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SOIL SALINITY ASSESSMENT FOR CROP PRODUCTION SUSTAINABILITY IN JIBIA IRRIGATION SCHEME, KATSINA STATE, NIGERIA

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ABSTRACT

Cases of soil salinity have been observed in the Jibia Irrigation Scheme (JIS), threatening sustainable crop production. This study assesses soil salinity a critical factor influencing land degradation, to develop actionable remediation strategies. Soil samples were randomly collected from the upper 0–30 cm of soil at three operational treatment areas within the project: a 3,060-hectare area served by pumping systems and a 206-hectare area served by gravity systems. Samples were analysed in the laboratory for electrical conductivity (EC) and exchangeable bases. The EC values exhibited considerable variability, ranging from 0.29 dS/m to 5.47 dS/m, which reflects significant differences in soil salinity across the sites. Laboratory analyses revealed exceptionally high concentrations of exchangeable sodium (Na^+) relative to other essential bases; calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+). The percent base saturation (PBS) values further highlighted deficiencies: potassium ranged from 1.37% to 11.50%, magnesium from 1.46% to 6.70%, calcium from 13.90% to 36.46%, and sodium dominated at 45.56% to 76.62%. These imbalances in soil nutrient levels impair crop yields and quality, exacerbating economic losses and food insecurity in the scheme area. The study recommends implementing a series of remediation strategies to restore the productivity of the degraded farmlands. These strategies include soil leveling or grading, application of gypsum or calcium chloride to ameliorate salinity, and crop production practices that are tolerant to sodium. This study presents a thorough assessment of the effects of soil salinity in the JIS and practical recommendations to enhance soil health and support sustainable agricultural practices in the area.

Keywords: Soil Salinity, Land Degradation, Electrical Conductivity (EC), Exchangeable Bases, Remediation

INTRODUCTION

Soil degradation is a serious problem in the modern era. It will undoubtedly remain a significant issue throughout the 21st century, complicating efforts to sustain livelihoods and provide food for the world's teeming population a tall order. Soil degradation has remained a threat to sustainable agriculture, particularly in arid and semiarid regions of the world (Batakanwa, Mahoo, & Kahimba, 2015).

The rising demand for food in the 21st century driven by accelerated population growth has led to an over 300% increase in irrigation, facilitating a significant expansion of intensive agriculture (Boitt, Tian, Black, Wakelin, & Condron, 2018; Kuti *et al.,* 2018).

For over a century, the agro-climatic conditions in the Sudano-Sahelian region of Nigeria have necessitated irrigation. With limited surface water, particularly in arid and semi-arid areas, and the escalating impacts of climate change making water even scarcer, increased use of groundwater is inevitable, which in turn exacerbates soil salinisation (Batakanwa et al., 2015; Kuti et al., 2018).

Salinisation is the process of the accumulation of salts in soil due to the evaporation of salt-laden water at the soil surface, occurring in arid and semi-arid areas. Soil salinity engenders inadequate plant nutrient absorption, inflicts toxicity on plants, and damages some soil physical properties, all of which affect the overall productivity of crops (Yang et al., 2020). Approximately 1 billion hectres or 3% of the global land surface is affected by salinity, thereby threatening agricultural sustainability (Yang et al., 2020).

Jibia is part of the northern part of Katsina State and is recognised as the most vulnerable area to desertification characterised by low vegetation, climatic, and soil quality indexes (James et al., 2018). In response to the severe drought of the early and mid-1970s, the federal government of Nigeria established the River Basin Development Authority (RBDA) to develop irrigation infrastructure for increased agricultural production and rapid rural development (Musa, Baba, & Beli, 2015). Since its completion in 1989, the irrigation scheme has demonstrated significant economic benefits, greatly improving the quality of life for people in the Jibia area and surrounding areas.

Nonetheless, there have been reported cases of soil degradation in the scheme. Therefore, in this study, the salinity level in the soil was evaluated as an important step aimed at making feasible plans for the sustainability of crop production in the study area.

MATERIALS AND METHODS

Study Area

The study area is located in Jibia Local Government Area of Katsina State. The investigated area (Figure 1) lies between the coordinates 7º 12′ 0″ and 7º 18′ 7″ E and 13º 5′ 6″ and 13º 5′ 20″ N and covers 3,472 hectres. The altitude ranges from 391 to 439 meters above sea level. The study area is located in the semi-arid region of the state, which receives an average of 672 mm a minimum of 78.49 mm, and a maximum of 275.15 mm. Most of the rainfall falls in this area in 4 to 5 months, roughly from June to September. Overall, the area is characterised by great variability in climatic conditions due to the long dry season of about seven months between October, March, and April. May is typically, the hottest month, whereas August tends to be the wettest. The area has an average wind speed of over 10 mph, resulting in high wind speeds. Agriculture became one of the most important activities of the people, although there were other non-agricultural activities through which people earned a living.

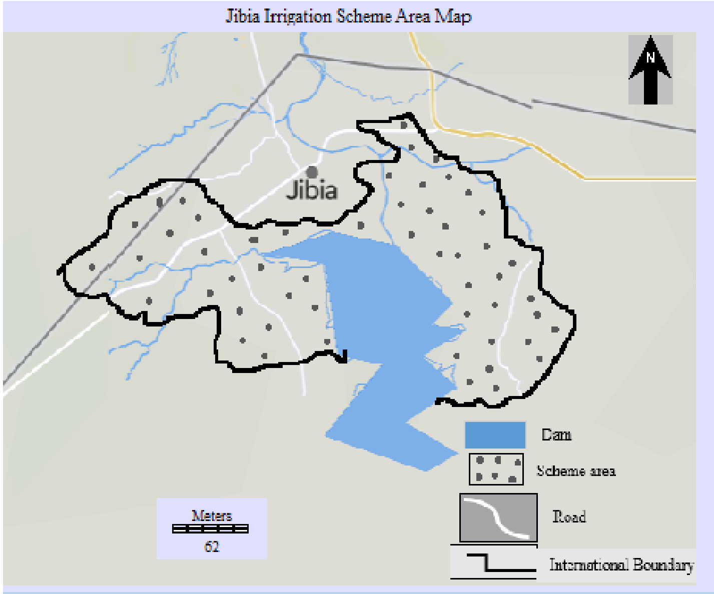

Figure 1: Jibia LGA map showing the study area
Source: Modified from Mapcarta

Data Collection

We collected soil samples from an adequate number of sites scattered across the entire study area. The irrigation scheme area was divided into six sections to supply water to the farmlands. This was in line with the division of the main canals, F1 through F6, which draw water from the two compensating reservoirs, R1 and R2, located on the eastern and western front sides of the dam, respectively, and with a gravity control chamber in the middle (Figure 2). The main canals, which draw water from the compensating reservoirs and the gravity control chamber, supply water to the sub-canals used by farmers for irrigating their farmlands.

Soil samples were collected from the primary farming areas of the scheme along the three functional canals (F1, F2, and Gravity). These canals have been the dominant channels for irrigation since the scheme's inception.

The sampling technique employed followed the methodology outlined by Clement *et al.*, (2010). A quadrat measuring 15 cm by 15 cm, along with a hand shovel and a ruler, was utilized to extract soil samples at each sampling site. The samples were taken from holes dug to a depth of 0–30. Ten of the eighty-two samples that were gathered were put in plastic bags for examination in a laboratory. These samples were tested for soil electrical conductivity (EC) and exchangeable bases to assess the concentration of ions, using the most widely accepted techniques for measuring soil salinity. Calibration of laboratory equipment, such as pH meters, electrical conductivity meters, and spectrometers, was also conducted to ensure accurate measurements.

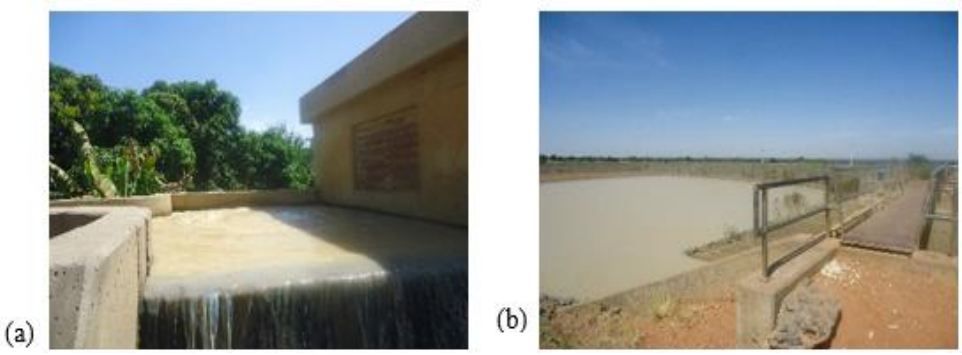

Figure 2: (a) Gravity control chamber (b) one of the compensating reservoirs-R1

Electrical Conductivity (EC) Measurement

Electrical Conductivity (EC) is one of the most commonly used methods for measuring the salt concentration in soil. The study uses a hand-held EC metre with extracted soil solution. The electrical conductivity (EC) of soil extract was measured using a 1:5 soil-to-water dilution, following the procedure prescribed by Gartley (2011).

$EC_{1:5}$ is a comprehensive parameter reflecting information on effective soil salinity under a certain soil water content and is convenient to obtain with sound comparability and repeatability.

The EC of a 1:5 soil extract is often used to describe soil salinity in almost all international periodicals [14, 15]. Soil EC measurement is expressed in deciSiemens per metre (dS/m) (Lhissou et al., 2014).

Exchangeable Bases for the Determination of Ions

Table 1: Electrical Conductivity (EC) and Exchangeable Base Measurements

Sampling site	E.C1:5 (dS/m)	Exchangeable Bases				ESP = Exchangeable {(Na)/(Ca + Mg + K + Na)} x 100
		Ca (ppm)	Mg (ppm)	K (ppm)	Na (ppm)	
$F1_2$	0.29	2.83	0.4	2.97	5.19	45.57
G_3	0.39	8.17	1.2	1.45	18.89	63.58
$F2_{26}$	1.02	4.83	1.4	0.73	16.4	70.21
G_5	0.82	9.83	0.4	1.99	14.74	54.67
$F1_8$	0.34	2.83	1	3.56	12.25	62.37
$F2_1$	0.37	3.5	1	1.54	8.51	58.49
G_{10}	5.47	11.83	1	5.76	50.1	72.94
$F2_3$	0.37	3	0.8	1.25	16.54	76.61
$F2_{25}$	0.53	9	0.6	2.33	17.3	59.19
$F2_{10}$	0.78	11.5	1.2	3.99	21.59	56.4

Exchangeable bases, also known as exchangeable cations, consist of Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+} and are the major contributing elements to soil salinity in semi- and arid soils. Determining exchangeable bases is another method that is considered very useful for assessing salinity in soils.

Soil samples taken from the sampling sites were subjected to laboratory analysis, from which the exchangeable bases were extracted from the saturated soil paste. Table 1 describes the concentrations of these chemical elements, respectively.

Exchangeable base measurements are usually reported in parts per million (ppm). The total exchangeable bases, expressed as milligram equivalents per 100 g of soil, were measured after leaching the soils with ammonium acetate buffered to a pH of 7.0, as shown by Thomas (1990). The quantities of Ca^{2+} and Mg^{2+} in the leaching solution were measured using an atomic absorption spectrophotometer. The remaining potassium and sodium were analysed through flame photometry, following the method Debela *et al.,* (2011) described.

Statistical Analysis

The analysis of exchangeable bases was presented as a percentage of the total amounts of calcium, magnesium, potassium, and sodium, offering insights into the relative proportions of each exchangeable base element on the soil of the study area. The electric conductivity was estimated, and the results were presented as an average value for the entire study area, reflecting the overall salinity level.

Additionally, the mean and standard deviation for the other species were calculated to assess the average values and variability of each soil property.

RESULTS AND DISCUSSION

The study area's EC measurements, ranging from 0.29 dS/m to 5.47 dS/m (Table 1), reveal diverse patterns of quantities with high variability in their occurrences with average values of 1.038 dS/m, and standard deviation of 1.576. Salinity levels are determined using EC measurements according to the methodology utilised by Schultheis et al., (2020). Soils are characterised as non-saline when dS/m values are < 2 dS/m. Soil is said to be slightly saline when values range from 2–4 dS/m. Meanwhile, moderately saline-referred soil has a range between 4–8 dS/m. Soils with values ranging from 8–16 dS/m are characterized as strongly saline soil.

Hence, when the dS/m values are between > 16 dS/m is classified as very strongly saline. The values observed (Table 1) indicate that one of the sample sites is slightly affected by saline formation ($F2_{26}$) and the other identified sample site has a moderate saline formation (G_{10}). At the same time, the remaining sample sites are classified with non-saline soil formation having values < 2 dS/m. Saline soils, often called "white alkali" soils, are characterized by noticeable salt deposits on the surface. Many salts in the soil solution positively influence soil structure and enhance water infiltration (Zamora Re, 2022).

During the field study, it was observed that farmlands along gravity control canals where irrigation activities were far more frequent year-round were the most risky and susceptible to higher concentrations of soluble salts and exchangeable sodium. This may be due to too much water available on the arable land, which leads to soil saturation and waterlogging. Mineral salts are carried upward by capillary action to the soil surface, they undergo crystallization as the water evaporates, resulting in saline soil surfaces (Figure 3).

Figure 3: Excessive water on agricultural lands leads to saturation issues, which in turn causes waterlogging

Therefore, the variability in electrical conductivity (EC) across different sites can be attributed to over-irrigation or improper drainage, which leads to salt accumulation in the soil, increasing EC. Likewise, EC variability can be affected by variations in rainfall and evaporation rates, soil moisture, and salt accumulation. In semi-arid regions, elevated evaporation rates can cause salts to accumulate in the upper soil layers, resulting in higher EC levels (Hassan et al., 2021). Additionally, alternating baseline measurements were conducted to determine which farming lands in the study area were affected by salt. The results indicate the proportion of each base-forming cation (Table 1), measured in parts per million (ppm). These data show the concentration of these bases in the soils studied. Specifically, the calcium content (Ca^{2+}) ranged between 2.83 and 11.50 ppm, with an average concentration of approximately 6.732 ppm. Magnesium had a mean concentration of 0.9 ppm with a narrow range of 0.4 to 1.4 ppm. The values for potassium (K^+) varied from 0.73 to 5.76 ppm. In comparison, sodium (Na^+) had a wider range from 5.19 to 50.1 ppm, with the mean concentration being high at around 18.151 ppm (Figure 4), showing that sodium levels are generally elevated at all locations examined. The optimal values for each exchangeable base in soil may vary depending on plant needs, soil type, and local growing conditions. Therefore, the ideal range for calcium (Ca^{2+}) is between 1000 and 2000 ppm; Magnesium (Mg^{2+}) should be in the range of 100 to 200 ppm; Potassium (K^+) requires an optimal range of 100 to 250 ppm; and sodium (Na^+) should ideally be less than 70 ppm (Great Lakes Laboratories, 2001). The study also examines the relationship between electrical conductivity and calcium, magnesium, potassium, sodium, and exchangeable sodium content (ESP) levels. The resulting correlation matrix has a scale between -1 and +1, showing the strength of the relationship between them and the direction of these relationships. Therefore, a high positive correlation of about 0.8 can be seen between the salinity of $E.C_{1:5}$ and sodium, indicating that as the salinity increases, the sodium content also increases accordingly. This is often seen in saline soils, where the buildup of sodium contributes to higher salinity. On the other hand, the correlation matrix indicates a negative correlation with values close to -1 (-0.7) between ESP and magnesium. This suggests that as ESP increases, magnesium availability decreases, possibly due to high sodium levels affecting magnesium retention in soil. Furthermore, a weak correlation between potassium and E.C1:5 with values close to 0 suggests that salinity and potassium content may have little or no relationship in the sample area. However, soil sodium status can be assessed using several important indicators, including the exchangeable sodium percentage (ESP). Exchangeable Sodium Percentage (ESP) is a reliable indicator used to identify salt-contaminated soils and classify them as saline, sodic, or saline-sodic.

Given this, the status of sodium concentration in the soils of the study area was effectively assessed using the Exchangeable Sodium Percentage (ESP) formula according to UNSW (2007) (Table 1). The ESP results yielded percentages between 45.57% and 76.61%, an average of 62.003% with a standard deviation of 9.3% thus, indicating that like electrical conductivity ($E.C_{1:5}$) has varying wide proportional spatial distribution of salinity levels across samples, possibly due to different soil types or irrigation practices. The ESP scale measures the cation exchange capacity (CEC) percentage of soil occupied by sodium ions (Na^+). Soil is classified as sodic when sodium ions account for 15% or more of its composition (Harter & Motis, 2016).

The results of the ESP analysis (Table 1) at all the sampling sites showed the presence of very sodium-rich soils. Lemon & Hall (2021) found that topsoil with an ESP greater than 6 and subsoils with an ESP greater than 16 are classified as high in sodium. Generally, the results show a significantly high proportion of sodium ions in the soil. Increased levels of elevated ESP can adversely affect soil structure, leading to reduced permeability, dispersive, crust formation, hard consolidation, and compaction. These changes ultimately hinder plant root growth and production reducing yield (Figure 4). Conversely, the results of this study show that the soils at the sampling sites have low concentrations of calcium, magnesium, and potassium (Table 1) and may have various negative effects on soil health, plant growth, and crop productivity. These nutrient elements neutralise organic acids during cell uptake (Scavo et al., 2019).

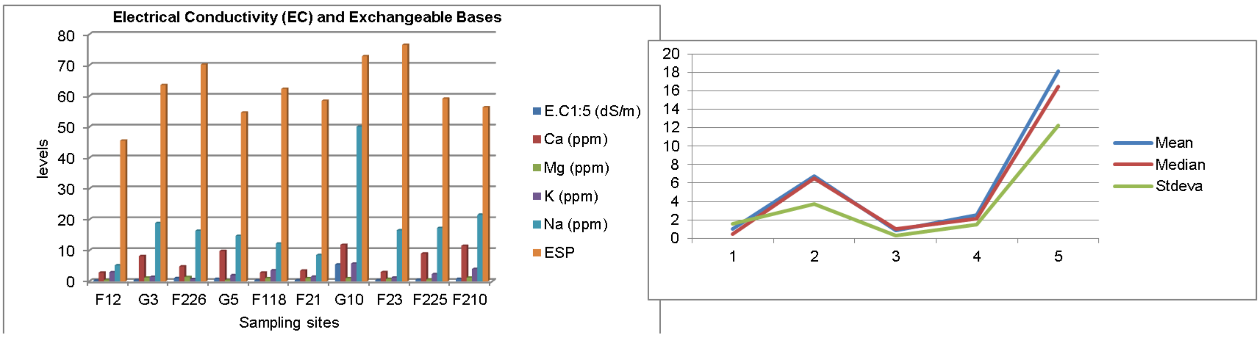

Figure 4: Statistical chart of the measurements (a) EC & Exchangeable Bases (b) Descriptive statistics

Figure 5: Shows the formation of (b) saline soil, (b) sodic soil, and (c) saline-sodic soil from the sampled site areas

Lower concentrations of these elements are associated with high levels of exchangeable sodium formations, indicating poor soil structure in clay-dominated soils. The exchangeable bases for soil nutrient balance typically require percentage ranges of 40-80% Ca, 10-40% Mg, and 1-5% K. Percent Base Saturation (PBS) calculations showed that: Potassium between 1.37% and 11, 50% fluctuated; Magnesium was 1.46–6.7%; Calcium was 13.90 to 36.46%; and sodium status varied between 45.56% and 76.62% of the respective sampling sites. The proportions of calcium, magnesium, and potassium in the soil at the sampling sites are below the required percentage levels. The concentrations of sodium are too high, which leads to the deterioration of essential soil nutrients and consequently impairs plant growth.

Furthermore, the observed sodium dominance in the soil has notable agricultural implications. When sodium levels exceed those of other essential nutrients such as calcium, magnesium, and potassium, it disrupts soil structure and leads to various adverse effects on agricultural productivity (Machado & Serralheiro, 2017).

CONCLUSION

Irrigated fields often have saline soils, especially in semi-arid and arid areas where irrigation is used to compensate for inadequate rainfall. The practices associated with irrigation cause significant environmental problems, affecting soil quality, biodiversity, and the ability to produce crops, posing serious environmental challenges. Soil salinity measured by electrical conductivity and exchangeable sodium percentage (ESP), is a major factor in soil degradation and harms water uptake and overall crop yield. Soil salinity is assessed through percent base saturation calculations, which indicate the amounts of exchangeable bases such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), and potassium (K^{+}) found in soil samples. Soil productivity can be affected by high or low concentrations of neutral salts or exchangeable bases, causing farmers to fail to utilize irrigated agricultural lands to their full potential.

RECOMMENDATIONS

Soil salinity is the second largest factor contributing to land degradation, negatively impacting agricultural productivity and environmental health. To remediate the degraded soils in the study area, it is essential to excavate silted areas. Additionally, overgrown weeds should be removed from the excess drainage channels.

Levelling the land is important to ensure proper irrigation water application, especially in cultivable farmlands with uneven topography. Adapting innovative soil management techniques and control methods is important for restoring soils with low or high exchangeable base concentrations. Techniques such as leaching, applying gypsum, compost, manure, and growing salt-resistant plants can improve soil fertility and structure. Additionally, plants genetically engineered to tolerate salt stress can help reduce the loss and abandonment of unproductive cropland.

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