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Original Research

Spatial and Seasonal Variation in Irrigation-Water Quality and Soil Macronutrient Status in Selected Fadama Fields along River Chanchaga, Minna, Nigeria

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Abstract

Proper management of irrigation-water chemistry is important for maintaining soil quality and sustaining vegetable production in peri-urban fadama systems. This study evaluated spatial and seasonal variation in the physicochemical properties of irrigation water along an approximately 20-km corridor of River Chanchaga, Minna, Nigeria, and characterized the macronutrient status of associated cultivated soils. Water and topsoil samples were collected during the wet season (May–July 2025) and dry season (January–March 2026) from four river locations (L1–L4) and a comparative borehole irrigation-water source (C1). Water-quality data were evaluated using General Linear Models and two-way analysis of variance (ANOVA), whereas soil properties were interpreted descriptively because the field-level soil samples were composites rather than independently replicated observations. Dry-season electrical conductivity (EC) increased markedly across the monitoring locations, ranging from 1,201.33 to 1,365.33 µS cm^{-1}, corresponding to the FAO slight-to-moderate restriction category for irrigation use. Sodium Adsorption Ratio (SAR) remained low, ranging from 0.086 to 0.229, while chloride concentrations remained below the FAO guideline throughout the study period. The cultivated soils were predominantly sandy loam, with high sand content (80.00–81.80%), low soil organic carbon (0.56–0.76 g kg^{-1}), and low effective cation exchange capacity (4.60–6.17 cmol kg^{-1}). Available phosphorus was particularly low (0.22–0.92 mg kg^{-1}), while exchangeable potassium ranged from 0.04 to 0.15 cmol kg^{-1}. Total nitrogen ranged from 0.43 to 1.31 g kg^{-1}, whereas exchangeable calcium was the dominant measured base (2.54–3.85 cmol kg^{-1}). The findings demonstrate that seasonal changes in irrigation-water salinity occur alongside soil limitations associated with coarse texture, low organic-carbon status, low exchange capacity, and acidic soil reaction. Continued irrigation-water monitoring together with balanced, soil-test-based fertility management is therefore important for sustaining vegetable production within the River Chanchaga agricultural corridor.

1. Introduction

Agricultural production in the Southern Guinea Savanna zone of Nigeria, is strongly influenced by seasonal rainfall patterns. Although rainfall supports crop production during the wet season, irrigation is particularly important for sustaining vegetable production during the dry season. Surface water from rivers flowing through urban and peri-urban catchments i commonly used to support dry-season cultivation. The Physical and chemical quality of such water is therefore an important consideration because repeated irrigation may alter the chemical environment of receiving soils and, depending on water quality, soil properties and drainage conditions, contribute to the development salinity or sodicity-related constraints (Ayers and Westcot, 1994; Ziegler Rivera *et al.*, 2023).

River Chanchaga is an important water resource for peri-urban fadama farmers in Minna, Niger state, Nigeria. The river traverse areas influenced by urbanization, domestic activities, agriculture, and other human interventions, previous studies have documented spatial and temporal variation in its water-quality characteristics (Amadi *et al.*, 2012; Wakili *et al.*, 2017; Ojutiku *et al.*, 2023). Such variations are relevant to irrigation management because changes in dissolved ion concentrations and other physical and chemical properties may influence water suitability for repeated agricultural use.

The implication of irrigation water quality for crop production also depends on the properties of the receiving soils. Coarse-textured soils with low soil organic-carbon content and low

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cation exchange capacity generally has limited capacity to retain exchangeable nutrient cations. Conversely, soil reaction and mineral composition also influence nutrient retention and availability particularly phosphorus. Consequently, evaluating irrigation-water quality alongside the nutrient status and relevant physical and chemical properties of cultivated soils provides a broader basis for understanding the conditions under which irrigated crop production occurs.

These relationships are particularly relevant to the production of vegetable like fluted pumpkin (*Telfairia occidentalis*), a commonly cultivated leafy vegetable in fadama farming systems of Nigeria. Previous studies in the Chanchaga area have investigated agrochemical effects on soil, and ground-water, soil salinity, irrigation practices, and river water quality (Adeoye *et al.*, 2015; Kuti *et al.*, 2018; Musa *et al.*, 2021). However, the extent to which seasonal variation in irrigation-water quality can be considered alongside the macronutrient status of soils in cultivated Fadiman field remains insufficiently characterized in the available local evidence. An assessment integrating these two components would provide useful baseline information for irrigation-water monitoring and soil fertility management in the area.

Therefore, this study aimed to determine the spatial and seasonal variation in the physical and chemical properties of River Chanchaga irrigation water and to characterize the macronutrient status of selected cultivated fadama soils in Minna, Nigeria.

2. Materials and Methods

2.1 Study area and spatial monitoring framework

Minna, the capital of Niger State, is located within the Southern Guinea Savanna zone of north-central Nigeria and experiences a tropical wet-and-dry climate, with the rainy season generally extending from April to October and the dry season from November to March. Mean annual rainfall is approximately 1,200–1,300 mm, while mean annual air temperature is about 26.7 °C, with relative humidity increasing during the rainy season and declining during the dry season (Musa *et al*., 2021; Kolo *et al*., 2023; NASA-POWER, 2026). River Chanchaga is an important drainage channel within Minna, receiving runoff from agricultural fields, residential settlements and other developed areas. Its flow is influenced by seasonal rainfall, with increased runoff and river volume during the wet season and reduced flow during the dry season. Tagwai Dam provides an important upstream hydrological feature, while the river corridor downstream passes through increasingly urbanised and agricultural environments. Land-use activities include bank-side farming, block making, laundry, construction, sand dredging and small-scale manufacturing, which may contribute dissolved and particulate materials to the river through runoff, erosion and direct discharge (Yunusa and Abdulkadir, 2017; Wakili *et al*., 2017; Yusuf *et al.,* 2024). These climatic, hydrological and land-use characteristics provide a basis for interpreting seasonal water-quality variation, as wet-season runoff may mobilise contaminants from surrounding surfaces while increased river volume may promote dilution; conversely, reduced dry-season flow and evaporation may increase the concentration of some dissolved constituents.

Field monitoring was conducted along an approximately 20-km agricultural corridor of River Chanchaga in Minna, Niger State, Nigeria, within the Southern Guinea Savanna ecological zone. Five sampling locations were selected to represent different positions and environmental settings along the monitoring corridor (Table 1 and Figure 1).

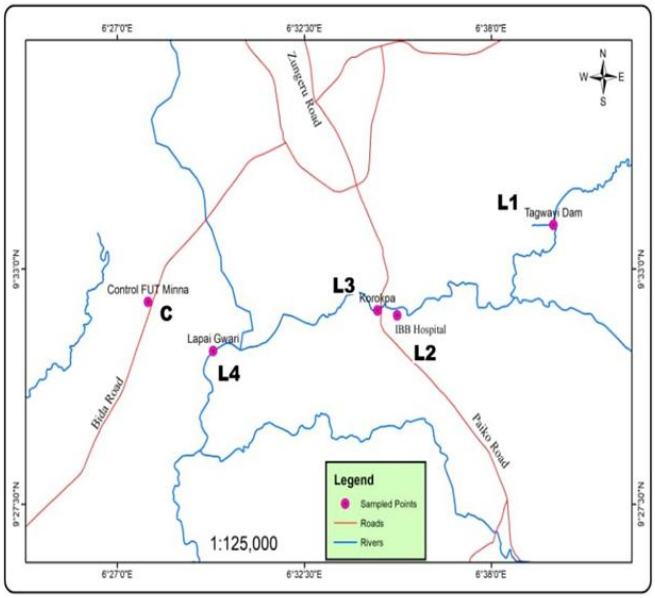

Figure 1. Sampling locations along River Chanchaga

Table 1. Geographical coordinates, elevation, and description of sampling locations

Location	Site	River position	Latitude	Longitude	Elevation (m)
C1	Borehole reference	Comparative irrigation-water source	09°32′14″ N	06°27′54″ E	206
L1	Tagwai Dam	Upstream	09°34′02″ N	06°39′50″ E	254
L2	IBB Hospital	Urban-influenced midstream	09°31′55″ N	06°31′14″ E	232
L3	Koropka	Urban-influenced midstream	09°31′02″ N	06°34′39″ E	226
L4	Lapai Gwari	Downstream	09°31′05″ N	06°29′49″ E	214

C1 was a borehole source used as a comparative irrigation-water reference rather than a pristine control. L1 was located around the Tagwai Dam axis and represented the upstream section of the river. L2, located around the IBB Hospital axis, and L3, located around the Koropka axis, represented urban-influenced midstream sections. L4, located around Lapai Gwari, represented the downstream section of the monitored corridor.

River-water samples were collected monthly from four River Chanchaga locations (L1–L4) and a comparative borehole-irrigated location (C1) during the wet season (May–July 2025) and dry season (January–March 2026). Three independent field replicates were collected at each location during each of the six sampling occasions, giving nine samples per location per season and 90 samples overall. Samples were collected at approximately 20–30 cm below the water surface and maintained separately for laboratory analysis. Means and standard deviations were calculated from the three field replicates for each location and sampling occasion. The wet and dry seasons were operationally defined by their respective three-month sampling periods.

2.2 Target soil selection and sampling

Soil sampling focused on an active agricultural area within the urban-influenced midstream section represented by L2. Ten farmers in the area were interviewed, and three were purposively selected using the field-selection criteria described by Ederigbe *et al*. (2024). These criteria included having cultivated the same land for more than five years, willingness to make the land available for the study without charge, and willingness to maintain the experimental plots during the study period. The earlier study also considered fields where farmers had experienced reduced crop yields over the preceding five years. The three selected fields were designated F1, F2 and F3. All were cultivated with fluted pumpkin (Telfairia occidentalis) and irrigated with River Chanchaga surface water during the dry season. Because selection depended on eligibility, willingness and access, the fields were not randomly selected; consequently, the findings should be interpreted as applying to the selected farms rather than as statistically representative of all irrigated farms along the river.

Topsoil samples were collected from the 0–15 cm depth using a stainless-steel soil auger. Within each selected field, three separate 6 × 6 m sampling areas were demarcated at different locations to account for within-field spatial variability. Nine soil cores were collected from each area following a W-shaped sampling pattern, giving 27 cores per field. The 27 cores from the three sampling areas were combined and thoroughly mixed to obtain one composite sample representative of each field. Thus, the three sampling areas contributed to a single field-level composite sample and did not constitute independent laboratory replicates. The composite samples were air-dried, gently crushed and passed through a 2-mm stainless-steel sieve before laboratory analysis.

2.3 Water-quality laboratory analyses

Water samples were collected in pre-washed 1-L polyethylene bottles and transported immediately to the laboratory for analysis. Water pH and electrical conductivity (ECw) were determined in situ using a calibrated multi-parameter digital probe (HI-98129, Hanna Instruments). Total dissolved solids (TDS) were determined gravimetrically following oven drying at 180 °C.

Calcium (Ca^{2+}) and magnesium (Mg^{2+}) were determined by EDTA titration, while sodium (Na^{+}) and potassium (K^{+}) were measured using a digital flame photometer (FP902, PG Instruments). Chloride (Cl^{-}) was determined by the Mohr titrimetric method using silver nitrate.

Nitrate-nitrogen (NO_3^{-}-N) was determined spectrophotometrically using the salicylic acid method described by Kanno *et al*. (1968). Phosphate-phosphorus (PO_4-P) was determined using the ascorbic acid method (APHA, AWWA and WEF, 2017; Method 4500-P E). Absorbance measurements were made using a UV-Visible spectrophotometer (UV-1800, Shimadzu). Biochemical oxygen demand (BOD_5) was determined using the five-day test (APHA, AWWA and WEF, 2017; Method 5210 B), while chemical oxygen demand (COD) was determined using the closed-reflux method (APHA, AWWA and WEF, 2017; Method 5220 C or 5220 D, as applicable). Nitrate-nitrogen and phosphate-phosphorus concentrations were expressed as mg L^{-1} NO_3^{-}-N and mg L^{-1} P, respectively, while BOD_5 and COD were expressed as mg O_2 L^{-1}.

The Sodium Adsorption Ratio (SAR) was calculated to assess the potential sodicity hazard using:

$$\mathrm{SAR} = \frac{(Na+)}{\sqrt{1/2(\mathrm{Ca2+})+(\mathrm{Mg2+})}} \qquad (1)$$

where Ca^{2+}, Mg^{2+}, and Na^{+} are expressed in meq L^{-1}.

2.4 Soil physicochemical characterization

Soil pH was measured in a 1:2.5 soil-to-water suspension using a digital glass-electrode pH meter, while electrical conductivity was determined in a 1:1 soil-to-water extract and reported as $EC_{1:1}$ (dS m^{-1}). Total nitrogen was determined using the macro-Kjeldahl method (Bremner, 1996), available phosphorus was extracted using Bray No. 1 and determined colorimetrically (Bray and Kurtz, 1945), and soil organic carbon was determined using the Walkley-Black wet oxidation method (Walkley and Black, 1934). Exchangeable Ca, Mg, K and Na were extracted with neutral 1.0 M NH_4OAc (pH 7.0). Calcium and magnesium were measured by atomic absorption spectrophotometry, while potassium and sodium were determined by flame photometry. Exchangeable acidity was extracted with 1.0 M KCl and determined by titration with 0.05 M NaOH. Effective cation exchange capacity (ECEC) was calculated as the sum of exchangeable Ca, Mg, K and Na and exchangeable acidity, with all components expressed in cmolc kg^{-1} soil.

2.5 Statistical analysis

Water-quality data were analysed using the General Linear Model (GLM) and two-way analysis of variance (ANOVA) in Minitab version 20.2 to evaluate the effects of sampling location, season and their interaction. The model was expressed as:

The general model was expressed as:

$$Y_{ijk} = \mu + L_i + S_j + (LS)_{ij} + \varepsilon_{ijk} \quad (2)$$

Where:
Y_{ijk} = observed value of the response variable;
μ = overall mean;
L_i = fixed effect of sampling location;
S_j = fixed effect of season;
$(LS)_{ij}$ = Location × Season interaction; and
ε_{ijk} = residual error.

Where significant effects occurred, means were separated using Tukey's Honestly Significant Difference (HSD) test at $\alpha = 0.05$. Three independent field samples collected at each location during each monthly sampling occasion constituted the field replicates; laboratory repeat measurements were not treated as independent observations.

Soil physicochemical properties were summarised descriptively because the three sampling areas within each field were combined into one composite sample. Consequently, the three selected fields provided three field-level composite samples, and no inferential comparisons among sampling areas or seasonal soil differences were made.

3. Results and Discussion

3.1 Dynamics of irrigation-water quality and hazard diagnostics

3.1.1 Hydrogen ion activity (pH)

River Chanchaga irrigation-water pH varied significantly with both location and season ($p < 0.001$; Table 3). During the wet season, mean pH ranged from 6.47 ± 0.11 at L3 to 7.34 ± 0.36 at L4, whereas dry-season values ranged from 6.80 ± 0.12 at L1 to 7.17 ± 0.23 at L3 (Table 2).

The significant location × season interaction ($F = 11.719$, $p < 0.001$) indicates that the spatial pattern of pH differed between seasons. The relatively low wet-season values at L2 and L3 may reflect changes in runoff and river inputs during the rainfall period. Similar seasonal variation in water chemistry has been reported within the Chanchaga catchment (Wakili *et alet al*., 2017).

Most measured pH values were within the FAO 29 range of 6.50–8.40. The wet-season value at L3 (6.47) was marginally below the lower guideline value. This isolated departure does not indicate widespread acidity of the irrigation source. Overall, the measured pH values suggest that extreme acidity or alkalinity was not a dominant irrigation-water constraint during the study period. The general pattern agrees with the conditions reported for the Chanchaga Irrigation Scheme by Musa *et al.* (2021).

3.1.2 Electrical conductivity and salinity hazard

Electrical conductivity exhibited a pronounced seasonal variation. The effect of sampling location was not significant ($F = 0.392$, $p = 0.813$), whereas season had a highly significant effect ($F = 92.644$, $p < 0.001$). The location × season interaction was also not significant ($F = 0.251$, $p = 0.908$; Table 3), indicating that the seasonal variation in EC was consistent across sampling locations. Mean EC increased from 213.89–433.56 µS cm^{-1} during the wet season (These values fall within the FAO 29 category associated with no restriction on irrigation use) to 1,201.33–1,365.33 µS cm^{-1} during the dry season. This increase indicates a marked seasonal change in the electrical conductivity of the irrigation water. However, TDS did not show a significant seasonal effect ($p = 0.606$). Although EC and TDS are related indicators of dissolved constituents, they are not analytically interchangeable, and their relationship depends on ionic composition and measurement procedures. The contrasting statistical responses were retained following verification of the raw data and repetition of the analysis. Therefore, the seasonal EC variation is interpreted independently, without assuming a corresponding significant change in total dissolved solids.

A marked increase occurred during the dry season, when EC ranged from 1,201.33 ± 628.24 µS cm^{-1} at L3 to 1,365.33 ± 573.20 µS cm^{-1} at C1.

Table 2. Selected seasonal physicochemical properties of River Chanchaga irrigation water

Parameter	pH		EC (µS cm^{-1})		TDS (mg L^{-1})		Cl$^-$ (mg L^{-1})	
Season	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
C1	6.85 ± 0.44	7.07 ± 0.44	433.56 ± 71.42	1365.33 ± 573.20	437.89 ± 299.70	324.00 ± 116.76	55.01 ± 44.89	80.17 ± 11.91
L1	6.68 ± 0.15	6.80 ± 0.12	222.00 ± 80.06	1248.00 ± 770.01	250.22 ± 211.49	225.67 ± 90.84	33.12 ± 18.40	52.99 ± 18.58
L2	6.50 ± 0.18	7.10 ± 0.17	213.89 ± 53.89	1320.67 ± 725.72	177.00 ± 193.16	323.67 ± 143.77	38.05 ± 37.56	24.60 ± 24.21
L3	6.47 ± 0.11	7.17 ± 0.23	264.00 ± 106.38	1201.33 ± 628.24	287.00 ± 215.88	275.00 ± 102.63	37.27 ± 12.39	72.58 ± 7.90
L4	7.34 ± 0.36	6.93 ± 0.23	414.00 ± 105.78	1222.67 ± 606.92	386.44 ± 304.98	284.67 ± 97.15	27.87 ± 4.94	74.76 ± 4.93
FAO guideline/ interpretation	6.50–8.40	6.50–8.40	<700: no restriction	700–3000: slight–moderate restriction	<450: no restriction	<450: no restriction	<141.80: no restriction	<141.80: no restriction

Note: Values are mean ± standard deviation except SAR. FAO classifications are based on Ayers and Westcot (1994)

The river locations similarly recorded 1,222.67–1,320.67 µS cm^{-1}. The dry-season values therefore fell within the 700–3,000 µS cm^{-1} category classified by FAO 29 as slight-to-moderate restriction for irrigation use (Ayers and Westcot, 1994).

The pronounced seasonal increase in EC is consistent with concentration of dissolved ions under reduced river discharge and increased evaporative conditions during the dry season. The present values are higher than the 0.163 dS m^{-1} reported for irrigation water from Chanchaga Irrigation Scheme I by Kuti *et al*. (2018), although comparison should be made cautiously because the studies differed in sampling locations, sampling periods, and analytical design. Amadi *et al.* (2012) similarly reported substantial variation in conductivity along River Chanchaga, indicating that the river-water chemistry varies with hydrological and local catchment conditions.

The dry-season EC values have implications for repeated irrigation because increasing dissolved-ion concentration can increase the osmotic concentration of the soil solution and potentially impose a greater salinity constraint on crops. However, the present study did not directly measure root-zone salinity, crop physiological response, or yield. The EC results should therefore be interpreted as an irrigation-water quality indication rather than as evidence of demonstrated crop injury.

3.1.3 Total dissolved solids

Total dissolved solids varied among sampling occasions, but the two-way ANOVA showed no significant effect of location ($p = 0.150$), season ($p = 0.606$), or location × season interaction ($p = 0.276$; Table 3).

The absence of a statistically significant seasonal effect for TDS, despite the strong seasonal effect observed for EC, indicates that the two measurements should not be treated as interchangeable indicators in this dataset. TDS values ranged from 177.00 to 437.89 mg L^{-1} during the wet season and from 225.67 to 324.00 mg L^{-1} during the dry season. All recorded values were below the 450 mg L^{-1} FAO 29 value used for the no-restriction category.

The results demonstrate that EC and TDS provided different statistical patterns in the monitored water. This may reflect differences in the ionic composition and temporal behaviour of dissolved constituents rather than a contradiction between the two measurements.

Previous investigations in the Chanchaga area have also reported variability in dissolved-solids-related water-quality parameters. Amadi *et al.* (2012) identified both natural processes and anthropogenic activities as contributors to spatial and temporal variation in River Chanchaga water quality, including influences associated with activities within the river catchment. Kuti *et al*. (2018) likewise evaluated irrigation-water quality at Chanchaga Irrigation Scheme I, demonstrating that the irrigation source is subject to measurable variation in water-quality characteristics. These previous observations support interpretation of the present TDS results within the broader context of multiple local inputs rather than assigning the measured dissolved-solids concentrations to one source.

3.1.4 Sodium adsorption ratio and sodicity hazard

SAR remained low across the sampling locations and seasons. Wet-season values ranged from 0.141 to 0.196, whereas dry-season values ranged from 0.086 to 0.229 (Table 5). All values were below 3.0, indicating a low sodicity hazard under the measured conditions (Ayers and Westcot, 1994).

The low SAR values indicate that the seasonal increase in EC was not accompanied by a comparably high sodium hazard. Sodium concentrations remained relatively low in relation to calcium and magnesium. This pattern is consistent with the generally low SAR values reported for irrigation water within the Chanchaga irrigation system by Kuti *et al*. (2018).

The results therefore suggest a low immediate risk of sodium-induced structural deterioration from the measured irrigation water. Nevertheless, long-term assessment should consider cumulative irrigation inputs, drainage conditions, soil texture, and the balance of sodium relative to calcium and magnesium in the receiving soil.

Table 3. Location × Season effects on physicochemical properties of River Chanchaga water

Parameter	Location F	Location p	Season F	Season p	Location × Season F	Interaction p
pH	6.101	<0.001	18.615	<0.001	11.719	<0.001
EC	0.392	0.813	92.644	<0.001	0.251	0.908
TH	3.625	0.009	0.007	0.934	2.936	0.026
TA	0.974	0.427	55.470	<0.001	0.582	0.676
TDS	1.739	0.150	0.268	0.606	1.304	0.276
Ca^{2+}	5.303	<0.001	1.511	0.223	3.214	0.017
Mg^{2+}	8.146	<0.001	30.616	<0.001	10.277	<0.001
Na^{+}	4.323	0.003	10.423	0.002	5.891	<0.001
K^{+}	1.745	0.148	58.318	<0.001	0.631	0.642
Cl^{-}	6.453	<0.001	22.837	<0.001	4.555	0.002
NO_3-N	4.660	0.002	10.263	0.002	1.547	0.197
PO_4-P	1.371	0.252	111.091	<0.001	1.323	0.268
BOD	1.118	0.354	50.556	<0.001	0.340	0.850
COD	3.134	0.019	9.756	0.002	2.111	0.087

Note: Significance was evaluated at $\alpha = 0.05$.

Table 4. Physical and chemical characteristics of cultivated soils associated with River Chanchaga irrigation

Property	Unit	F1 Wet	F2 Wet	F3 Wet	F1 Dry	F2 Dry	F3 Dry
Sand	%	80.00	81.80	80.00	–	–	–
Silt	%	8.28	9.28	10.00	–	–	–
Clay	%	11.72	8.92	9.00	–	–	–
Texture	–	SL	SL	SL	–	–	–
pH	–	5.86	6.19	5.76	6.38	6.32	5.98
EC	dS m^{-1}	0.037	0.179	0.184	0.123	0.188	0.132
SOC	g kg^{-1}	0.60	0.58	0.60	0.76	0.56	0.64
TN	g kg^{-1}	0.43	1.00	1.03	1.31	0.96	1.10
Available P	mg kg^{-1}	0.92	0.22	0.33	0.25	0.30	0.26
Exchangeable Ca	cmol kg^{-1}	3.34	3.85	3.68	3.30	2.54	3.25
Exchangeable Mg	cmol kg^{-1}	0.40	1.32	1.14	1.12	0.88	0.96
Exchangeable K	cmol kg^{-1}	0.04	0.15	0.12	0.13	0.14	0.15
Exchangeable Na	cmol kg^{-1}	0.27	0.10	0.08	0.16	0.08	0.09
Exchangeable acidity	cmol kg^{-1}	1.34	0.67	1.15	1.25	0.96	1.70
ECEC	cmol kg^{-1}	5.39	6.09	6.17	5.96	4.60	6.15

Note: Soil data are presented descriptively. Particle-size distribution was determined for the wet-season soil samples; therefore, dry-season particle-size and texture values are not reported. SL = sandy loam.

3.1.5 Specific-ion toxicity: chloride

Chloride concentrations were significantly affected by location ($p < 0.001$), season ($p < 0.001$), and their interaction ($p = 0.002$; Table 3). During the wet season, concentrations ranged from 27.87 ± 4.94 mg L^{-1} at L4 to 55.01 ± 44.89 mg L^{-1} at C1. During the dry season, concentrations ranged from 24.60 ± 24.21 mg L^{-1} at L2 to 80.17 ± 11.91 mg L^{-1} at C1.

Despite the observed spatial and seasonal variation, all measured chloride concentrations remained below the FAO 29 threshold of 141.8 mg L^{-1} for surface irrigation. Chloride therefore did not constitute a specific-ion toxicity constraint during the study period.

The particularly low dry-season chloride concentration at L2 occurred alongside relatively low Ca^{2+}, Mg^{2+}, and Na^{+} concentrations (Table 5). This combination indicates a low ionic concentration at that sampling point, although the specific process responsible cannot be established because individual inflows or discharge sources were not separately sampled.

3.2 Implications for fadama topsoil properties

3.2.1 Soil Physical Characteristics and Nutrient-Retention Capacity

The cultivated soils had high sand contents of 80.00–81.80% and relatively low clay contents of 8.92–11.72%, giving the measured wet-season samples a sandy-loam texture (Table 4). These coarse-textured characteristics are consistent with soils developed in the Minna area under Basement Complex geological conditions (Okoli *et al.*, 2023).

The combination of high sand content and relatively low clay content is consistent with the low ECEC values of 4.60–6.17 cmol kg^{-1} observed in the fields. Soil organic carbon was also low, ranging from 0.56 to 0.76 g kg^{-1}. Together, these characteristics indicate limited retention capacity for exchangeable nutrient cations.

The coarse texture and low SOC may increase the susceptibility of nutrients to movement beyond the immediate root zone, particularly under high rainfall or intensive irrigation. The low SOC values indicate limited organic-matter reserves and are comparable with the low organic-carbon status reported by Ederigbe *et al.* (2024) for similarly managed agricultural soils in the Minna area.

However, nutrient losses through leaching were not measured directly in the present study. The observed soil characteristics should therefore be interpreted as conditions associated with potential nutrient-retention limitations rather than as direct measurements of nutrient loss.

3.2.2 Exchangeable potassium and calcium status

Exchangeable potassium ranged from 0.04 to 0.15 cmol kg^{-1} across the cultivated fields. These values were below the 0.20 cmol kg^{-1} critical value cited by Esu (1991), indicating potentially inadequate potassium status for sustained crop production.

The low exchangeable K concentrations occurred in soils characterized by relatively low ECEC. This combination suggests limited capacity for retention of exchangeable potassium. Nevertheless, the present study cannot establish whether the low soil K resulted from leaching, crop removal, insufficient fertilizer application, or other management processes because these components were not quantified. This interpretation is consistent with potassium-retention limitations reported in adjacent fadama systems (Yaman *et al.*, 2020).

Exchangeable calcium was the dominant measured exchangeable base, ranging from 2.54 to 3.85 cmol kg^{-1}. The relatively greater contribution of Ca to the exchangeable-base

Table 5. Calcium, magnesium, sodium concentrations and Sodium Adsorption Ratio of River Chanchaga irrigation water

Location	Season	Ca^{2+} (meq L^{-1})	Mg^{2+} (meq L^{-1})	Na^{+} (meq L^{-1})	SAR
C1	Wet	1.350	0.644	0.191	0.192
C1	Dry	1.368	0.450	0.165	0.173
L1	Wet	1.055	0.677	0.131	0.141
L1	Dry	1.088	0.435	0.200	0.229
L2	Wet	1.138	0.610	0.183	0.196
L2	Dry	0.297	0.058	0.047	0.111
L3	Wet	1.196	0.456	0.150	0.165
L3	Dry	1.304	0.487	0.082	0.087
L4	Wet	1.263	0.330	0.142	0.159
L4	Dry	1.327	0.360	0.079	0.086

Note: Ca^{2+}, Mg^{2+}, and Na^{+} concentrations are expressed in meq L^{-1} for SAR calculation.

pool is compatible with the base status of soils developed from Basement Complex materials in the region (Okoli *et al.*, 2023).

3.2.3 Seasonal variation in total nitrogen

Total nitrogen ranged from 0.43 to 1.03 g kg^{-1} during the wet season and from 0.96 to 1.31 g kg^{-1} during the dry season (Table 4). The dry-season values were therefore numerically higher than the wet-season values in all three fields. The highest measured TN concentration was 1.31 g kg^{-1} in F1 during the dry season, while the lowest was 0.43 g kg^{-1} in F1 during the wet season. Because the soil samples were composite field-level samples and no independent replication was available for statistical comparison of seasons, this pattern should be regarded as a descriptive seasonal difference rather than a statistically demonstrated seasonal effect.

The higher dry-season TN concentrations may reflect differences in nutrient inputs, crop management, mineralization, crop uptake, residue inputs, and nitrogen losses between the two production periods. Dry-season vegetable production commonly involves irrigation and fertilizer application, and studies of irrigated vegetable production in Nigeria have demonstrated the use of nitrogen fertilizer during dry-season cultivation (Egbebi *et al.*, 2024). However, fertilizer types, application rates, timing, and field histories were not quantified in the present study. It would therefore be inappropriate to attribute the observed TN pattern solely to fertilizer application.

The higher dry-season TN values may also reflect reduced rainfall-driven flushing compared with the wet season. Conversely, irrigation during dry-season cultivation may still promote downward movement of soluble nitrogen compounds. The measured TN concentrations therefore represent the net outcome of several interacting processes, including nutrient inputs, crop uptake, mineralization and immobilization, and environmental losses.

3.2.4 Available phosphorus constraint

Available phosphorus represented one of the most pronounced nutrient constraints in the cultivated soils. Concentrations ranged from 0.22 to 0.92 mg kg^{-1}, substantially below the 8.0–10.0 mg kg^{-1} range cited by Esu (1991) as desirable for vegetable production in Nigerian soils.

The low available-P concentrations occurred in soils with pH values ranging from 5.76 to 6.38 and exchangeable acidity of 0.67–1.70 cmol kg^{-1}. Under acidic conditions, phosphorus availability may be reduced through reactions involving iron and aluminium compounds. The combination of low measured available P and acidic soil reaction therefore indicates a soil chemical environment in which phosphorus availability may be constrained.

The presence of phosphate in irrigation water does not necessarily imply a correspondingly high available-P concentration in the receiving soil. Phosphorus can be retained in soil mineral and organic pools and its availability is influenced by soil reaction, mineralogy, organic matter, and previous nutrient management. The present results consequently indicate the need for soil-test-based phosphorus management rather than reliance on irrigation-water nutrient inputs. The observed phosphorus constraint is therefore compatible with the chemical conditions of the studied soils and with phosphorus limitations reported for savanna fadama soils by Adeoye *et al.* (2015).

Organic-matter management and correction of soil acidity were justified by soil-test results may improve the soil environment for phosphorus availability. However, amendment rates should be determined from site-specific soil assessments.

3.3 Statistical validation of spatial and seasonal variation in irrigation water quality

The two-way ANOVA revealed parameter-specific patterns of spatial and seasonal variation in River Chanchaga irrigation water (Table 3). Seasonal effects were particularly pronounced for PO_4-P, electrical conductivity (EC), K^{+}, total alkalinity (TA) and biochemical oxygen demand (BOD), indicating that temporal variation was a major component of the observed changes in these parameters. In contrast, magnesium, sodium,

chloride, nitrate-nitrogen, total hardness and chemical oxygen demand (COD) exhibited significant spatial differences, demonstrating that water quality was not uniform across the sampling locations. These findings indicate that the relative contributions of spatial and seasonal variation differed among the measured physicochemical properties.

Location × season interactions were significant for total hardness, Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-} and pH. This indicates that seasonal changes in these parameters were dependent on sampling location rather than following a uniform pattern throughout the river corridor. Conversely, the absence of significant interactions for several other parameters suggests that their seasonal responses were comparatively consistent across locations. Notably, EC showed a significant seasonal effect without significant location or interaction effects, whereas TDS showed no significant spatial or seasonal variation. This contrast further demonstrates that related water-quality indicators may exhibit different statistical responses and should be interpreted according to their individual measurement results.

Overall, the findings establish that irrigation-water quality along the Chanchaga corridor is characterised by a combination of seasonal variation, spatial heterogeneity and location-dependent seasonal responses. This supports the importance of monitoring multiple sampling locations across different seasons rather than relying on measurements from a single location or sampling period. Although previous studies have documented spatial and temporal variability in the Chanchaga catchment (Amadi *et al*., 2012; Wakili *et al*., 2017), the present ANOVA results establish patterns of variation rather than identifying their specific causes. Potential contributions from runoff, agricultural activities, domestic discharges and geological conditions therefore remain contextual explanations requiring independent source-specific investigation.

4. Conclusions and Recommendations

4.1 Conclusions

The study demonstrated clear seasonal variation in the physicochemical characteristics of River Chanchaga irrigation water and identified important nutrient constraints in associated peri-urban fadama soils in Minna, Nigeria. During the wet season, EC remained below 700 µS cm^{-1} at all monitored locations, corresponding to the FAO category associated with no restriction on irrigation use. During the dry season, EC increased substantially, ranging from 1,201.33 to 1,365.33 µS cm^{-1}, placing the water within the FAO slight-to-moderate restriction category for irrigation salinity. In contrast, SAR remained low at 0.086–0.229, and chloride concentrations remained below the FAO guideline throughout the monitoring period.

The cultivated soils were predominantly sandy loam, with high sand content, low SOC, and low ECEC. Available phosphorus was particularly low, ranging from 0.22 to 0.92 mg kg^{-1}, while exchangeable potassium ranged from 0.04 to 0.15 cmol kg^{-1}. Soil pH ranged from 5.76 to 6.38, with measurable exchangeable acidity. These properties indicate important inherent soil-fertility and nutrient-retention constraints within the cultivated fields.

The findings demonstrate that seasonal irrigation-water salinity and inherent soil-fertility constraints occur simultaneously within the River Chanchaga agricultural corridor. The study does not establish that the measured irrigation-water chemistry caused the observed soil nutrient status because fertilizer inputs, irrigation volumes, drainage, nutrient budgets, and long-term soil-water fluxes were not directly quantified. Nevertheless, the simultaneous occurrence of elevated dry-season EC and low soil nutrient-retention characteristics supports the need for integrated monitoring of irrigation-water quality and soil fertility.

4.2 Recommendations for peri-urban fadama production

1. Strengthen seasonal irrigation-water and soil monitoring. Regular monitoring should be undertaken across the irrigation locations, with particular attention to the dry season when electrical conductivity (EC) increases substantially. Field-level EC measurements can provide a practical means of identifying periods of elevated irrigation-water salinity. Monitoring should also include sodium adsorption ratio (SAR) and chloride in irrigation water, alongside soil pH, soil organic carbon (SOC), available phosphorus, exchangeable potassium and effective cation exchange capacity (ECEC), to identify changes in water quality and soil fertility during continued irrigation.

2. Adopt integrated, soil-test-based soil fertility management. Organic-matter management should be improved through the incorporation of well-decomposed organic amendments or suitable crop residues to improve SOC and support nutrient-retention capacity. Phosphorus and potassium deficiencies should be addressed through balanced fertilizer application guided by soil-test results. Where soil acidity requires correction, lime application should be based on appropriate soil-test recommendations. Amendment and fertilizer rates should also account for the nutrient composition of the materials used.

3. Improve irrigation and salinity management during the dry season. Irrigation management should account for the higher dry-season EC values. Where soil permeability and drainage conditions are adequate, site-specific leaching management may help limit salt accumulation within the crop root zone. The amount and frequency of additional irrigation water should be determined from local soil, crop, drainage and irrigation conditions rather than applying a fixed rate universally.

4. Undertake further field-based investigations to establish long-term irrigation effects. Future studies should quantify fertilizer application rates, irrigation volumes, soil-water movement, drainage, salt accumulation, nutrient losses and

crop yield. These measurements would provide a stronger basis for evaluating relationships between irrigation-water chemistry, soil nutrient dynamics, salinity development and crop performance under continued irrigation.

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