W. N., Owuor, P. O., & Kengara, F. O. (2015). Effect of anthropogenic activities on the water quality of Amala and Nyangores tributaries of River Mara in Kenya. *Environmental Monitoring and Assessment, 187*(11), 691.https://doi.org/10.1007/s10661-015-4913-8

Nyilitya, B., Mureithi, S., Bauters, M., & Boeckx, P. (2021). Nitrate source apportionment in the complex Nyando tropical river basin in Kenya. *Journal of Hydrology, 594*, 125926.https://doi.org/https://doi.org/10.1016/j.jhydrol.2020.125926

Organisation for Economic Co-operation and Development. (1982). *Eutrophication of Waters: Monitoring, Assessment and Control*. Paris: Organisation for Economic Co-operation and Development.

Randall, D. J., & Tsui, T. K. N. (2002). Ammonia toxicity in fish. *Marine Pollution Bulletin, 45*(1), 17-23.https://doi.org/https://doi.org/10.1016/S0025-326X(02)00227-8

Schindler, D. W., Carpenter, S. R., Chapra, S. C., Hecky, R. E., & Orihel, D. M. (2016). Reducing Phosphorus to Curb Lake Eutrophication is a Success. *Environmental Science & Technology, 50*(17), 8923-8929.https://doi.org/10.1021/acs.est.6b02204

Ur Rehman, T., Waseem, H., Ali, B., Haleem, A., Abid, R., Ahmed, S., Gilbride, K. A., & Ali, M. (2024). Mitigation of Sugar Industry Wastewater Pollution: Efficiency of Lab-Scale Horizontal Subsurface Flow Wetlands. *Processes, 12*(7), 1400. doi:10.3390/pr12071400

van Vliet, M. T. H., Thorslund, J., Strokal, M., Hofstra, N., Flörke, M., Ehalt Macedo, H., Nkwasa, A., Tang, T., Kaushal, S. S., Kumar, R., van Griensven, A., Bouwman, L., & Mosley, L. M. (2023). Global river water quality under climate change and hydroclimatic extremes. *Nature Reviews Earth & Environment, 4*(10), 687-

702.https://doi.org/10.1038/s43017-023-00472-3

Wang, S.-W., & Fan, C. (2023). Challenges of Water Quality Management for Agricultural Development. *Water, 15*(10), 1816. doi:10.3390/w15101816

WHO. (2022). *Guidelines for drinking-water quality*. Retrieved from Geneva: https://www.who.int/

Withers, P. J. A., & Jarvie, H. P. (2008). Delivery and cycling of phosphorus in rivers: A review. *Science of The Total Environment, 400*(1), 379-395.https://doi.org/https://doi.org/10.1016/j.scitotenv.2008.08.002

Wurtsbaugh, W. A., Paerl, H. W., & Dodds, W. K. (2019). Nutrients, eutrophication and harmful algal blooms along the freshwater to marine continuum. *WIREs Water, 6*(5), e1373.https://doi.org/https://doi.org/10.1002/wat2.1373