Comparative assessment of soil fertility status in irrigated and rainfed agricultural systems in northern Nigeria

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Abstract

Soil fertility decline constrains agricultural productivity in sub-Saharan Africa, yet comparative assessments of fertility status between irrigated and rainfed systems in Northern Nigeria remain limited. This study compared soil fertility status between irrigated and rainfed agricultural lands in Dawakin Kudu Local Government Area, Kano State, to identify system-specific fertility constraints and inform targeted nutrient management strategies. Sixty soil samples (30 from each system) were collected using systematic grid sampling (200 m × 200 m) at 0-20 cm depth. Soil texture, pH, organic carbon (OC), total nitrogen (N), available phosphorus (P), exchangeable bases (Ca, Mg, K, Na), exchangeable acidity (EA), and effective cation exchange capacity (ECEC) were analyzed. Micronutrients (Zn, Cu, Mn, Fe) were extracted using DTPA and analyzed by atomic absorption spectrophotometry. Fertility status was classified using Esu (1991) rating criteria for Nigerian Savanna soils. Data were analyzed using descriptive statistics and independent samples t-tests. Both systems exhibited sandy loam texture (mean sand 60.7-60.8%, clay 15.9-16.2%) with slightly acidic pH (6.05-6.15). Critical fertility limitations were identified in both systems: organic carbon (0.68-0.76%, rated LOW), total nitrogen (0.06-0.07%, LOW), available phosphorus (4.03-4.05 mg/kg, LOW), and effective cation exchange capacity (4.26-4.45 cmol(+)/kg, LOW). Exchangeable bases showed medium ratings: Ca (2.61-2.74 cmol(+)/kg), Mg (0.75 cmol(+)/kg), and K (0.22-0.27 cmol(+)/kg). Exchangeable acidity was significantly higher in irrigated (0.65 cmol(+)/kg) than rainfed systems (0.39 cmol(+)/kg). Micronutrients were rated HIGH in both systems: Zn (16.5-18.9 mg/kg), Cu (2.50-2.79 mg/kg), Mn (31.6-34.1 mg/kg), and Fe (177.0-192.4 mg/kg), indicating no micronutrient deficiencies. Both irrigated and rainfed systems face similar critical macronutrient constraints (OC, N, P) and low nutrient retention capacity (ECEC). Irrigation did not markedly improve macronutrient fertility status but significantly increased soil acidity. The low phosphorus availability despite high iron concentrations suggests P fixation by iron oxides. Integrated soil fertility management focusing on organic matter restoration, phosphorus availability enhancement, and nitrogen supplementation is essential for both systems. Micronutrient fertilization is not a priority.

Keywords: Soil fertility, irrigation, rainfed agriculture, tropical soils, Esu rating, Nigeria, organic carbon, phosphorus deficiency, micronutrients

INTRODUCTION

Soil fertility degradation is recognized as the fundamental constraint to agricultural productivity in sub-Saharan Africa (SSA), affecting approximately 65% of agricultural land and contributing to chronic food insecurity (Sanchez, 2002; Vanlauwe *et al.*, 2015). Nigeria, Africa's most populous nation with over 200 million people and agriculture employing approximately 70% of the population, faces unprecedented challenges in sustaining soil productivity while meeting growing food demands (Nkonya *et al.*, 2016). The Northern Guinea Savanna agroecological zone, characterized by sandy soils, low organic matter, and mono-modal rainfall (600-1000 mm annually), is particularly vulnerable to soil fertility decline through continuous cropping, minimal external inputs, and accelerated erosion (Bationo 2007; Kamara *et al.*, 2018). Soil fertility decline in Nigerian Savanna soils has been documented over several decades. Adeoye and Agboola (1985) reported widespread deficiencies in nitrogen (N), phosphorus (P), and organic carbon (OC) across Nigerian agricultural soils. Ewulo *et al.* (2008) observed progressive deterioration in soil chemical properties, with organic matter content declining from >2% in the 1960s to <1% in recent decades. Studies by Kang and Juo (1983) and Lombin (1987) identified P deficiency as a primary limiting factor for crop production in Northern Nigerian soils, attributed to high P-fixation capacity of iron and aluminum oxides in these highly weathered tropical soils.

Irrigation agriculture has expanded significantly in Northern Nigeria over the past three decades as a strategy to increase cropping intensity and enhance productivity during the dry season (Hussaini *et al.*, 2015; Kano Agricultural and Rural Development Authority, 2020). However, the impact of irrigation on soil fertility status—particularly in comparison to adjacent rainfed systems remains poorly understood. Globally, research has shown that irrigation can have complex effects on soil chemical properties: potentially enhancing nutrient cycling through increased biomass production (Lado *et al.*, 2004), but also accelerating nutrient leaching, altering pH dynamics, and in some cases leading to salt accumulation (Jalali and Merrikhpour, 2008; Levy *et*

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al., 2011). Studies from other regions have documented significant differences in soil fertility between irrigated and rainfed systems. Singh *et al.* (2014) in India reported higher organic carbon and available N in irrigated than rainfed soils due to increased crop residue inputs. Conversely, Wang *et al.* (2008) in China observed lower pH and higher exchangeable acidity in irrigated soils, attributed to accelerated base cation leaching. Jalali and Merrikhpour (2008) in Iran found that long-term irrigation led to depletion of available P and K despite higher fertilizer inputs, suggesting enhanced nutrient removal through intensified cropping.

In Nigeria, comparative studies between irrigated and rainfed systems are scarce. Mbagwu and Osuigwe (1985) reported that irrigation improved soil structural properties but did not systematically assess fertility status. Adepetu and Adetunji (1995) noted declining soil organic matter in intensively cultivated irrigated schemes but provided limited comparative data with rainfed systems. Garba *et al.* (2012, 2019) documented nutrient mining under both systems but emphasized the need for system-specific fertility assessments to guide appropriate management interventions. Micronutrient status in Nigerian soils has received limited research attention despite growing recognition of micronutrient deficiencies in agricultural systems and their implications for crop nutritional quality and human health (Alloway, 2008; Cakmak, 2008). Early work by Enwezor (1976) and Osiname *et al.* (1973) suggested generally adequate micronutrient levels in Nigerian Savanna soils, but systematic assessments using modern analytical techniques are lacking. The interaction between irrigation management and micronutrient availability is particularly complex, as altered soil moisture regimes influence redox conditions, organic matter dynamics, and the chemistry of iron and manganese oxides that control availability of several micronutrients (Marschner, 2012; Lindsay, 1991).

Despite the expansion of irrigation infrastructure in Northern Nigeria, systematic comparative assessments of soil fertility between irrigated and rainfed systems using standardized rating criteria remain scarce. This study aimed to: (1) determine and compare selected soil physical and chemical properties between irrigated and rainfed agricultural lands; (2) assess fertility status using Esu (1991) rating criteria; (3) compare micronutrient concentrations between systems; and (4) identify system-specific fertility constraints to inform targeted nutrient management strategies.

MATERIALS AND METHODS

Study Area

The study was conducted in Dawakin Kudu Local Government Area (LGA), Kano State, Northern Nigeria (11°45' N, 8°30' E), located in the Northern Guinea Savanna agroecological zone. The area experiences a tropical wet-and-dry climate with mean annual rainfall of 800-900 mm concentrated between May and October, and mean annual temperature of 26-28°C. The dry season (November-April) is characterized by the dry and dusty Harmattan winds from the Sahara Desert.

Sampling Design and Soil Collection

A spatial survey was designed and employed, with stratification into irrigated and rainfed land-use systems. Within each system, 30 sampling points were established using systematic grid sampling with 200 m × 200 m spacing to ensure adequate spatial coverage and statistical representation. Global Positioning System (GPS) coordinates were recorded for each sampling location. Soil samples were collected at 0-20 cm depth (plow layer) using a soil auger during the post-harvest period (November 2023). At each sampling point, five sub-samples were collected within a 5-meter radius and composited to obtain a representative sample of approximately 1 kg. Samples were air-dried, crushed, and passed through 2-mm sieves for laboratory analysis.

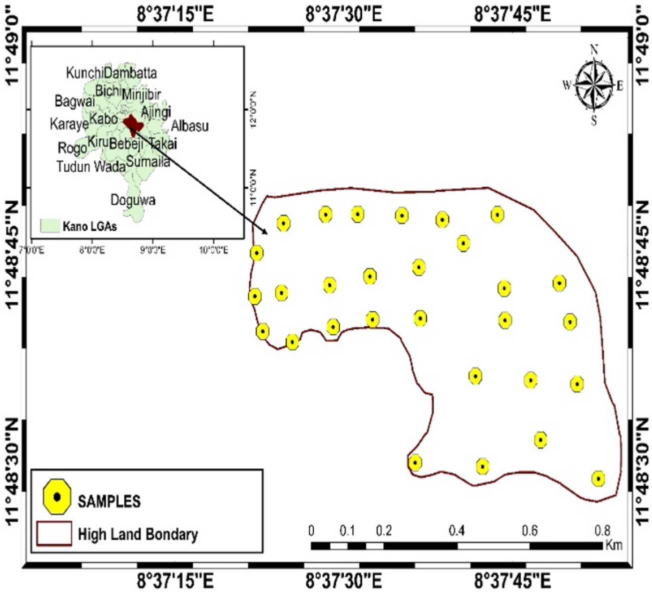

Figure 1: Map of used Rainfed land

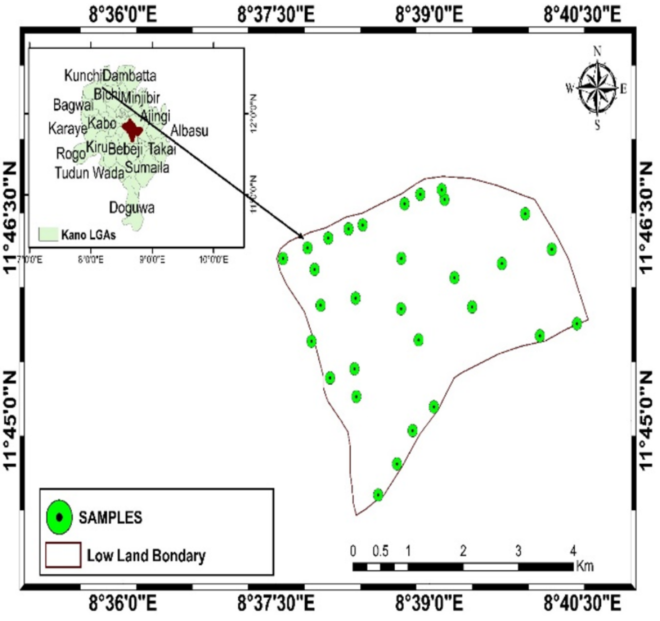

Figure 2: Map of used Irrigated land

Laboratory Analyses

Particle size distribution was determined by the hydrometer method after dispersion with sodium hexametaphosphate (Gee and Bauder, 1986). Soil pH was measured in 1:1 soil-water suspension using a glass electrode pH meter (Thomas, 1996). Soil organic carbon (OC) was determined by Mid-Infrared Spectroscopy (MIRS) following procedures described by Terhoeven-Urselmans *et al.* (2010), with calibration against Walkley-Black method.

Total nitrogen (N) was analyzed by MIRS with validation against Kjeldahl digestion method. Available phosphorus (P) was extracted by Bray-1 method and determined colorimetrically (Bray and Kurtz, 1945). Exchangeable bases (Ca, Mg, K, Na) were extracted with 1 M ammonium acetate (pH 7.0) and determined by atomic absorption spectrophotometry (AAS) for Ca and Mg, and flame photometry for K and Na (Chapman, 1965).

Exchangeable acidity (EA) was extracted with 1 M KCl and titrated with 0.01 M NaOH (McLean, 1965). Effective cation exchange capacity (ECEC) was calculated as the sum of exchangeable bases and exchangeable acidity. Micronutrients (Zn, Cu, Mn, Fe) were extracted using diethylenetriaminepentaacetic acid (DTPA) method (Lindsay and Norvell, 1978) and determined by atomic absorption spectrophotometry.

Data Analysis

Descriptive statistics was done for all soil properties in each land-use system. Independent samples t-tests were used to compare means between irrigated and rainfed systems, with significance set at $p < 0.05$. Soil fertility status was classified according to Esu (1991) rating criteria. Statistical analyses were performed using IBM SPSS Statistics Version 26 and Microsoft Excel 2019.

RESULTS

Soil Physical Properties

Particle Size Distribution and Textural Class

Table 1 presents descriptive statistics for particle size distribution in both land-use systems. Sand fractions dominated in both irrigated and rainfed systems, with mean values of 60.7% (SD = 8.76%) and 60.8% (SD = 6.09%) respectively. Sand content ranged from 45.7% to 76.7% in both systems, with coefficients of variation (CV) of 14.4% (irrigated) and 10.0% (rainfed), indicating moderate spatial variability. Skewness values were 0.51 (irrigated) and 0.82 (rainfed), suggesting slight positive skewness in the distribution of sand content.

Silt fractions showed mean values of 23.1% (irrigated) and 23.3% (rainfed), with ranges of 13.3-33.3% and 16.7-33.3% respectively. Standard deviations were 5.22% (irrigated) and 3.78% (rainfed), with CVs of 22.6% and 16.2% respectively, indicating moderate variability. Clay fractions were relatively low in both systems, with means of 16.2% (irrigated) and 15.9% (rainfed). Clay content ranged from 6.7% to 23.3%, with standard deviations of 4.31% (irrigated) and 3.40% (rainfed). The CVs were 26.6% (irrigated) and 21.4% (rainfed), representing the highest relative variability among the three particle size fractions.

According to USDA textural classification, both systems were predominantly sandy loam, with the combination of 60.7-60.8% sand, 23.1-23.3% silt, and 15.9-16.2% clay. Independent samples t-tests revealed no significant differences between irrigated and rainfed systems for any of the particle size fractions, indicating that both systems share similar parent materials and pedogenic processes.

Soil Chemical Properties

Soil Reaction (pH)

Soil pH values (Table 2) were slightly acidic in both systems, with means of 6.15 (irrigated) and 6.05 (rainfed). pH ranged from 5.02 to 7.08 in irrigated soils and 4.95 to 6.82 in rainfed soils. Standard deviations were 0.42 (ir-

Table 1: Descriptive Statistics of Particle Size Distribution in Irrigated and Rainfed Systems

Property	System	Min	Max	Mean	SD	CV (%)	Skewness	Kurtosis
Sand (%)	Irrigated	45.7	76.7	60.7	8.76	14.4	0.51	-0.95
	Rainfed	45.7	76.7	60.8	6.09	10.0	0.82	2.59
Silt (%)	Irrigated	13.3	33.3	23.1	5.22	22.6	0.21	-0.87
	Rainfed	16.7	33.3	23.3	3.78	16.2	0.91	2.11
Clay (%)	Irrigated	6.7	23.3	16.2	4.31	26.6	1.05	0.05
	Rainfed	6.7	23.3	15.9	3.40	21.4	0.97	2.17

Table 2: Descriptive Statistics of Soil Chemical Properties in Irrigated and Rainfed Systems

Property	System	Min	Max	Mean	SD	CV (%)	Skewness	Kurtosis
pH (1:1)	Irrigated	5.02	7.08	6.15	0.42	6.8	0.38	0.52
	Rainfed	4.95	6.82	6.05	0.39	6.4	0.92	0.46
OC (%)	Irrigated	0.22	2.11	0.76	0.42	55.3	1.17	1.53
	Rainfed	0.20	2.00	0.68	0.38	55.9	1.63	4.08
N (%)	Irrigated	0.02	0.11	0.06	0.02	33.3	0.67	-0.30
	Rainfed	0.02	0.11	0.07	0.01	14.3	1.51	19.2
P (mg/kg)	Irrigated	1.06	9.77	4.03	2.01	49.9	0.43	0.01
	Rainfed	0.99	11.0	4.05	2.57	63.5	0.73	0.72

rigated) and 0.39 (rainfed), with low coefficients of variation (6.8% and 6.4% respectively), indicating relatively uniform pH distribution within each system. Skewness values were 0.38 (irrigated) and 0.92 (rainfed). The difference in mean pH between systems (0.10 pH units) was not statistically significant (t = 1.02, p = 0.312), indicating that irrigation has not substantially altered soil reaction compared to rainfed conditions.

Organic Carbon and Total Nitrogen

Organic carbon (OC) content (Table 2) was low in both systems, with means of 0.76% (irrigated) and 0.68% (rainfed). OC ranged from 0.22% to 2.11% in irrigated soils and 0.20% to 2.00% in rainfed soils. Standard deviations were 0.42% (irrigated) and 0.38% (rainfed), with high coefficients of variation (55.3% and 55.9% respectively), indicating substantial spatial heterogeneity. Positive skewness (1.17 for irrigated, 1.63 for rainfed) and high kurtosis (1.53 and 4.08 respectively) suggest presence of localized high-OC patches. The difference in mean OC between systems (0.08%) was not statistically significant (t = 0.82, p = 0.416), indicating that irrigation has not enhanced organic carbon accumulation despite potentially higher biomass productivity.

Total nitrogen (N) content showed similar patterns, with means of 0.06% (irrigated) and 0.07% (rainfed). N ranged from 0.02% to 0.11% in both systems, with standard deviations of 0.02% (irrigated) and 0.01% (rainfed). Coefficients of variation were 33.3% (irrigated) and 14.3% (rainfed). Notably, rainfed N data exhibited extremely high kurtosis (19.2), suggesting presence of outliers or bimodal distribution. C:N ratios averaged 12.7:1 (irrigated) and 9.7:1 (rainfed), within the typical range (8-12:1) for tropical agricultural soils, indicating moderate organic matter decomposition rates (Stevenson, 1994).

Available Phosphorus

Available phosphorus (P) concentrations (Table 2) were remarkably similar between systems, with means of 4.03 mg/kg (irrigated) and 4.05 mg/kg (rainfed). P values ranged from 1.06 to 9.77 mg/kg (irrigated) and 0.99 to 10.98 mg/kg (rainfed), with standard deviations of 2.01 mg/kg (irrigated) and 2.57 mg/kg (rainfed). Coefficients of variation were high (49.9% and 63.5%), indicating substantial spatial variability. Skewness was positive (0.43 and 0.73), with kurtosis values of 0.01 and 0.72. The difference in mean P between systems was negligible and not statistically significant (t = -0.04, p = 0.968), suggesting that P availability is constrained by soil chemical properties (likely high P-fixation capacity) rather than differential management between systems.

Exchangeable Bases and Nutrient Ratios

Exchangeable calcium (Ca) showed means of 2.74 cmol(+)/kg (irrigated) and 2.61 cmol(+)/kg (rainfed), with ranges of 0.98-6.91 and 1.22-5.40 cmol(+)/kg respectively (Table 3). Standard deviations were 1.25 (irrigated) and 1.09 (rainfed), with high CVs (45.6% and 41.8%), indicating substantial spatial heterogeneity. The difference between systems was not significant (t = 0.45, p = 0.654).

Exchangeable magnesium (Mg) was identical in both systems at 0.75 cmol(+)/kg, with similar ranges (0.27-1.62 in irrigated; 0.27-1.48 in rainfed) and standard deviations (0.28 in both systems). CVs were 37.3% (irrigated) and 37.1% (rainfed). Exchangeable potassium (K) showed mean values of 0.22 cmol(+)/kg (irrigated) and 0.27 cmol(+)/kg (rainfed), with ranges of 0.08-0.44 and 0.07-0.57 cmol(+)/kg respectively. The rainfed system exhibited slightly higher mean K, though the difference approached but did not reach statistical significance (t = -1.82, p = 0.074).

Exchangeable sodium (Na) was low in both systems, with means of 0.09 cmol(+)/kg (irrigated) and 0.10 cmol(+)/kg (rainfed). Na ranged from 0.02 to 0.25 cmol(+)/kg, with no significant difference between systems (t = -0.54, p = 0.591). Ca:Mg ratios averaged 3.65:1 (irrigated) and 3.48:1 (rainfed), within the optimal range of 2-5:1 for balanced plant nutrition (Kopittke and Menzies, 2007). Ca:K ratios were 12.5:1 (irrigated) and 9.7:1 (rainfed), and Mg:K ratios were 3.41:1 (irrigated) and 2.78:1 (rainfed), all within acceptable ranges.

Exchangeable Acidity and Effective Cation Exchange Capacity

Exchangeable acidity (EA) showed a statistically significant difference between systems (Table 4). Irrigated soils had a mean EA of 0.65 cmol(+)/kg (range: 0.08-2.00), while rainfed soils averaged 0.39 cmol(+)/kg (range: 0.07-0.92). The difference was significant (t = 2.38, p = 0.021), indicating higher acidity in irrigated soils. Standard deviations were 0.43 (irrigated) and 0.22 (rainfed), with CVs of 66.2% and 56.4% respectively.

Table 3: Descriptive Statistics of Exchangeable Bases in Irrigated and Rainfed Systems

Property	System	Min	Max	Mean	SD	CV (%)	Skewness	Kurtosis
Ca (cmol(+)/kg)	Irrigated	0.98	6.91	2.74	1.25	45.6	1.38	2.55
	Rainfed	1.22	5.40	2.61	1.09	41.8	1.25	1.21
Mg (cmol(+)/kg)	Irrigated	0.27	1.62	0.75	0.28	37.3	0.95	1.20
	Rainfed	0.27	1.48	0.75	0.28	37.1	0.80	0.72
K (cmol(+)/kg)	Irrigated	0.08	0.44	0.22	0.09	40.9	0.50	-0.41
	Rainfed	0.07	0.57	0.27	0.14	51.9	0.44	-0.50
Na (cmol(+)/kg)	Irrigated	0.02	0.25	0.09	0.06	66.7	0.73	-0.10
	Rainfed	0.03	0.26	0.10	0.07	70.0	0.70	-0.32

Table 4: Descriptive Statistics of Exchangeable Acidity and ECEC in Irrigated and Rainfed Systems

Property	System	Min	Max	Mean	SD	CV (%)	Skewness	Kurtosis
EA (cmol(+)/kg)	Irrigated	0.08	2.00	0.65	0.43	66.2	1.45	2.08
	Rainfed	0.07	0.92	0.39	0.22	56.4	0.88	0.12
ECEC (cmol(+)/kg)	Irrigated	2.02	10.12	4.45	1.69	38.0	0.88	1.08
	Rainfed	2.25	7.75	4.26	1.39	32.6	0.79	0.30

Effective cation exchange capacity (ECEC) averaged 4.45 cmol(+)/kg in irrigated soils (range: 2.02-10.12) and 4.26 cmol(+)/kg in rainfed soils (range: 2.25-7.75). The difference was not statistically significant (t = 0.52, p = 0.605). Standard deviations were 1.69 (irrigated) and 1.39 (rainfed), with CVs of 38.0% and 32.6% respectively. The low ECEC values reflect the sandy texture and low organic matter content characteristic of both systems. Base saturation, calculated as [(sum of exchangeable bases)/ECEC] × 100, averaged 85.4% (irrigated) and 90.8% (rainfed), both indicating favorable base saturation levels (>80% is generally considered adequate for most crops; Brady and Weil, 2016).

Micronutrient Concentrations

DTPA-Extractable Micronutrients

Table 5 presents descriptive statistics for DTPA-extractable micronutrients. Zinc (Zn) concentrations averaged 18.9 mg/kg in irrigated soils (range: 2.34-44.7) and 16.5 mg/kg in rainfed soils (range: 2.36-39.2). Standard deviations were 10.19 (irrigated) and 9.15 (rainfed), with high CVs (53.9% and 55.5%), indicating substantial spatial variability. The difference between systems was not statistically significant (t = 0.98, p = 0.331).Copper (Cu) showed mean concentrations of 2.50 mg/kg (irrigated) and 2.79 mg/kg (rainfed), with ranges of 0.43-6.34 and 1.02-6.27 mg/kg respectively. Standard deviations were 1.23 (irrigated) and 1.30 (rainfed), with CVs of 49.2% and 46.6%. The difference was not significant (t = -0.92, p = 0.362).Manganese (Mn) concentrations averaged 34.1 mg/kg (irrigated) and 31.6 mg/kg (rainfed), with ranges of 10.3-72.6 and 15.0-57.2 mg/kg respectively. Standard deviations were 15.0 (irrigated) and 11.0 (rainfed), with CVs of 44.0% and 34.8%. The difference was not significant (t = 0.74, p = 0.463).

Iron (Fe) showed the highest concentrations among micronutrients, averaging 192 mg/kg (irrigated) and 177 mg/kg (rainfed). Fe ranged from 77.4 to 359 mg/kg (irrigated) and 109 to 359 mg/kg (rainfed), with standard deviations of 65.5 (irrigated) and 44.8 (rainfed). CVs were 34.0% (irrigated) and 25.3% (rainfed). The difference between systems was not statistically significant (t = 1.05, p = 0.299).

Soil Fertility Status Classification

Table 6 presents the fertility status classification of soil properties according to Esu (1991) rating criteria for Nigerian Savanna soils.

Both systems exhibited low fertility status for organic carbon, total nitrogen, available phosphorus, and ECEC the four most critical fertility parameters. These deficiencies represent major constraints to crop production and nutrient use efficiency in both irrigated and rainfed systems. Exchangeable bases (Ca, Mg, K) showed medium ratings in both systems, indicating adequate availability for most crops but potential for deficiency under intensive cropping without appropriate fertilization. Exchangeable Na was rated low to medium, with no indication of sodicity concerns (Exchangeable Sodium Percentage was <5% in all samples).

For micronutrients, all four elements (Zn, Cu, Mn, Fe) showed concentrations well above sufficiency thresholds established for Nigerian soils by Enwezor (1976) and more recent global compilations by Lindsay and Norvell (1978) and Alloway (2008). Critical levels are generally considered to be: Zn <0.5-1.0 mg/kg, Cu <0.2-0.5 mg/kg, Mn <5.0 mg/kg, and Fe <5.0 mg/kg (DTPA-extractable). All samples in this study exceeded these thresholds by substantial margins, indicating high micronutrient availability and no likelihood of micronutrient deficiency-induced yield limitations in either system.

Comparative Analysis: Irrigated vs. Rainfed Systems

Table 7 summarizes the statistical comparison of mean soil properties between irrigated and rainfed systems using independent samples t-tests.

Table 5: Descriptive Statistics of DTPA-Extractable Micronutrients in Irrigated and Rainfed Systems

Property	System	Min	Max	Mean	SD	CV (%)	Skewness	Kurtosis
Zn (mg/kg)	Irrigated	2.34	44.7	18.9	10.2	53.9	0.48	-0.17
	Rainfed	2.36	39.2	16.5	9.15	55.5	0.62	-0.27
Cu (mg/kg)	Irrigated	0.43	6.34	2.50	1.23	49.2	0.76	0.80
	Rainfed	1.02	6.27	2.79	1.30	46.6	0.81	0.25
Mn (mg/kg)	Irrigated	10.3	72.6	34.1	15.0	44.0	0.79	0.26
	Rainfed	15.0	57.2	31.6	11.0	34.8	0.82	0.29
Fe (mg/kg)	Irrigated	77.4	359	192	65.5	34.0	0.57	0.41
	Rainfed	109	359	177	44.8	25.3	1.50	3.68

Table 6: Fertility Status Classification of Soil Properties Using Esu (1991) Criteria

Parameter	Irrigated	Rainfed	Esu (1991) Rating	Fertility Class
Organic Carbon (%)	0.76	0.68	<1.0 = Low	LOW
Total Nitrogen (%)	0.06	0.07	<0.10 = Low	LOW
Available P (mg/kg)	4.03	4.05	<7.0 = Low	LOW
Ca (cmol(+)/kg)	2.74	2.61	2.0-5.0 = Medium	MEDIUM
Mg (cmol(+)/kg)	0.75	0.75	0.30-1.0 = Medium	MEDIUM
K (cmol(+)/kg)	0.22	0.27	0.15-0.30 = Medium	MEDIUM
Na (cmol(+)/kg)	0.09	0.10	<0.10 = Low (Na); 0.10-0.30 = Medium	LOW to MEDIUM
ECEC (cmol(+)/kg)	4.45	4.26	<6.0 = Low	LOW

Only two parameters showed statistically significant differences between systems: total nitrogen (higher in rainfed, p = 0.021) and exchangeable acidity (higher in irrigated, p = 0.021). The higher total N in rainfed systems (0.07% vs. 0.06%) is counterintuitive given potentially higher biomass production under irrigation, and may reflect differences in cropping systems (inclusion of legumes in rainfed rotations) or fertilization history. The significantly higher exchangeable acidity in irrigated soils (0.65 vs. 0.39 cmol(+)/kg) is consistent with global observations of accelerated base cation leaching under intensive irrigation (Jalali and Merrikhpour, 2008; Levy *et al.,* 2011).

Despite the statistically significant differences in these two parameters, the overall fertility status and major constraints were remarkably similar between irrigated and rainfed systems. Both systems exhibited identical ratings (LOW) for organic carbon, available phosphorus, and ECEC, and identical ratings (MEDIUM) for exchangeable bases. This finding indicates that irrigation has not substantially improved macronutrient fertility status despite potentially higher biomass inputs and more intensive management.

DISCUSSION

Soil Physical Properties and Implications for Fertility

The predominance of sandy loam texture in both systems (60.7-60.8% sand, 15.9-16.2% clay) reflects the geological parent materials (basement complex rocks) and advanced weathering characteristic of Nigerian Savanna soils (Areola and Faniran, 1977). The similarity in texture between irrigated and rainfed systems confirms that they share common pedogenic origins, validating the comparative approach. The moderate to high CVs for clay (21.4-26.6%) indicate spatial variability likely related to landscape position, erosional/depositional processes, and micro-topography (Wilding and Drees, 1983).

The sandy texture has important fertility implications. Low clay content directly contributes to low ECEC (4.26-4.45 cmol(+)/kg), limiting the soil's capacity to retain cations against leaching (Brady and Weil, 2016). Sandy soils also exhibit low water-holding capacity, rapid drainage, and susceptibility to erosion all of which accelerate nutrient losses (Bationo *et al.,* 2007). The moderate CVs for sand (10.0-14.4%) indicate relatively uniform texture within fields, suggesting that fertilizer recommendations can be standardized within each land-use type without excessive concern for texture-induced variability. Studies from similar agroecologies support these findings. Kamara *et al.* (2018) reported sandy loam texture with low ECEC (3.8-5.2 cmol(+)/kg) across Northern Nigerian Savanna soils. Garba *et al.* (2012) documented sand contents of 55-65% in Kano State agricultural soils with similar fertility constraints. The consistency across studies suggests that low ECEC is a regional characteristic requiring management strategies that minimize nutrient leaching.

Soil Reaction and Acidity

Mean pH values of 6.05-6.15 fall within the optimal range (6.0-6.5) for most cereal and vegetable crops (Brady and Weil, 2016), facilitating nutrient availability and minimizing aluminum toxicity. However, the significant difference in exchangeable acidity (EA) between irrigated (0.65 cmol(+)/kg) and rainfed (0.39 cmol(+)/kg) systems warrants attention. Higher EA in irrigated soils despite similar pH suggests accumulation of exchangeable Al^{3+} and H^+, which can become problematic if pH declines further (Sumner and Noble, 2003).

This pattern is consistent with global observations of irrigation-induced acidification. Jalali and Merrikhpour (2008) in Iran reported pH decline from 7.8 to 7.2 after 30 years of irrigation, attributed to accelerated base cation leaching and oxidation of organic matter. Wang *et al.* (2008) in China documented similar trends, with irrigated soils showing 0.3-0.5 pH unit decline compared

Table 7: Statistical Comparison of Soil Properties Between Irrigated and Rainfed Systems

Property	Irrigated Mean	Rainfed Mean	t-value	p-value	Significance
Sand (%)	60.7	60.8	-0.05	0.959	NS
Silt (%)	23.1	23.3	-0.18	0.857	NS
Clay (%)	16.2	15.9	0.31	0.761	NS
pH (1:1)	6.15	6.05	1.02	0.312	NS
OC (%)	0.76	0.68	0.82	0.416	NS
N (%)	0.06	0.07	-2.38	0.021	*
P (mg/kg)	4.03	4.05	-0.04	0.968	NS
Ca (cmol(+)/kg)	2.74	2.61	0.45	0.654	NS
Mg (cmol(+)/kg)	0.75	0.75	0.00	1.000	NS
K (cmol(+)/kg)	0.22	0.27	-1.82	0.074	NS
Na (cmol(+)/kg)	0.09	0.10	-0.54	0.591	NS
EA (cmol(+)/kg)	0.65	0.39	2.38	0.021	*
ECEC (cmol(+)/kg)	4.45	4.26	0.52	0.605	NS
Zn (mg/kg)	18.9	16.5	0.98	0.331	NS
Cu (mg/kg)	2.50	2.79	-0.92	0.362	NS
Mn (mg/kg)	34.1	31.6	0.74	0.463	NS
Fe (mg/kg)	192.4	177.0	1.05	0.299	NS

*NS = Not significant (p > 0.05); * = Significant at p < 0.05* to rainfed counterparts after 15-20 years. Levy *et al.* (2011) reviewed irrigation effects globally and identified enhanced leaching as a primary mechanism driving acidification in coarse-textured, low-buffered soils. The mechanism likely involves: (1) enhanced leaching of base cations (Ca^{2+}, Mg^{2+}, K^+) through increased water percolation, (2) potential application of acidifying fertilizers (e.g., ammonium-based N fertilizers) at higher rates in irrigated systems, and (3) increased nitrification-induced H^+ production under favorable moisture conditions (Bolan *et al.,* 2003). Given that EA is already significantly elevated in irrigated soils, monitoring pH trends and periodic liming may become necessary to prevent progressive acidification (Fageria and Baligar, 2008).

Organic Carbon and Total Nitrogen

The low organic carbon content (0.68-0.76%) represents a critical fertility constraint in both systems. According to Esu (1991), OC <1.0% is rated LOW, and values below this threshold are associated with poor soil structure, reduced water-holding capacity, low nutrient retention, and diminished biological activity (Lal, 2006; Vanlauwe *et al.,* 2015). The OC levels observed are substantially lower than the >2% considered necessary for sustainable tropical agriculture (Sanchez, 2002) and below the 1.0-1.5% minimum recommended for Nigerian Savanna soils (Lombin, 1987).

Studies across Northern Nigeria consistently document declining OC. Ewulo *et al.* (2008) reported OC declining from 1.8-2.2% in the 1960s to 0.6-0.9% by 2005 in continuously cropped fields. Garba *et al.* (2012) found mean OC of 0.52% in intensively cultivated areas of Kano State. Kamara *et al.* (2018) recorded OC of 0.45-0.78% across Northern Guinea Savanna sites, similar to the current study. The consistency of these low values reflects widespread organic matter depletion driven by continuous cropping, minimal residue return, crop residue removal for fodder and fuel, accelerated decomposition under high temperatures, and erosion on sloping lands (Bationo *et al.,* 2007). Importantly, irrigation did not enhance OC accumulation despite potentially higher biomass productivity. The mean OC in irrigated soils (0.76%) was only marginally and non-significantly higher than rainfed (0.68%). This contrasts with findings from more humid regions where irrigation-enhanced biomass return led to OC gains (Singh *et al.,* 2014). Possible explanations include: (1) complete crop harvest with minimal residue return in vegetable-dominated irrigated systems, (2) accelerated decomposition under favorable moisture-temperature combinations, (3) enhanced microbial activity consuming organic matter faster than it accumulates, and (4) relatively short duration of irrigation management (<20 years) insufficient to show measurable OC changes (Lal, 2004).

Total nitrogen (0.06-0.07%) is closely linked to OC, with approximately 95% of soil N bound in organic forms (Brady and Weil, 2016). The C:N ratios (9.7-12.7:1) fall within the typical range for tropical soils (8-12:1), indicating moderate decomposition rates (Stevenson, 1994). However, absolute N levels are critically low (Esu 1991: <0.10% = LOW), limiting N mineralization and requiring substantial N fertilization for crop production (Vanlauwe *et al.,* 2011). The significantly higher N in rainfed (0.07%) vs. irrigated (0.06%) systems, though the difference is small in absolute terms, may reflect inclusion of legumes (cowpea, groundnut) in rainfed rotations, contributing N through biological N_2 fixation (Giller, 2001). Irrigated systems in the study area are predominantly vegetable-cereal rotations with minimal legume integration, potentially explaining lower total N despite higher overall productivity.

Phosphorus Deficiency and Fixation

Available P (4.03-4.05 mg/kg) is critically deficient in both systems, rated LOW by Esu (1991) criteria (<7 mg/kg). These values are substantially below the 15-20 mg/kg considered adequate for most crops (Sanchez, 2002) and consistent with widespread P deficiency across West African soils (Bationo *et al.,* 2007; Nziguheba *et al.,* 2010). P deficiency in Nigerian Savanna soils has been extensively documented. Lombin (1987) identified P as the most limiting nutrient after N, with 80% of surveyed fields showing deficient P (<10 mg/kg). Kang and Juo (1983) demonstrated strong crop responses to P fertilization in Northern Nigerian soils. More recent studies by Garba *et al.* (2012) and Kamara *et al.* (2018) reported available P of 2.5-6.8 mg/kg, similar to the current findings. The mechanism of low P availability involves high P-fixation by iron (Fe) and aluminum (Al) oxides and hydroxides characteristic of highly weathered tropical soils (Sanchez and Uehara, 1980). The high DTPA-extractable Fe (177-192 mg/kg) in this study provides indirect evidence of substantial Fe oxide content. At slightly acidic pH (6.05-6.15), Fe oxides have high phosphate sorption capacity through ligand exchange mechanisms, converting soluble P to insoluble Fe-P forms (Lindsay, 1979; Hinsinger, 2001).

Exchangeable Bases and Cation Balance

Exchangeable Ca (2.61-2.74 cmol(+)/kg), Mg (0.75 cmol(+)/kg), and K (0.22-0.27 cmol(+)/kg) are rated MEDIUM by Esu (1991), indicating adequate but not abundant availability. These levels are sufficient to prevent deficiency symptoms in most crops but may become limiting under intensive cropping with high nutrient removal (Brady and Weil, 2016). The Ca:Mg ratios (3.48-3.65:1) are within the optimal 2-5:1 range recommended for balanced plant nutrition (Kopittke and Menzies, 2007). Ratios outside this range can induce antagonistic effects: high Ca:Mg (>10:1) can induce Mg deficiency, while low ratios (<2:1) can reduce Ca uptake (Fageria, 2001). The Ca:K ratios (9.7-12.5:1) and Mg:K ratios (2.78-3.41:1) are also within acceptable ranges, suggesting balanced cation nutrition. The similarity of exchangeable bases between systems indicates that irrigation has not substantially depleted or enriched these nutrients. However, the significantly higher exchangeable acidity in irrigated soils suggests ongoing base cation leaching, which could progressively reduce base saturation if not compensated by fertilization or liming (Sumner and Noble, 2003).

Exchangeable Na is low (0.09-0.10 cmol(+)/kg) with Exchangeable Sodium Percentage (ESP) <5% in all samples, indicating no sodicity concerns. This contrasts with some irrigation schemes globally where poor-quality irrigation water or inadequate drainage leads to Na accumulation and soil structure degradation (Oster and Jayawardane, 1998). The low Na likely reflects good-quality irrigation water (groundwater and surface water with low salinity) and adequate drainage in the sandy soils.

Effective Cation Exchange Capacity and Nutrient Retention

The low ECEC (4.26-4.45 cmol(+)/kg) is a fundamental constraint limiting nutrient retention and buffering capacity. ECEC <6 cmol(+)/kg is rated LOW by Esu (1991) and is characteristic of sandy, low-organic matter soils (Brady and Weil, 2016). The ECEC is determined primarily by clay mineralogy, organic matter content, and pH (Sumner and Noble, 2003). With clay contents of 15.9-16.2% and OC of 0.68-0.76%, both systems have minimal sources of negative charge for cation retention. Clay minerals in Northern Nigerian soils are predominantly low-activity clays (kaolinite) with inherently low CEC (Areola and Faniran, 1977). Organic matter typically contributes 30-70% of ECEC in tropical soils (Lal, 2006), but at OC <1%, this contribution is minimal. Low ECEC has critical management implications: (1) applied fertilizer cations (K^+, NH_4^+, Ca^{2+}, Mg^{2+}) are weakly retained and highly susceptible to leaching, reducing fertilizer use efficiency, (2) nutrient availability fluctuates rapidly with fertilization, leading to potential deficiency or toxicity, (3) soil buffering against pH changes is weak, increasing vulnerability to acidification, and (4) split fertilizer applications are essential to minimize leaching losses (Bationo *et al.*, 2007; Vanlauwe *et al.*, 2015). The similarity in ECEC between systems indicates that short- to medium-term irrigation has not altered soil exchange capacity. Long-term ECEC changes would require substantial increases in organic matter or changes in clay mineralogy, processes operating on decadal timescales (Lal, 2004).

Micronutrient Status

All four micronutrients (Zn, Cu, Mn, Fe) showed concentrations well above deficiency thresholds in both systems. DTPA-extractable Zn (16.5-18.9 mg/kg) far exceeds the critical level of 0.5-1.0 mg/kg (Lindsay and Norvell, 1978), Cu (2.50-2.79 mg/kg) exceeds 0.2-0.5 mg/kg, Mn (31.6-34.1 mg/kg) exceeds 5 mg/kg, and Fe (177-192 mg/kg) exceeds 5 mg/kg (Alloway, 2008). These findings are consistent with early studies by Enwezor (1976) and Osiname *et al.* (1973) who reported generally adequate micronutrient status in Nigerian Savanna soils, attributed to parent material mineralogy (Mn- and Fe-rich basement complex rocks) and relatively short duration of intensive cultivation compared to Asian systems where micronutrient depletion is widespread (Sillanpää, 1982; Zou *et al.*, 2012). The high Fe concentrations are particularly noteworthy given the low available P. High Fe-oxide content likely serves as a major P-fixation mechanism (Hinsinger, 2001), explaining the paradox of low P despite moderate base cation levels. Studies by Lombin (1987) in Northern Nigeria documented similar Fe-P relationships, with P sorption isotherms indicating high P-fixation capacity correlated with Fe-oxide content.

The similarity of micronutrient levels between irrigated and rainfed systems suggests that irrigation-induced changes in redox conditions, organic matter dynamics, or pH have not substantially altered micronutrient availability. This may reflect: (1) predominantly aerobic conditions in well-drained sandy soils even under irrigation, limiting redox-induced mobilization of Mn and Fe (Marschner, 2012), (2) buffering of micronutrient availability by high total reserves in parent materials, and (3) relatively short duration of irrigation management to manifest measurable changes in micronutrient pools.

System-Specific Fertility Constraints

The remarkably similar fertility status between irrigated and rainfed systems both rated low for OC, N, P, and ECEC indicates that the major fertility constraints are soil-inherent (texture, mineralogy, parent material) rather than management-induced. Irrigation has not overcome these fundamental limitations, nor has it substantially enhanced nutrient capital despite potentially higher biomass productivity and more intensive management.

This finding contrasts with studies from more humid tropical regions where irrigation led to measurable fertility improvements through enhanced residue return and nutrient cycling (Singh *et al.*, 2014). The difference likely reflects: (1) complete biomass harvest with minimal residue return in commercial vegetable production, (2) short duration of irrigation development (<20 years for most schemes in the study area), insufficient for measurable soil changes, (3) nutrient mining through intensive cropping exceeding nutrient inputs, and (4) enhanced leaching losses in sandy, low-buffered soils offsetting any gains from higher inputs. The significantly higher exchangeable acidity in irrigated soils, however, represents an irrigation-specific concern requiring monitoring and potential corrective action (liming) to prevent progressive acidification (Fageria and Baligar, 2008).

CONCLUSION

This comprehensive assessment of soil fertility in irrigated and rainfed agricultural systems in Northern Nigeria reveals that both systems share critical macronutrient deficiencies, with organic carbon (0.68-0.76%), total nitrogen (0.06-0.07%), available phosphorus (4.03-4.05 mg/kg), and ECEC (4.26-4.45 cmol(+)/kg) all rated LOW according to Esu (1991) criteria, representing fundamental limitations to crop productivity. Contrary to expectations, irrigation has not substantially improved macronutrient fertility status, suggesting that potential gains from higher inputs and productivity are offset by enhanced nutrient removal and leaching losses in the sandy, low-buffered soils characteristic of the region. A significant finding is that irrigation has substantially increased exchangeable acidity (0.65 vs. 0.39 cmol(+)/

kg, $p < 0.05$), indicating an emerging soil acidification risk that requires monitoring and potential corrective interventions. Severe phosphorus deficiency persists in both systems, likely constrained by high P-fixation mechanisms associated with elevated iron oxide content (Fe: 177-192 mg/kg), necessitating management strategies that address fixation rather than simply increasing application rates. In contrast, micronutrient status is adequate to high in both systems (Zn: 16.5-18.9 mg/kg; Cu: 2.50-2.79 mg/kg; Mn: 31.6-34.1 mg/kg; Fe: 177-192 mg/kg), with no evidence of deficiencies. The similarity in fertility constraints across both systems suggests that inherent soil properties exert stronger control over fertility than management system type, requiring integrated soil fertility management approaches that address organic matter restoration, phosphorus availability enhancement, and nitrogen supplementation through combined organic-inorganic sources as fundamental priorities for sustainable agricultural intensification in the region.

RECOMMENDATION

- Implement Integrated Soil Fertility Management (ISFM) combining organic matter restoration through crop residues, compost, and green manures with strategic nitrogen fertilization via split applications and legume integration to address critical macronutrient deficiencies in both systems.
- Adopt phosphorus-fixation mitigation strategies including banded fertilizer placement near root zones, organic amendments to enhance P availability, and appropriate P sources combined with phosphate-solubilizing microbial inoculants to overcome severe P deficiency constraints.
- Apply system-specific interventions with regular soil pH monitoring and corrective liming in irrigated systems to counteract acidification trends, while prioritizing legume integration, water harvesting techniques, and micro-dosing fertilizers in rainfed systems, supported by regular soil testing programs every 2-3 years to monitor fertility trends and ensure adaptive management.

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