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Hydrochemical Assessment and Irrigation Suitability Analysis of Ikpoba River Water

Osemudiamen OKORUWA[a], Fidelis CHUKWU[b*], Emmanuel OSAWE[c]

[a] *Science Laboratory Technology Department (Chemistry Option) University of Benin, Ahmadu Bello University (MBA), Nigeria*
[b] *Chemistry Department, Imo State University, Nigeria*
[c] *Department of Civil Engineering, Ambrose Alli University, Ekpoma, Edo State, Nigeria*

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Corresponding Author: Fidelis CHUKWU, E-mail: chukwufidelis@gmail.com
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ABSTRACT
This study assesses the irrigation potential and suitability of Ikpoba River by combining water quality analysis, hydrochemical character and advance statistical assessment and evaluation. Water samples collected were analyzed for physicochemical parameters, major cations (Na^+, Ca^{2+}, Mg^{2+}, K^+), anions (Cl^-, HCO_3^-, SO_4^{2-}) and heavy metals. Irrigation suitability was evaluated using standard indices such as Sodium Adsorption Ratio (SAR), Kelly's Ratio (KR), Percent Sodium (%Na), Gibb's plot, Piper's plot, Wilcox plot, Residual Sodium Carbonate (RSC), Magnesium Absorption Ratio (MAR) and Permeability Index (PI). Results indicate that Ikpoba River water is broadly suitable for irrigation for many crops but possessed localized increases in salinity and sodium hazard. With approximately 58% of %Na value, and as one of the major cations of the water is a water-quality sodium indicator, the water samples fall in doubtful near-unsatisfactory range for sodium hazard to soils and crops, as a result if used for irrigation the water could cause infiltration or structure problems over time. Also, Kelly's ratio of > 1 indicates excess sodium hazard for irrigation, by these indices, these waters would be considered not suitable for irrigation. The study recommends that if this water should be used for irrigational purpose there should be the need for soil amendments to blend the water with lower-Na water, apply gypsum ($CaSO_4$) to improve Ca:Na balance in soil, also routine monitoring, adoption of appropriate crop selection, drainage practices and integrated catchment management to protect long-term irrigation viability. These findings provide a baseline for sustainable irrigation planning in the Ikpoba basin.

Keywords: Irrigation, Ikpoba River, Pollution, Sodium Adsorption Ratio

1. Introduction

Irrigation water quality is a critical determinant of sustainable agricultural productivity, soil health, and food safety. Poor-quality irrigation water can introduce heavy metals, pathogens, and excess nutrients into agricultural soils, compromising crop yields and posing significant human health risks through the food chain (Idemudia & Aduba, 2024; Areguamen et al., 2023; Obayagbona & Odigie, 2025). In Nigeria, where irrigation is essential for enhancing agricultural productivity and building resilience against drought (Ojeah & Oriakhi, 2022; Ilaboya et al., 2024), the assessment of surface water suitability for irrigation is of paramount importance. The Ikpoba River in Edo State, southern Nigeria, represents a vital water resource that flows through the Benin City metropolitan area (Oluku & Asikhia, 2021), supporting multiple anthropogenic uses including domestic water supply, fishing, transportation, and irrigation. Previous investigations have documented moderate to poor water quality in the river, with reported exceedances of recommended limits for turbidity, coliforms, heavy metals (lead, cadmium, and mercury), and nutrients (Chukwuka & Ogbeide, 2021; Adegbite et al., 2018; Atikpo et al., 2023; Oroke et al., 2020). These deteriorating conditions have been attributed to diverse pollution sources, including unregulated abattoirs, breweries, soft-drink production facilities, storm drains, car washes, open defecation, and domestic wastewater discharge (Igbinosa et al., 2021), compounded by land-use changes and riparian degradation within the basin (Ibeanu et al., 2023; Adewumi et al., 2023). Despite the growing body of research on the Ikpoba River, existing studies have largely focused on general physicochemical characterization and drinking water suitability, with limited emphasis on irrigation-specific quality assessment. Moreover, few studies have systematically evaluated seasonal variations in irrigation water quality or applied comprehensive irrigation water quality indices to determine the river's suitability for agricultural use throughout the year. The potential for contaminated irrigation water to adversely affect crop growth, soil properties, and human health via bioaccumulation remains insufficiently quantified for this river system. Consequently, there is a critical knowledge gap regarding the Ikpoba River's fitness for irrigation purposes, particularly in light of its documented pollution burden and the dependence of local agricultural communities on this resource.

Figure 1. Ikpoba River in Benin City and its use for Irrigation.

This study addresses this gap by conducting a comprehensive assessment of the Ikpoba River's water quality specifically for irrigation use at Idogbo Settlement, Benin City. The specific objectives were to: (i) evaluate the physicochemical and microbiological parameters of river water relevant to irrigation suitability; (ii) determine seasonal variations in water quality parameters; and (iii) apply established irrigation water quality indices to assess the river's suitability for agricultural use during both wet and dry seasons. By integrating seasonal monitoring with irrigation-specific quality criteria, this study provides novel, evidence-based insights into the risks associated with using Ikpoba River water for irrigation and contributes to sustainable water resource management in the basin.

2. Material and Methods

2.1. Study area

The study was conducted at the Ikpoba River within Idogbo Settlement, located in the rainforest belt of Edo State, South-South Nigeria (Figure 3). The river originates from the Ishan Plateau in Uhunmwonde Local Government Area, flows through Benin City, and eventually joins the Niger Delta system via the Ossiomo River (Sam-Uroupa & Ogbeibu, 2020; Oyetunji et al., 2019; Ihimekpen & Igibah, 2023; Okonofua et al., 2019). Located approximately at 6.3°–6.5°N, 5.6°–5.7°E, the river drains a catchment of approximately 922 km² through areas including Ikpoba Hill, Ikpoba Slope, Oredo, and Ikpoba-Okha (Ikhile, 2016). It features a dendritic drainage pattern in its upper reaches and maintains perennial flow with strong seasonality, 56% derived from groundwater baseflow and 44% from direct runoff (Anani et al., 2020; Erhokpaidamwen, 2021).

Figure 2. The Ikpoba dam

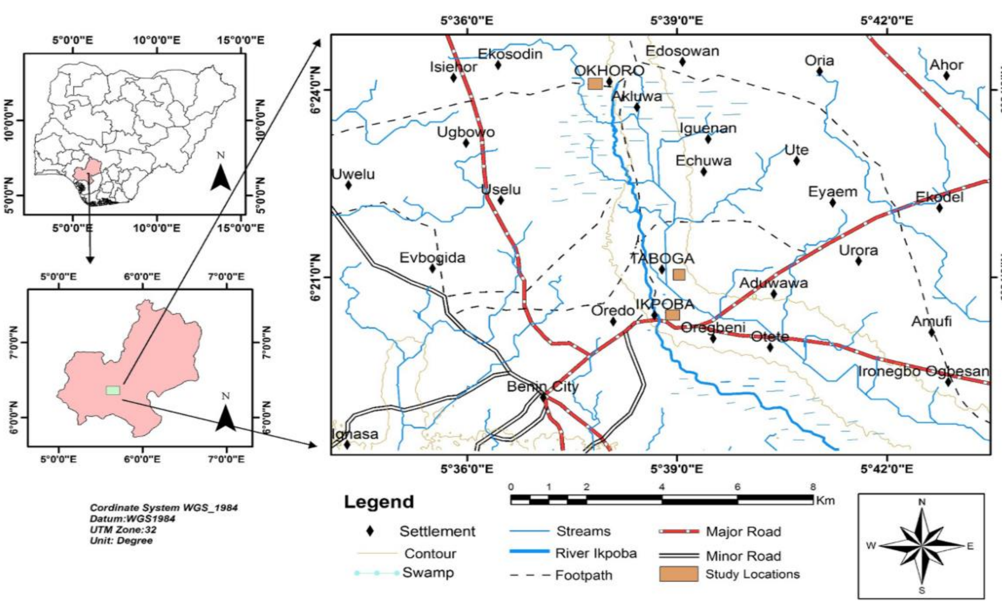

Figure 3. Geographical location of Ikpoba River

The channel averages 10–12m in width, with seasonal depth variation peaking at approximately 3.2 m during high flows and declining to approximately 1.9 m during low flows (Agashua et al., 2023; Schepers et al., 2025). The study area falls within a tropical wet and dry climate, receiving 1,800–2,600 mm of annual rainfall (Agashua et al., 2023; Schepers et al., 2025). The rainy season spans from May to October, while the dry season extends from November to April. Average temperatures during the humid season are approximately 25 °C, rising to around 28 °C in the dry season; the climate is characterized as moist in the southern region and sub-moist in the northern. The dry season coincides with the primary irrigation period when river water is extensively utilized for agricultural purposes. The Ikpoba Dam (reservoir) presented in Figure 2 supplies approximately 90,000 m^3/day to approximately one million people and buffers river flows, while periodic dredging maintains storage capacity and reduces flood risk (Ezugwu et al., 2013; Chukwuka and Ogbeide, 2021a). The river supports fishing, irrigation, domestic water supply, canoe transport, and small industries, and holds sacred status in Edo (Bini) tradition (Igibah &Ihimekpen, 2022a; Edjere et al., 2016). Land use within the basin has shifted markedly from tropical rainforest to secondary forest, farmland, oil-palm stands, grazing land, and expanding urban development (Ibeanu et al., 2023; Mogborukor and Bakoji, 2021). Riparian bamboo buffers have been widely cleared, while sand and gravel mining, road and bridge construction, and bank reinforcement activities have disturbed natural sediment transport and increased erosion (Adewumi et al., 2023; Okura et al., 2025). Consequently, the river suffers from elevated heavy metals, eutrophication, habitat loss, and invasive water hyacinth infestations, though it remains biologically productive, supporting fish, benthic invertebrates, and waterbirds (Ogbomida et al., 2023; Romanus et al., 2018; Aso et al., 2025).

2.2. Sample collection

Water samples were collected at intervals of 10 meters along the river's length during a 30-day period in the month of July, which is the peak period of rainfall, which is also the peak period of the farming activities where water from the river serves its irrigational purpose. The water samples were collected from five (5) different locations and were preserved in sampling bottles, placed in an icebox, and subsequently analyzed using the required instruments. Samples were collected three (3) times a day, morning, afternoon, and evening, over this 30-day period across the five different locations representing:

•Upstream section: Relatively less disturbed, with clearer water and surrounded by natural vegetation.

•Midstream section: Passing through Benin City, heavily influenced by domestic effluents, municipal waste discharge, and runoff from markets and abattoirs.

•Downstream section: Characterized by agricultural activities, sand mining, and potential industrial discharges, with increased turbidity and sediment load (Agashua et al., 2023).

2.3. Field (in-situ) Analysis

pH, which indicates the acidity or basicity of water (Adubor et al., 2025), was measured using a portable pH meter calibrated with standard buffers. Electrical Conductivity (EC), which serves as an indicator of dissolved salts (Ikpa et al., 2016), was measured using a portable conductivity meter and recorded in μS/cm. Total Dissolved Solids (TDS) were derived from EC using a standard conversion factor and recorded in mg/L (ppm). Dissolved Oxygen (DO), which refers to the quantity of oxygen dissolved in water and is crucial for aquatic life, was measured using a portable DO meter and recorded in mg/L. Turbidity, which quantifies the cloudiness of water caused by suspended particles, was measured using a portable turbidimeter and recorded in Nephelometric Turbidity Units (NTU) (Akpe et al., 2018).

2.4. Laboratory Analyses

Alkalinity was determined by the titrimetric method using phenolphthalein and methyl orange indicators, with results expressed as $CaCO_3$ equivalent. Total hardness was determined by EDTA titration using Eriochrome Black T (EBT) as an indicator. Calcium and magnesium were determined by EDTA titration; magnesium was calculated by subtracting calcium from total hardness. Chloride was determined by the Mohr argentometric method using silver nitrate and chromate as an indicator. Sulfate was determined by the turbidimetric method, measuring barium sulfate precipitate turbidity with a spectrophotometer. Nitrate was determined spectrophotometrically by measuring color intensity produced by reaction with specific reagents. Heavy metals were analyzed by atomic absorption spectrophotometry (AAS) following preservation, digestion, and filtration of water samples. Results were used to quantify contamination, apply pollution indices, assess human and ecological health risks, and guide remediation strategies.

3. Results and Discussions

Table 1 below presents the results of the physicochemical, cationic, anionic, and heavy-metal analyses conducted on river water samples collected across the study area. The analyses were designed to investigate the water's physicochemical composition and spatial variability, evaluate whether key parameters comply with irrigation-water quality standards, and interpret water-quality indices using standard statistical tools.

3.1. Physicochemical parameters

Table 1 presents a detailed result of physicochemical, cationic, anionic, and heavy-metal present in the water samples analyzed in this study. The color range is between 6.0 and 7.0 Pt. Co with an average of approximately 6.4 Pt. Co against the permissible limit of 15 Pt. Co; hence, all samples fall well below the allowable limit. This indicates the water is aesthetically clear and free from significant organic contamination, colloidal matter, or dissolved metals that could impart color. pH range between 6.0 and 6.99, with an average of approximately 6.5 against the permissible range of 6.0 and 8.5; also, all samples fall within the acceptable range, though most are on the lower side, indicating slightly acidic to near-neutral conditions. A low pH of close to 6.0 can increase the solubility of metals (like Fe, Mn, and Pb) (Ibe et al., 2025a), which may cause corrosion of pipes and affect taste. Electrical Conductivity (EC) ranges between 25 and 105 μS/cm, far below the permissible range of 900 – 1200 μS/cm. The EC values are very low, which indicates low dissolved ionic content. Such low conductivity is good for drinking (Omoregie et al., 2025) but may also reflect low mineral content, meaning water is not highly buffered against pH changes.

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Table 1. Water quality index and heavy metals

		SITE 1			SITE 2			SITE 3			SITE 4			SITE 5				
Parameter	**Units**	**MS**	**AS**	**ES**	**MS**	**AS**	**ES**	**MS**	**AS**	**ES**	**MS**	**AS**	**ES**	**MS**	**AS**	**ES**	**Desirable level**	**Maximum Allowed Level**
Colour	**Pt.Co**	**6.2**	**6.24**	**6.31**	**6**	**6.01**	**6.5**	**6.7**	**6.8**	**7**	**6.6**	**6.68**	**7**	**6**	**6.04**	**6.1**		**15**
pH		6.97	6.99	6.82	6.45	6.01	6.49	6.2	6.04	6.45	6.45	6.05	6.95	6.3	6.36	6.91	6.000-8.500	6.000-8.500
EC	**uS/cm**	84	100	105	31	42	95	27	26	98	38	41	90	25	34	102	900	1200
TDS	**mg/l**	42	50	52.5	15.5	21	47.5	13.5	13	49	19	20.5	45	12.5	17	51	<200.000	500
Alkalinity	**mg/l**	24.96	24.89	25.51	26.98	28.95	26.81	28.06	28.81	26.98	26.98	28.76	25.04	27.62	27.36	25.18	30.000-500.000	30.000-500.000
Turbidity	**NTU**	0.84	1	6.41	0.31	0.42	5.8	0.27	0.26	5.98	0.38	0.41	5.49	0.25	0.34	6.22	0	5
Cl	**mg/l**	25.2	30	31.5	9.3	12.6	28.5	8.1	7.8	29.4	11.4	12.3	27	7.5	10.2	30.6		250
$SO_4 2^{-}$	**mg/l**	7.64	9.1	9.56	2.82	3.82	8.65	2.46	2.37	8.92	3.46	3.73	8.19	2.28	3.09	9.28	<50.000	250
$NO3^{-}$	**mg/l**	4.37	5.2	5.46	1.61	2.18	4.94	1.4	1.35	5.1	1.98	2.13	4.68	1.3	1.77	5.3	0	<10.000
PO_4^{3-}	**mg/l**	1.51	1.8	1.89	0.56	0.76	1.71	0.49	0.47	1.76	0.68	0.74	1.62	0.45	0.61	1.84	0.025	0.1
Na	**mg/l**	9.24	11	11.55	3.41	4.62	10.45	2.97	2.86	10.78	4.18	4.51	9.9	2.75	3.74	11.22		200
Mg2+	**mg/l**	2.69	3.2	3.36	0.99	1.34	3.04	0.86	0.83	3.14	1.22	1.31	2.88	0.8	1.09	3.26	50	150
Ca2+	**mg/l**	1.36	1.62	1.7	0.5	0.68	1.54	0.44	0.42	1.59	0.62	0.66	1.46	0.41	0.55	1.65	50	150
Fe3+	**mg/l**	0.92	1.1	1.16	0.34	0.46	1.05	0.3	0.29	1.08	0.42	0.45	0.99	0.28	0.37	1.12	0.01	0.3
Zn2+	**mg/l**	0.53	0.63	0.66	0.2	0.26	0.6	0.17	0.16	0.62	0.24	0.26	0.57	0.16	0.21	0.64	0.01	0.4
Mn2+	**mg/l**	0.36	0.43	0.45	0.13	0.18	0.41	0.12	0.11	0.42	0.16	0.18	0.39	0.11	0.15	0.44	0	<0.050
Cu2+	**mg/l**	1.01	1.2	1.26	0.37	0.5	1.14	0.32	0.31	1.18	0.46	0.49	1.08	0.3	0.41	1.22	0	1
Ni2+	**mg/l**	0.34	0.4	0.42	0.12	0.17	0.38	0.11	0.1	0.39	0.15	0.16	0.36	0.1	0.14	0.41		0.02
Cd2+	**mg/l**	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.003	0.003
Cr6+	**mg/l**	0.08	0.09	0.09	0.03	0.04	0.09	0.02	0.02	0.09	0.03	0.04	0.08	0.02	0.03	0.09	0.05	0.05
Pb2+	**mg/l**	0.05	0.06	0.07	0.02	0.03	0.06	0.02	0.02	0.06	0.02	0.03	0.06	0.02	0.02	0.06	0.01	0.01
Hg	**mg/l**	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001		0.001

As	**mg/l**	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001		0.01
COD	**mg/l**	26.04	31	32.55	9.61	13.02	29.45	8.37	8.06	30.38	11.78	12.71	27.9	7.75	10.54	31.62	10	10
DO	**mg/l**	9.54	6.98	8.56	10.74	8.44	9.03	10.39	7.32	8.88	13.52	7.58	10.75	9.43	6.83	8.56	3.000-8.000	4.000-8.000
BOD	**mg/l**	1.05	0.77	0.94	1.18	0.93	0.99	1.14	0.81	0.98	1.49	0.83	1.18	1.04	0.75	0.94	<3.000	<3.000

MS = Morning Sample, AS = Afternoon Sample, ES = Evening Sample

The range of 12.5 – 52.5 mg/L was observed for total dissolved solids (TDS). With a permissible limit of 200 mg/L (as desired by the WHO) and up to 500 mg/L (maximum). It falls far below the recommended limit, confirming excellent water quality with respect to mineral content. However, very low TDS may give the water a "flat" taste since minerals that impart palatability (like Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) are low (Ibe et al., 2025). All values of alkalinity are slightly below the minimum desirable limit (30 mg/L), as low alkalinity implies weak buffering capacity against pH fluctuations, making the water more vulnerable to acidification from natural processes (rainwater, soil leaching) or anthropogenic inputs. Most samples of turbidity are below the permissible limit, except a few (6.22 NTU, 6.41 NTU), which slightly exceed the guideline. Elevated turbidity may indicate the presence of suspended solids, microbial contamination, or colloidal clay. This requires attention since turbidity can shield microorganisms from disinfection. Overall, the river Ikpoba possesses excellent quality in terms of color, EC, and TDS. The pH is within safe limits but slightly acidic in some samples. Alkalinity is consistently low, which may affect buffering capacity, as turbidity is generally acceptable, but some samples exceed limits, indicating occasional contamination events (Balogun et al., 2023). Hence, the water appears to be of good physicochemical quality, with minimal dissolved solids and clear appearance, but requires monitoring for low alkalinity (poor buffering) and turbidity spikes, which could be linked to runoff or suspended matters (Okonofua et al., 2019).

3.2. Cations and anions

Overview of Anions: Chloride (Cl^{-}) content ranges from 7.5 to 31.5 mg/L. With its highest values of 30.6 mg/L observed in site 5, which may indicate domestic/industrial inputs, evaporation concentration, or saline intrusion. Chloride is conservative, which means it does not readily precipitate or react, so it is a good trace of pollution and salinity. The values of sulfate (SO_4^{2-}) vary between 2.3 and 9.5 mg/L. Moderate concentrations may arise from geological sources (gypsum, pyrite oxidation) or fertilizers. High sulfate in irrigation water can cause soil salinity and scaling, but values here are relatively low to moderate. The sulfate concentrations in this study are well within safe limits for drinking and irrigation. They indicate minimal anthropogenic pollution and are most likely influenced by natural geochemical processes. The nitrate (NO_3^{-}) concentrations across all samples are low to moderate, averaging 3.27 mg/L, which is well within safe limits for drinking, irrigation, and aquatic life. Variations indicate localized anthropogenic influence, but no alarming pollution levels. With a range between 1.3 and 5.5 mg/L, the values are below the WHO drinking water limit (50 mg/L), but their presence suggests agricultural runoff, fertilizer use, or sewage contamination, which is ecologically important since nitrates can accelerate eutrophication. Phosphate (PO_4^{3-}) levels in this study range from 0.45–1.89 mg/L. While a few samples fall within natural background limits, the majority exceed the recommended threshold for unpolluted waters, pointing to nutrient enrichment and potential pollution sources such as fertilizer runoff, sewage discharge, or detergents. Sustained high concentrations may contribute to eutrophication and ecological imbalance. Phosphate is typically retained in soil, so presence in water suggests recent input.

Overview of Cations: Sodium (Na^+) ranges within 2.75–11.55 mg/L, well below the maximum allowable limit of 200 mg/L. Although elevated sodium can lead to sodicity hazards in irrigation water (affecting soil permeability/structure) and can also contribute to SAR (Sodium Adsorption Ratio), which is key in irrigation classification. The values of potassium (K^+) are, however, relatively high compared to natural groundwater, 4.25 – 17.85 mg/L. Potassium is typically low in natural water because it is easily fixed in clay minerals (Ibe et al., 2025b), so higher levels suggest fertilizer input or anthropogenic sources. Magnesium (Mg^{2+}) with a range of 0.8 – 3.36 mg/L was detected in this study, which, in combination with Ca^{2+}, contributes to hardness. Also, the ratios of Mg^{2+}/Ca^{2+} can affect water suitability for drinking and irrigation. Calcium (Ca^{2+}) ranges between 0.41 and 1.7 mg/L. Which is lower compared to sodium and potassium — may indicate cation exchange in soils, where Ca^{2+} is replaced by Na^+/K^+. Calcium is essential for reducing sodicity effects in irrigation.

Cation–Anion Balance: Total cations ($Na^+ + K^+ + Mg^{2+} + Ca^{2+}$) per sample are generally in the range of approximately 15–34 mg/L, while the total anions ($Cl^- + SO_4^{2-} + NO_3^- + PO_4^{3-}$) are similar, indicating a reasonably balanced ionic system. This balance suggests data quality is consistent, and the water chemistry is controlled by both geogenic (rock-water interaction) and anthropogenic inputs (fertilizer, wastewater, agriculture).

Irrigation perspective with respect to Cation–Anion Balance: Na^+ and Cl^- are within low to moderate hazard ranges, though continued accumulation could affect soil, suggesting both natural and anthropogenic input, while NO_3^- and PO_4^{3-} suggest fertilizer impact, so agricultural activities will be influenced by groundwater. Low Ca^{2+} and Mg^{2+} compared to Na^+/K^+ indicate possible ion exchange processes, and the low level of Ca^{2+} is a pointer that water could have higher SAR values, as such, requiring monitoring for long-term irrigation use, especially regarding sodicity (Abdel-Fattah et al., 2020).

3.3 Irrigation Quality Assessment

Salinity and Alkalinity Hazards

Alkalinity (as mg/L $CaCO_3$) ranged between 24.89 and 28.95 mg/L, highest in Site 2 Afternoon and lowest in Site 1 Afternoon. Moderate alkalinity levels suggest minimal risk of soil pH buildup (Kamalu et al., 2025); however, cumulative effects on poorly drained soils need monitoring. Chloride (Cl^-) values varied widely from 7.5–31.5 mg/L, with higher values in Site 1 Evening (31.5 mg/L) indicating possible localized salinity buildup risk. WHO recommends Cl^- below 250 mg/L for irrigation; all sites are well below this, so no severe salinity hazard exists presently.

Nutrient Parameters: Nitrate (NO_3^-) levels ranged between 1.3 and 5.46 mg/L, with the highest in Site 1 Evening, while Phosphate (PO_4^{3-}) levels were 0.45–1.89 mg/L, highest in Site 1 Evening and lowest in Site 5 Morning. These values can support plant growth as fertilizers (Egbiki et al., 2020) but may contribute to eutrophication in downstream waters. Moderate nutrient levels are beneficial but need monitoring to avoid excessive nutrient loading (Abubakar, 2021).

Sodium and Sodicity Hazards: Na^+ levels (2.75–11.55 mg/L) are highest in Site 1 Evening. SAR is calculated using Na^+, Ca^{2+}, and Mg^{2+} to fully assess sodicity hazard. Generally, SAR < 10 indicates low sodium hazard; preliminary values here seem below the critical range.

Trace Metals and Toxicity: Metals like Fe^{3+}, Zn^{2+}, and Cu^{2+} were found in small concentrations, mostly below FAO limits for irrigation (e.g., Fe < 5 mg/L). Heavy metals (Pb^{2+}, Cr^{6+}, Ni^{2+}, etc.) were detected in trace amounts far below toxic thresholds. Cd^{2+}, Hg, and As were below detectable limits (<0.001 mg/L), which is desirable since these are highly toxic (Momta et al., 2024), an indication that there is no immediate risk of metal toxicity for crops (Ihimekpen & Igibah, 2023) or soil, but continued monitoring is essential (Enuneku & Ineh, 2020).

Organic Pollution Indicators

COD (7.75–32.55 mg/L) and BOD (0.75–1.49 mg/L) levels indicate mild organic pollution, with the highest COD at Site 1 Evening. DO levels ranged between 6.83 and 13.52 mg/L, highest in Site 4 Morning, indicating well-oxygenated water suitable for irrigation (Onyenechere et al., 2022)

Spatial and Temporal Variations

Spatially: Site 1 consistently recorded the highest pollutant concentrations; Site 5 had the lowest, suggesting possible upstream pollution sources. Temporally, evening samples showed slightly elevated levels for most parameters, possibly due to cumulative anthropogenic activities during the day (Fasipe et al., 2021)

Overall Irrigation Suitability

Based on FAO and WHO guidelines, salinity risk is low, just as sodicity hazard is also likely low; minimal risk is associated with toxic metals with mild organic pollution and moderate nutrients, which could be beneficial for crops. Hence, water from all sites could possess quality for irrigation with localized monitoring for nutrients and salinity buildup; however, a comprehensive conclusion can only be drawn in tandem with other statistical assessments.

SAR (Sodium Adsorption Ratio) is a measure of the proportion of sodium ions relative to calcium and magnesium in water, and SAR is commonly interpreted along with Electrical Conductivity (EC) to classify water for irrigation.

Variation Across Sites

Site 1 had the highest SAR values (1.056–1.181), with EC also higher (84–105 µS/cm). Indicates slightly more sodium contribution, but still safe. Site 2 and Site 3 Morning and afternoon samples showed the lowest SAR values (0.589–0.748), with low EC (26–42 µS/cm). Evening samples rose to approximately 1.1 due to increased sodium concentrations. Site 4 and Site 5 showed similar patterns to Site 2 and 3: lower SAR in morning/afternoon (<0.75) and higher SAR in evening (approximately 1.1–1.16).

$$SAR = \frac{[Na^+]_{meq/L}}{(\{[Ca^{2+}{}_{meq/L}] + [Mg^{2+}]_{meq/L}\}/2)^{1/2}} \quad (1)$$

$$[Na^+]_{meq/L} = \frac{[Na^+]_{mg//L}}{23.0}$$

$$[Na^+]_{meq/L} = \frac{Na_{(mg//L)}}{23.0}$$

$$[Ca^{2+}]_{meq/L} = \frac{Ca_{(mg//L)}}{40.08/2} = \frac{Ca}{20.04}$$

$$[Mg^{2+}]_{meq/L} = \frac{Mg_{(mg//L)}}{24.305/2} = \frac{Mg}{12.1525}$$

This suggests diurnal variation: sodium concentration increases towards evening, possibly due to evaporation or reduced dilution. While Electrical Conductivity (EC) values range from 25 to 105 µS/cm, with EC < 250 µS/cm an indication of low salinity hazard, which will be suitable for all crops, the river water samples are all well below critical salinity levels, so no salinity hazard is present. All samples have SAR < 2; hence, they fall into the low sodium hazard category, indicating no sodium hazard. Although evening samples consistently showed higher SAR and EC, meaning sodium concentration increases during the day. Sites 1 and 5 Evening showed the highest sodium levels (SAR approximately 1.16, EC >100 µS/cm), but they were still safe for irrigation. Combined SAR–EC values suggest that all water samples are suitable for irrigation across all sites and times. The water from all sites is classified as excellent for irrigation (low sodium and salinity hazard). However, monitoring is important because slight evening increases in sodium could accumulate over time in soils, especially under poor drainage conditions. Regular assessment of long-term irrigation impacts on soil permeability and structure is also needful.

Table 2. Sodium Adsorption Ratio (SAR) for the various locations

Sample	Na (mg/L)	Ca (mg/L)	Mg (mg/L)	SAR
Site1 Morning	9.24	1.36	2.69	1.056
Site1 Afternoon	11	1.62	3.2	1.153
Site1 Evening	11.55	1.7	3.36	1.181
Site2 Morning	3.41	0.5	0.99	0.643
Site2 Afternoon	4.62	0.68	1.34	0.748
Site2 Evening	10.45	1.54	3.04	1.124
Site3 Morning	2.97	0.44	0.86	0.6
Site3 Afternoon	2.86	0.42	0.83	0.589
Site3 Evening	10.78	1.59	3.14	1.141
Site4 Morning	4.18	0.62	1.22	0.709
Site4 Afternoon	4.51	0.66	1.31	0.739
Site4 Evening	9.9	1.46	2.88	1.094
Site5 Morning	2.75	0.41	0.8	0.576
Site5 Afternoon	3.74	0.55	1.09	0.672
Site5 Evening	11.22	1.65	3.26	1.165

Common irrigation guidance (US Salinity Laboratory):

SAR < 10 — excellent; 10–18 — good to fair; 18–26 — poor; >26 — very poor.

As presented in Table 2, all your samples have SAR approximately within the range of 0.58 – 1.18, which is very low and falls well within the "excellent" category for sodium hazard to soil structure, as low SAR suggests low risk of sodium-induced infiltration/structure problems, while high SAR values indicate a risk of sodium hazard in irrigation water, where sodium can displace calcium and magnesium in the soil, leading to poor soil structure, reduced permeability, and lower crop productivity.

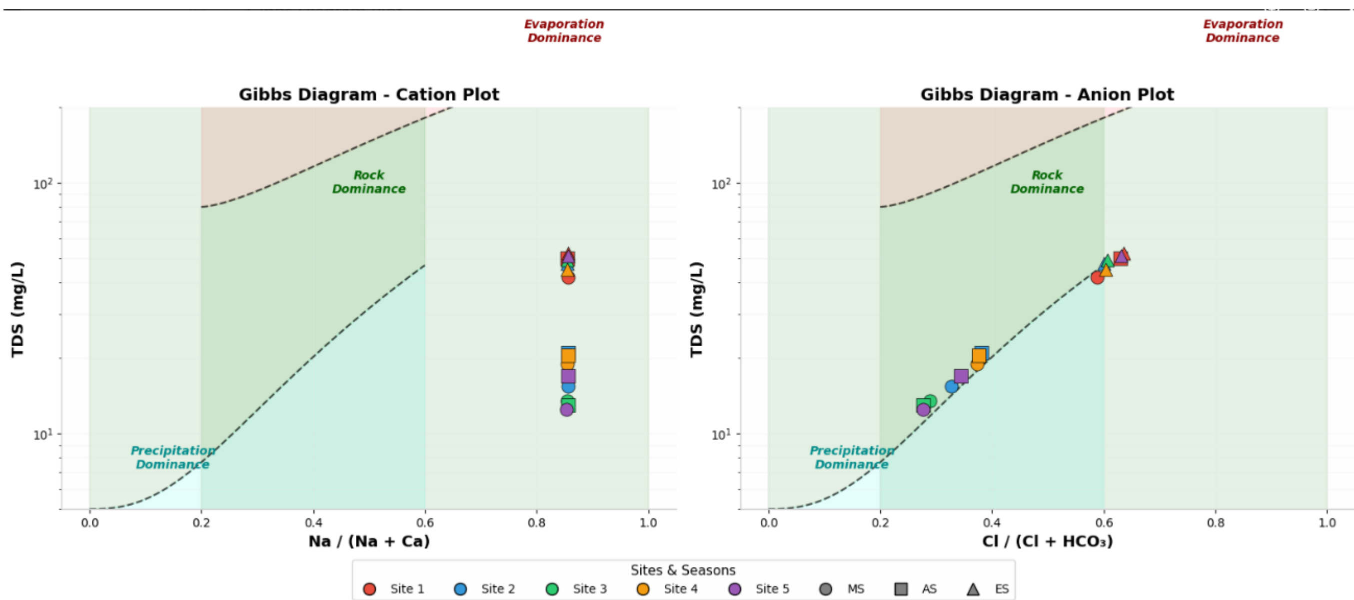
3.4. Gibb's Plot analysis

The Gibbs plot is used to identify the processes that control water chemistry, especially in groundwater. It helps us see whether the dominant control is precipitation dominance (rainfall, atmospheric input), rock dominance (water-rock interaction, like weathering of minerals), or evaporation or crystallization dominance (high evaporation, often in arid areas) processes. The Gibb's ratio values for various locations in Table 3 showed the anion and cation relationship with TDS for all locations. The Gibbs plot analysis is used to interpret the mechanisms controlling the chemistry of water.

The Gibbs Ratio Values for cations and anions are high (close to 1), indicating that the water chemistry is mainly controlled by rock–water interaction (weathering) and slightly influenced by evaporation–crystallization, while all the TDS Values (12.5–52.5 mg/L) presented in Table 3 are low, which means the water is fresh, and the ionic concentration is primarily due to rock weathering of silicate and carbonate minerals. The samples (ratio approximately 0.87, TDS < 200) lie near the boundary between rock dominance and early evaporation dominance, confirming rock–water interaction as the major geochemical process controlling ion composition.

Table 3. Gibbs Ratios for the various locations

Site	Na (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)	TDS (mg/L)	Gibbs (Na) = Na/(Na+Ca)	Gibbs (Cl) = Cl/(Cl+SO_4^{2-})
1	9.24	1.36	25.2	7.64	42	0.871	0.767
2	11	1.62	30	9.1	50	0.872	0.767
3	11.55	1.7	31.5	9.56	52.5	0.872	0.767
4	3.41	0.5	9.3	2.82	15.5	0.872	0.767
5	4.62	0.68	12.6	3.82	21	0.872	0.767
6	10.45	1.54	28.5	8.65	47.5	0.872	0.767
7	2.97	0.44	8.1	2.46	13.5	0.871	0.767
8	2.86	0.42	7.8	2.37	13	0.872	0.767
9	10.78	1.59	29.4	8.92	49	0.872	0.767
10	4.18	0.62	11.4	3.46	19	0.871	0.767
11	4.51	0.66	12.3	3.73	20.5	0.872	0.767
12	9.9	1.46	27	8.19	45	0.871	0.767
13	2.75	0.41	7.5	2.28	12.5	0.87	0.767
14	3.74	0.55	10.2	3.09	17	0.872	0.767
15	11.22	1.65	30.6	9.28	51	0.872	0.767



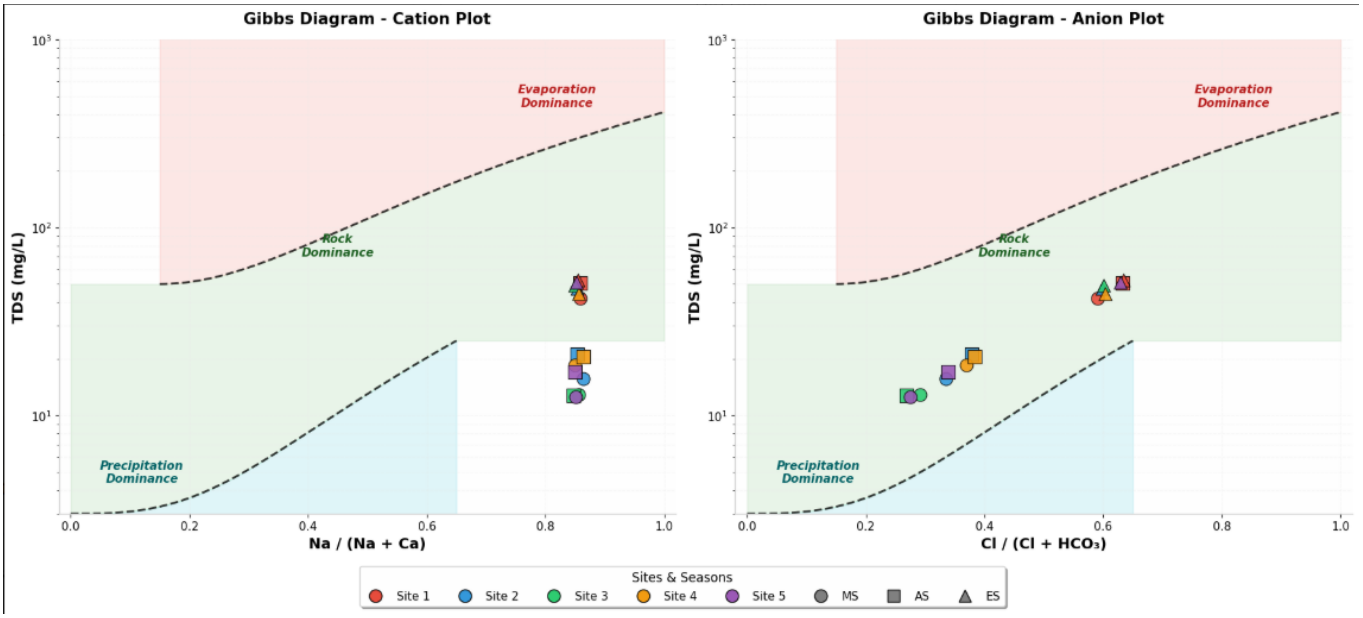


Figure 3. Gibb's Plot analysis

Table 4. Interpretation of the Gibbs Ratio

Control Mechanism	**Na/(Na+Ca) or Cl/(Cl+SO$_4^{2-}$)**	**Typical TDS (mg/L)**	**Interpretation**
Precipitation dominance	< 0.35	Low	Direct influence from rainfall
Rock dominance	0.35 – 0.80	Moderate	Weathering of rocks and soil minerals
Evaporation–crystallization dominance	> 0.80	High	Concentration due to evaporation

Hence, the Gibbs plot reveals that the Ikpoba River is freshwater with TDS < 200 mg/L. The dominant process controlling water chemistry is rock weathering, as presented in Table 4, primarily of silicate and carbonate minerals, with minor evaporative influence. No strong evidence of anthropogenic (pollution) influence, since both TDS and major ion concentrations are well below WHO/FAO limits. The Gibb's diagram in Figure 3 has a left triangle, which consists of the cations (Ca^{2+}, Mg^{2+}, Na^{+} + K^{+}); the right triangle, which consists of the anions (Cl^{-}, SO_4^{2-}, HCO_3^{-}/CO_3^{2-}); and the central diamond, consisting of the overall water type (hydrochemical facies) as presented in Table 5. Each point represents the relative percentage of major ions (in meq/L), not concentrations in mg/L. The positions indicate the dominance of certain ions and overall water character.

Table 5. Dominant Trend of Gibb's analysis

Site	Major Cations	Major Anions	Dominant Facies Trend
1	$Na^+ > Mg^{2+} > Ca^{2+}$	$Cl^- > HCO_3^- > SO_4^{2-}$	**Na–Cl type**
2	$Na^+ > Mg^{2+} > Ca^{2+}$	$Cl^- > HCO_3^- > SO_4^{2-}$	**Na–Cl type**
3	$Na^+ > Mg^{2+} > Ca^{2+}$	$Cl^- > HCO_3^- > SO_4^{2-}$	**Na–Cl type**
4	$Na^+ > Mg^{2+} > Ca^{2+}$	$HCO_3^- > Cl^- > SO_4^{2-}$	**Na–HCO_3 type**
5	$Na^+ > Mg^{2+} > Ca^{2+}$	$Cl^- > HCO_3^- > SO_4^{2-}$	**Na–Cl type**

Where HCO_3^- is represented by Alkalinity, since bicarbonate dominates in natural waters.

Cation Plot: All samples cluster tightly at Na/(Na+Ca) approximately 0.85 to 0.86, indicating strong sodium dominance over calcium across all sites and seasons. This is characteristic of water that has undergone significant rock-water interaction (silicate weathering or ion exchange).

Anion Plot: The samples show two distinct groupings:

MS & AS (Morning and Afternoon): Lower $Cl/(Cl+HCO_3)$ ratios (approximately 0.28 to 0.38), meaning bicarbonate dominates over chloride typical of dilution from rainfall/groundwater recharge.

ES (Early Summer): Higher ratios (approximately 0.59–0.64), indicating chloride enrichment likely due to evaporative concentration during the dry season.

Overall: All samples fall in the Rock Dominance zone, confirming that hydrochemistry is primarily controlled by water-rock interaction rather than precipitation or evaporation. The seasonal shift in the anion plot reflects dilution during monsoon periods and concentration during summer.

3.5. Piper Plot

A Piper Plot is a graphical tool commonly used in hydrogeology and water quality studies to classify and interpret the chemical characteristics of water samples. It helps in understanding water types, hydrochemical facies, and evolution of groundwater.

Interpretation of Piper Plot Zones

The Piper plot typically divides into different zones in the diamond field as highlighted in Table 6.

Table 6. Zones in the diamond for Piper's plot

Sample	Ca^{2+} %	Mg^{2+} %	Na^{+} %	Cl^{-} %	SO_4^{2-} %	NO_3^{-}+PO_4^{3-} %	Cat (meq/L)	An (meq/L)	Diamond X	Diamond Y
Site1_Morning	9.82	32.03	58.15	71.94	16.1	11.96	0.691	0.988	0.4619	-0.2989
Site1_Afternoon	9.83	32.01	58.16	71.93	16.1	11.96	0.823	1.176	0.4620	-0.2987
Site1_Evening	9.82	32.01	58.17	71.93	16.11	11.96	0.864	1.235	0.4621	-0.2987
Site2_Morning	9.79	31.98	58.23	71.93	16.1	11.97	0.255	0.365	0.4626	-0.2980
Site2_Afternoon	9.83	31.95	58.22	71.93	16.1	11.97	0.345	0.494	0.4625	-0.2981
Site2_Evening	9.83	32.01	58.16	71.93	16.11	11.96	0.782	1.118	0.4620	-0.2988
Site3_Morning	9.89	31.89	58.22	71.90	16.12	11.98	0.222	0.318	0.4624	-0.2981
Site3_Afternoon	9.81	31.97	58.22	71.91	16.13	11.97	0.214	0.306	0.4626	-0.2981
Site3_Evening	9.84	32.03	58.13	71.93	16.11	11.96	0.807	1.153	0.4617	-0.2991
Site4_Morning	9.88	32.06	58.06	71.94	16.11	11.95	0.313	0.447	0.4611	-0.2999
Site4_Afternoon	9.78	32.00	58.23	71.93	16.1	11.97	0.337	0.482	0.4626	-0.2980
Site4_Evening	9.84	32.01	58.16	71.93	16.11	11.96	0.7	1.059	0.4619	-0.2988
Site5_Morning	9.94	31.97	58.09	71.91	16.13	11.96	0.206	0.294	0.4613	-0.2995
Site5_Afternoon	9.81	32.05	58.14	71.95	16.09	11.96	0.3	0.4	0.4618	-0.2990
Site5_Evening	9.82	31.99	58.19	71.93	16.1	11.97	0.839	1.2	0.4623	-0.2984

Table 7. Interpretation of Piper Plot Zones

Zone	Description	Water Type
I	Ca–HCO_3 type	Fresh recharge or shallow groundwater
II	Na–Cl type	Marine or saline influence, ion exchange
III	Mixed type	Transition waters, mixing processes
IV	Na–HCO_3 type	Cation exchange or silicate weathering

Sites 1–3 have high Na^{+} and Cl^{-} concentrations and low Ca^{2+} and SO_4^{2-}, an indication of saline or ion-exchanged water most likely due to seawater intrusion (Ilaboya et al., 2023), water–rock interaction, and agricultural return flow or contamination, while the characteristic features under which the sediments were formed or deposited are Sodium–Chloride type (Na–Cl). Site 4 has higher alkalinity (HCO_3^{-}) and moderate Na^{+} and lower Cl^{-} and SO_4^{2-} values as presented in Table 7, indicating carbonate weathering dominance, while the characteristic features under which the sediments were formed or deposited are Sodium–Bicarbonate (Na–HCO_3), signifying freshwater recharge zones or areas of active silicate weathering. Site 5 is similar to Sites 1–3, with Na^{+} and Cl^{-} dominance and moderate alkalinity as shown in Figure 4, indicating partial mixing, while the

characteristic features under which the sediments were formed or deposited are Sodium–Chloride type (Na–Cl), which could represent transition water between fresh and saline zones (Idemudia et al., 2023).

1. Major Ion Hydrochemical Facies

The relative percentages of the major cations and anions, the water type is uniform across every single sample:

Cation Profile: Dominated heavily by Sodium (Na^{+} *approximately* 58%), followed by Magnesium (Mg^{2+} *approximately* 32%) and very low Calcium (Ca^{2+} *approximately* 9.8%).

Anion Profile: Strongly dominated by Chloride (Cl^{-} *approximately* 71.9%), with moderate Sulfate (SO_4^{2-} *approximately* 16.1%) and lower Nitrate/Phosphate ($NO_3^{-} + PO_4^{3-}$ *approximately* 11.9%).

Hydrochemical Facies: Na-Cl type (Saline/Halite dominant). In a typical hydrogeological context, this usually points towards seawater intrusion, deep ancient brine influence, or severe anthropogenic pollution

2. Temporal and Spatial Variations (Or Lack Thereof)

Spatial (Site to Site): There is virtually no spatial variation. For instance, Na^{+} stays strictly between 58.06% and 58.23% across all 5 distinct geographic sites.

Temporal (Diurnal Changes): The relative percentages do not shift from morning to evening. However, there is a massive, consistent jump in absolute concentration during the Evening sampling across almost all sites.

Example (Site 1): Total cations rise from 0.691 meq/L (Morning) to 0.864 meq/L (Evening).

Example (Site 2): Total cations spike from 0.255 meq/L (Morning) to 0.782 meq/L (Evening).

This implies that while the source of the water remains identical (identical ion ratios), the concentration increases in the evening. This could lead to evening wastewater discharge cycles or evaporation effects concentrated over the course of the day, as the river is surface water.

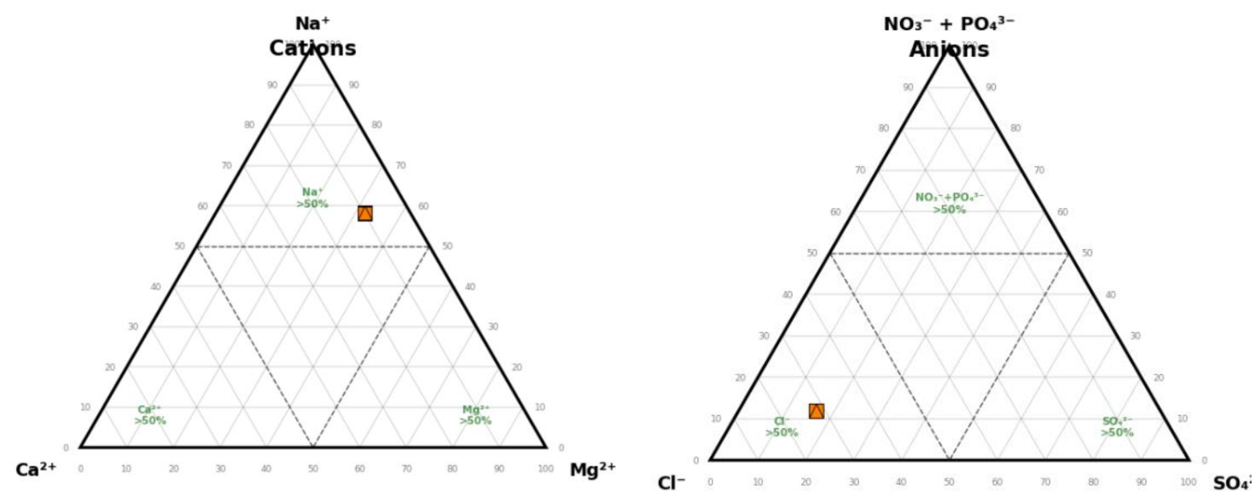
3. Piper Diagram Projection (Diamond X & Y)

The Diamond X and Y coordinates are mathematical projections used to map the trilinear data onto the central diamond of a Piper Diagram.

Diamond X (approximately 0.46): Places the points squarely in the right quadrant of the diamond.

Diamond Y (approximately -0.30): Places the points in the lower half of the diamond.

This explicitly represents primary salinity (saline water dominated by alkali metals and strong acids—i.e., Na-Cl or Na-SO_4 type).



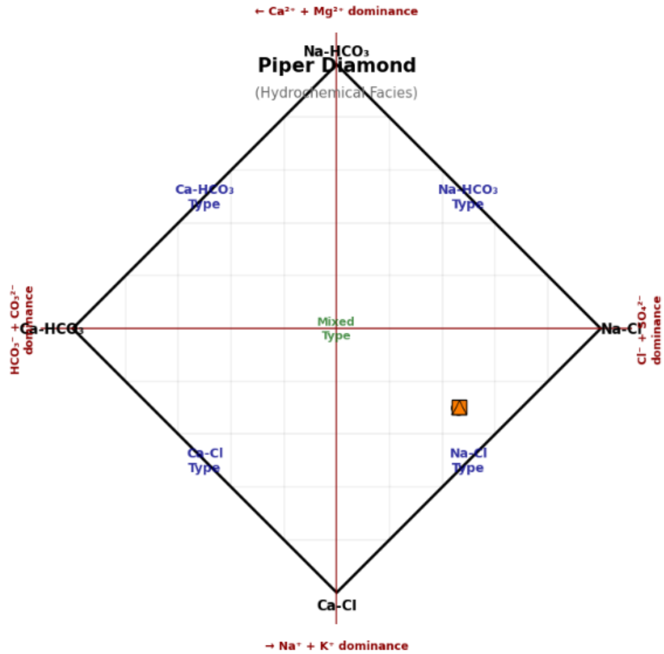


Figure 4. Piper plot

Hence, the major water type is sodium–chloride (Na–Cl), and the geochemical process is ion exchange, evaporation concentration, or saline intrusion, while the hydrological implication is that Sites 1–3 and 5 may be influenced by mineral dissolution, agricultural runoff, or domestic/industrial inputs (Ihimekpen & Igibah, 2022b), while Site 4 represents relatively fresh recharge water with bicarbonate dominance (Ufuah et al., 2023) as shown in Table .8

Table 8. Hydrochemical Character

Parameter	**General Trend**
Cations	$Na^+ > Mg^{2+} > Ca^{2+}$
Anions	$Cl^- > HCO_3^- > SO_4^{2-}$
Dominant Water Type	**Na–Cl facies**
Possible Origin	Ion exchange, saline influence, or anthropogenic contamination
Outlier	Site 4 shows $Na–HCO_3$ facies (fresh recharge water influence)

3.6 Percent Sodium (%Na)

All samples give a very consistent value around approximately 58.1% as shown in Table 9 and fall into the upper part of the "permissible / doubtful" class (borderline toward the "doubtful" range), which indicates a fairly high proportion of sodium among the measured cations. This %Na value is the percentage of sodium in the major cations of the water, which is a water-quality sodium indicator. Typical irrigation-water guidance classifies sodium % roughly as <20% — excellent, 20–40% — good to permissible, 40–60% — doubtful, and >60% — unsatisfactory. Sodium is high enough relative to Ca and Mg that soil structure and infiltration could be affected over time (sodicity problems—soil dispersion, decreased permeability).

Table 9. Percent Sodium (%Na)

Site	Sample	Na (mg/L)	Ca (mg/L)	Mg (mg/L)	Na meq/L	Ca meq/L	Mg meq/L	%Na
1	MS	9.24	1.36	2.69	0.4017	0.0679	0.2214	**58.14**
1	AS	11	1.62	3.2	0.4783	0.0808	0.2633	**58.15**
1	ES	11.55	1.7	3.36	0.5022	0.0848	0.2765	**58.16**
2	MS	3.41	0.5	0.99	0.1483	0.025	0.0815	**58.22**
2	AS	4.62	0.68	1.34	0.2009	0.0339	0.1103	**58.21**
2	ES	10.45	1.54	3.04	0.4543	0.0768	0.2502	**58.15**
3	MS	2.97	0.44	0.86	0.1291	0.022	0.0708	**58.21**
3	AS	2.86	0.42	0.83	0.1243	0.021	0.0683	**58.21**
3	ES	10.78	1.59	3.14	0.4687	0.0793	0.2584	**58.12**
4	MS	4.18	0.62	1.22	0.1817	0.0309	0.1004	**58.05**
4	AS	4.51	0.66	1.31	0.1961	0.0329	0.1078	**58.22**
4	ES	9.9	1.46	2.88	0.4304	0.0729	0.237	**58.15**
5	MS	2.75	0.41	0.8	0.1196	0.0205	0.0658	**58.08**
5	AS	3.74	0.55	1.09	0.1626	0.0274	0.0897	**58.13**
5	ES	11.22	1.65	3.26	0.4878	0.0823	0.2683	**58.18**

However, absolute salinity (EC) is low to moderate in your data (EC values you supplied are mostly low), so combined salinity + sodicity effects may vary. Low EC reduces the "protective" effect of salts on soil structure, making sodium's adverse effects more likely. With approximately 58%, the water samples fall in the doubtful → near-unsatisfactory range for sodium hazard to soils/crops; if used for irrigation, the water could cause infiltration or structural problems over time (Egun and Oboh, 2022).

3.7 Wilcox Plot

Figure 5 revealed all samples plot at low EC and very low SAR. By Wilcox categories (EC in μS/cm and SAR classes). Percent sodium (Na%) for all samples is high, approximately 58% for every site, with Na% computed using Na, Ca, and Mg in mg/L converted to meq/L. EC values are all low (25–105 µS/cm), so salinity class is C1 (low salinity), but sodium hazard is in the "permissible/doubtful" range (around the 40–60% horizontal band). Although salinity is low, relatively high sodium hazards could be a concern for sensitive crops or longer-term soil structure. The highest EC is 105 µS/cm (Site 1 — Evening), and the highest SAR is 1.181 (Site 1 — Evening); both are still very low for irrigation concerns as presented in Table 10.

Table 10. Wilcox class for different sites

Site	Time	EC (µS/cm)	%Na	Wilcox class
Site 1	Morning	84	58.1	Excellent to Good
Site 1	Afternoon	100	58.2	Excellent to Good
Site 1	Evening	105	58.2	Excellent to Good
Site 2	Morning	31	58.2	Excellent to Good
Site 2	Afternoon	42	58.3	Excellent to Good
Site 2	Evening	95	58.2	Excellent to Good
Site 3	Morning	27	58.1	Excellent to Good
Site 3	Afternoon	26	58.1	Excellent to Good
Site 3	Evening	98	58.1	Excellent to Good
Site 4	Morning	38	58.2	Excellent to Good
Site 4	Afternoon	41	58.2	Excellent to Good
Site 4	Evening	90	58.2	Excellent to Good
Site 5	Morning	25	58.3	Excellent to Good
Site 5	Afternoon	34	58.2	Excellent to Good
Site 5	Evening	102	58.2	Excellent to Good

All 15 samples plot in the far left of the diagram (EC = 25 – 105 µS cm^{-1}) with a Sodium Percentage of approximately 58 %. Because the salinity hazard (EC) is very low, every single point falls inside the "Excellent to Good" zone.

Salinity hazard is negligible (all EC values are well below the 250 µS cm^{-1} threshold that separates low-salinity water from medium-salinity water).

Sodium hazard is moderate (%Na approximately 58 %), but because the total salt concentration is very low, the sodium cannot accumulate rapidly in the soil.

Management recommendation: with respect to Wilcox plot the water is suitable for irrigation of most crops on most soil types with little likelihood of developing soil salinity or sodicity under normal irrigation practices. No special leaching or amendment requirements are necessary, though routine monitoring is always advisable if the water source is subject to seasonal changes.

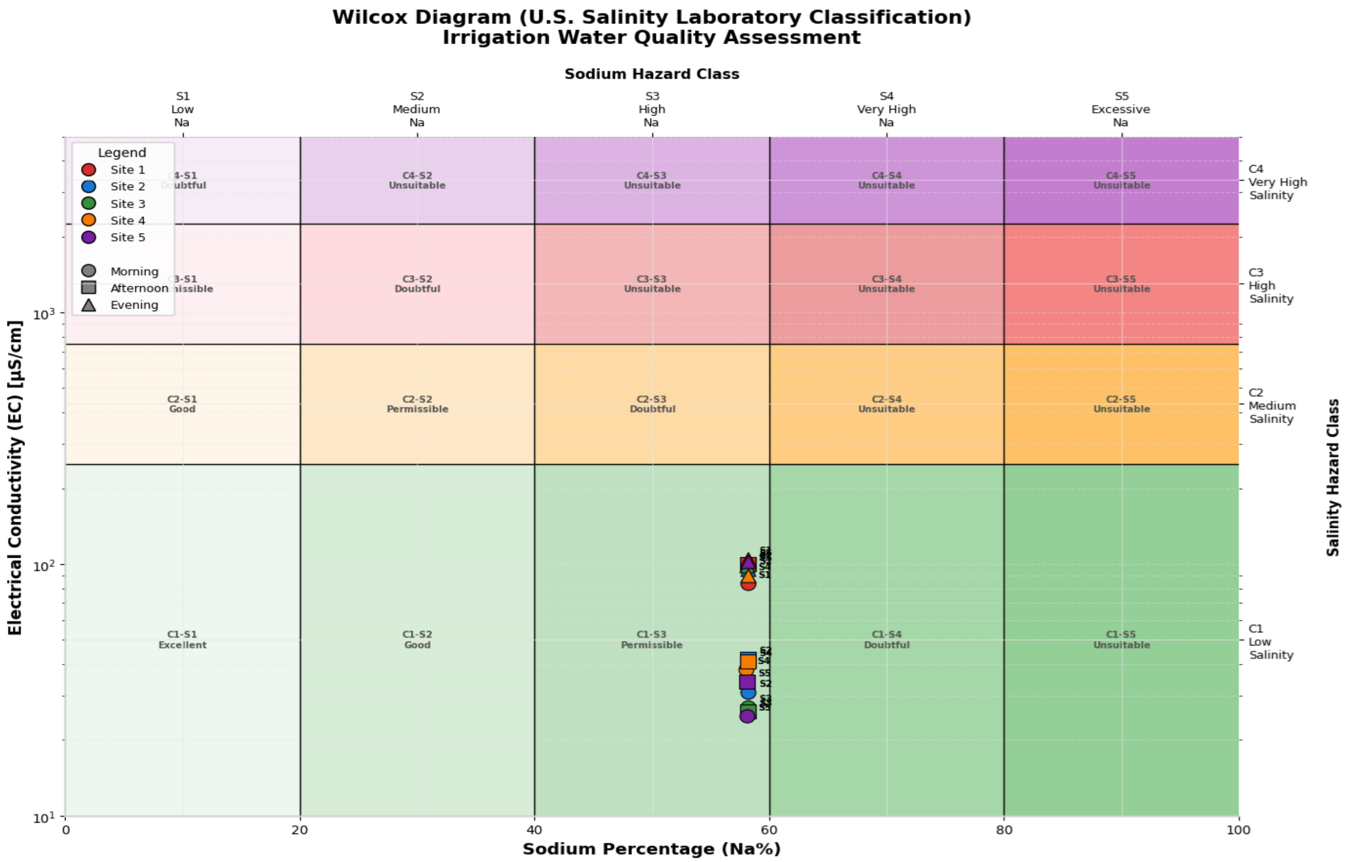


Figure 5. Wilcox Plot: SAR (y) vs Electrical Conductivity (x)

3.8 Kelly's ratio

Kelly's ratio (KR) serves as a parameter for evaluating the quality of irrigation water by comparing the concentration of sodium ions (Na^+) to the total concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions. This ratio is measured in milliequivalents per liter (meq/L). Kelly's ratio of less than 1 signifies that the water is typically appropriate for irrigation, whereas a ratio exceeding 1 indicates a surplus of sodium, rendering the water unsuitable due to possible soil permeability problems (i.e., water is unsuitable for irrigation under the Kelly criterion).

$$KR = \frac{[Na^+]}{[Ca^{2+}] + [Mg^{2+}]} \quad (2)$$

Table 11. Kelly's ratio

Site	Site1	Site1	Site1	Site2	Site2	Site2	Site3	Site3	Site3	Site4	Site4	Site4	Site5	Site5	Site5
Replicate	MS	AS	ES	MS	AS	ES	MS	AS	ES	MS	AS	ES	MS	AS	ES
KR (rounded)	1.39	1.39	1.39	1.394	1.394	1.39	1.393	1.394	1.388	1.384	1.394	1.39	1.386	1.389	1.392

Site mean KR (by site): Site1 = 1.390, Site2 = 1.393, Site3 = 1.392, Site4 = 1.389, Site5 = 1.389.

All the samples have Kelly's ratio of approximately 1.38–1.39 (> 1) as shown in Table 11; by this index, these waters would be considered not suitable for irrigation (sodium hazard). Because KR > 1 across the board, consider mitigation if you must use this water for irrigation: blend with lower-Na water, apply gypsum ($CaSO_4$) to improve Ca:Na balance in soil, increase leaching.

Percent Sodium (mg/L):

Percent Sodium (% Na) is a common parameter used in irrigation water quality analysis to assess the sodium hazard of water. It indicates the proportion of sodium ions relative to other major cations (calcium, magnesium, potassium).

$$\%Na = \frac{(Na^+ \text{ (meq/L)} + K^+ \text{ (meq/L)})}{(Ca^{2+} \text{ (meq/L)} + Mg^{2+} \text{ (meq/L)} + (Na^+ \text{ (meq/L)} + K^+ \text{ (meq/L)})} \quad (3)$$

Conversion factors used: Na ÷ 23.0, Ca ÷ 20.04, Mg ÷ 12.1525.

3.9 Permeability Index (PI) using Doneen's formula:

The Permeability Index (PI) is an important irrigation water quality parameter used to evaluate the suitability of water for agricultural use, particularly its effect on soil permeability. High sodium content relative to calcium and magnesium can reduce soil permeability, which affects water infiltration and plant growth. PI provides a way to assess this risk.

Table 12. Permeability Index (PI)

Sample	Site1 MS	Site1 AS	Site1 ES	Site2 MS	Site2 AS	Site2 ES	Site3 MS	Site3 AS	Site3 ES	Site4 MS	Site4 AS	Site4 ES	Site MS	Site AS	Site5_ ES
PI (%)	160.38	143.93	140.87	346.59	278.68	151.85	395.8	413.5	149.2	292.64	283.34	153.73	419.05	322.5	142.81
Doneen Class	Class I (Good)	Class I (Good)	Class I (Good)	Class I (Good)	Class I (Good)	Class I (Good)	Class I (Good)	Class I (Good)	Class I (Good)	Class I (Good)	Class I (Good)	Class I (Good)	Class I (Good)	Class I (Good)	Class I (Good)

$$PI = \frac{[Na^{+}] + [HCO_3^{-}]^{1/2}}{[Ca^{2+}] + [Mg^{2+}] + [Na^{+}]} \times 100 \quad (4)$$

Classification (Doneen):

Class I: PI > 75% good / suitable for irrigation

Class II: 25% < PI ≤ 75% — moderate / permissible

Class III: PI ≤ 25% — unsuitable

All 15 samples fall into Doneen Class I (PI > 75%) as shown in Table 12, indicating the waters are good with respect to permeability (i.e., they are unlikely to cause permeability reduction problems in soils used for irrigation). Several samples have very high PI values (>200–400%), which arises because measured Ca and Mg concentrations are very low relative to Na (in meq/L), making the denominator small. Numerically this is valid under the formula but worth noting: very high PI simply emphasizes the dominance of Na (and the low Ca/Mg) in meq units. Based on Doneen's Permeability Index (PI), all water samples from Sites 1–5 fall under Class I, indicating that the waters possess excellent permeability characteristics and are suitable for irrigation without adverse effects on soil permeability.

3.10 Residual Sodium Carbonate (RSC)

Residual Sodium Carbonate (RSC) is an important hydrochemical parameter used to assess the suitability of water for irrigation. RSC measures the amount of carbonate and bicarbonate ions that remain in water after precipitation of calcium and magnesium as insoluble carbonates. A high RSC indicates a risk of increased soil sodicity, reduced infiltration, and poor soil structure. It evaluates the effect of carbonate and bicarbonate concentrations on the availability of calcium and magnesium in the soil (Igibah et al., 2022).

The residual sodium carbonate (RSC meq/l) is calculated as follows:

$$RSC = ([HCO_3^{-}] + [CO_3^{2-}]) - ([Ca^{2+}] + [Mg^{2+}]) \quad (5)$$

Table 13. RSC for each sample (meq/L)

Site1 MS	Site1 AS	Site1 ES	Site2 MS	Site2 AS	Site2 ES	Site3 MS	Site3 AS	Site3 ES	Site4 MS	Site4 AS	Site4 ES	Site5 MS	Site5 AS	Site5 ES
0.21	0.154	0.149	0.433	0.435	0.209	0.469	0.487	0.202	0.408	0.434	0.191	0.466	0.43	0.153

RSC estimates the excess of carbonate and bicarbonate (which tie up calcium and magnesium) over the available calcium + magnesium in irrigation water. It's used to judge the sodium hazard to soils. The Mean RSC per site are Site 1: 0.171 meq/L, Site 2: 0.359 meq/L, Site 3: 0.386 meq/L, Site 4: 0.345 meq/L and Site 5: 0.350 meq/L as shown in Table 13. The commonly used interpretation bands are:

- RSC < 1.25 meq/L — Safe for irrigation
- RSC 1.25–2.5 meq/L — Marginal (may cause problems long-term)
- RSC > 2.5 meq/L — Unsuitable (risk of sodium hazards, dispersion, poor infiltration)

3.11 Magnesium Absorption Ratio

The Magnesium Absorption Ratio (MAR) is a hydrochemical index used to evaluate the suitability of water for irrigation purposes, particularly its effect on soil structure and permeability. High magnesium concentration in irrigation water can have adverse effects on soil quality, reducing its infiltration capacity.

Magnesium Adsorption Ratio (%) expresses the proportion of magnesium relative to the sum of calcium and magnesium in irrigation water:

$$MAR = \frac{Mg_{(meq/L)}}{[Mg_{(meq/L)} + Ca_{(meq/L)}] \times 100} \quad (6)$$

Table 14. MAR (%) all sites

Site	Replicate MARs (%) (MS, AS, ES)	Mean ± SD (%)
1	76.53, 76.51, 76.52	**76.52 ± 0.01**
2	76.55, 76.47, 76.50	**76.51 ± 0.04**
3	76.32, 76.52, 76.51	**76.45 ± 0.11**
4	76.44, 76.60, 76.49	**76.51 ± 0.08**
5	76.29, 76.57, 76.51	**6 0.15**

All MAR values are about 76%, as shown in Table 14. Common irrigation guidance treats MAR > 50% as indicating a high magnesium hazard, which is relatively high Mg compared with Ca and can negatively affect soil structure and crop growth over time. A low MAR (commonly less than 50%) is generally considered acceptable for irrigation—calcium predominates, and soil structure is less likely to be harmed by excess magnesium. High MAR (typically > 50%) indicates magnesium dominance. High Mg relative to Ca can reduce soil infiltration and permeability, reduce availability of some nutrients to plants, and harm crop yields for Mg-sensitive crops or on poorly drained soils. The data in all five sites show MAR at approximately 76.5%, well above the usual 50% guideline. This indicates a consistent, strong magnesium dominance in the water at all sampled sites and suggests potential risk to soil structure and crop performance if used repeatedly for irrigation without management.

4. Conclusions

All site values are within the acceptable range for pH; EC values and TDS are well below the desirable/maximum values. SAR values are very low; hence, there is no sodium risk for soil structure. Percent sodium at approximately 58% is borderline, suggesting a potential long-term sodium build-up risk if irrigation is continuous without soil management. Turbidity is above the max allowed; this can clog sprinkler/drip systems and reduce infiltration. PO_4^{3-} are well above the maximum allowed, presenting a risk of eutrophication and biofouling of irrigation lines; COD measurements exceed the stated limit, an indication of organic pollution that can affect soil biology and clogging; BOD values are low, suggesting non-biodegradable organics may be present. Conclusively, the water is chemically suitable with respect to salinity/sodicity (pH, EC, TDS, and SAR), but it fails for irrigation of food (edible) crops because of elevated heavy metals (Fe, Zn, Mn, Pb, Ni, and Cr), high phosphate (PO_4^{3-}), and high COD/turbidity in some samples. Use of unrestricted irrigation of vegetables/food crops is not recommended due to unacceptable values for %Na and MAR without treatment or mitigation, as accumulation of these metals in soils and crops is the principal reason to avoid irrigating food crops with this water (Adegun et al., 2024).

The following recommendations are needed:

This river water should not be used for unrestricted irrigation of vegetables, fruit, or other crops destined for human consumption until the heavy metals (Pb, Ni, Fe, Zn, Mn, Cr) and phosphate/COD issues are resolved or shown to be safe by crop-specific risk assessment and soil monitoring. Heavy metals will bioaccumulate in edible tissues and in soil over time. For non-food / industrial / ornamental crops: The river water may be usable if spray irrigation is avoided and regular monitoring of soil metal accumulation is done. For the use of the river water for food crops: Treating the water should be done for metal and phosphate removal. The river water can also be blended with cleaner water to dilute contaminants; also, there could be the need to test soils and crops periodically for metal accumulation before and during irrigation. Operational precautions if irrigation proceeds: Using drip/subsurface irrigation can be used to reduce leaf contact and human exposure, or irrigating leafy vegetables and root crops eaten raw should be avoided. Also, soil amendments (lime, gypsum) should be avoided. A soil-monitoring program for monitoring of heavy metals and salinity should be implemented. Monitoring and further steps: Composite samples should be retested while focusing on heavy metals, phosphate, COD, turbidity, and seasonal variability while testing soils and a few representative crops for metal uptake before expanding irrigation.

Artificial Intelligence (AI) Usage Disclosure

Artificial intelligence (AI) tools were used solely for language editing, grammar correction, and improvement of manuscript readability during the preparation of this article. The authors retained full responsibility for the scientific content, data analysis, interpretation of results, and conclusions presented in the manuscript. AI tools were not used to generate research data, results, analyses, or scientific interpretations.

Compliance with Ethical Standards (COPE)

The authors confirm that this manuscript complies with the ethical standards required by the Khazar Journal of Water and Environment (KJWE). The work is original, has not been published previously, and is not under consideration elsewhere. All sources have been appropriately cited, and the manuscript is free from plagiarism, data fabrication, and data falsification.

Author Declarations

Authors' contributions: Concept: O.O., Design: F.C., Data collection: O.O., Analysis: O.O. F.C, Writing: O.O., F.C., Review: E.O., Plagiarism: E.O.

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