


# Impact of Paddy Fields on Soil Salinity and Sodicity at Kalimbeza Rice Project, Namibia

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## Abstract

Long-term rice (*Oryza sativa* L.) paddy field cultivation can lead to negative impact on the crop productivity and yield stability. Soil salinity and sodicity which are closely related to unsustainable cultivation management and soil properties that affect plant growth and agricultural productivity. The objective of this study was to evaluate the long-term impact of cultivation of paddy rice on field salinity and/or sodicity accumulation in the Zambezi River floodplains of Namibia. Soil samples were collected from four randomly selected rice paddy fields under cultivation for 5, 10 years and non-cultivated areas under the project. A soil pH of 5.5 was measured in the 10-year paddy fields compared with 6.7 in the non-cultivated area, revealing soil acidification and not salinity or sodicity, resulting from long-term rice cultivation. The electrical conductivity (EC) of 50.5 mS/m found in the 10-year paddy fields was nearly three times (17.6) in the non-cultivated area and 16.8 in the 5-year paddy fields. The highest Na concentration (2.52 meq/L) was found in paddy fields cultivated for 10 years, compared to 1.0 and 0.7 meq/L in the fields cultivated for 5 years and in the non-cultivated areas, respectively. The highest SAR (2.5) was observed in the 10-year paddy fields, compared to 1.32 and 1.46 in the 5-year and non-cultivated areas, respectively. The results revealed an accumulation of salinity and sodicity. However, the EC (<400 mS/m) and SAR

(<13) indicated normal soil conditions. EC strongly and positively correlated with Na ( $r = 0.979$ ), magnesium ( $r = 0.733$ ), calcium ( $r = 0.932$ ), and SAR ( $r = 0.79$ ), and negatively correlated with C:N ratio ( $r = -0.752$ ). SAR strongly and positively correlated with Na ( $r = 0.844$ ) and negatively with C:N ratio ( $r = -0.845$ ). This revealed the need for soil management strategies that would prevent acidifying effect due to depletion of soil exchangeable bases including the use of acidifying fertilizers, inefficient use of exchangeable bases leading to excessive leaching, unbalanced plant utilization of exchangeable bases leading to nutrient imbalances and depletion of bases, and inefficient use of bases leading to excessive leaching of exchangeable bases in the soil. These findings can serve as a baseline for selecting sustainable paddy field management practices at the Kalimbeza Rice Project and in similar agro-ecologies.

### Keywords

Electrical Conductivity, Floodplains, Namibia, Rice, Salinity, Sodicity

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## 1. Introduction

The African (*Oryza glaberrima* L.) and Asian (*Oryza sativa* L.) rice are the two species vital for cultivation in floodplains and seasonal wetlands in Sub-Saharan Africa (SSA) [1]. The crop stands out as best-suited for cultivation in areas that are relatively fertile, but prone to seasonal floods [2] [3]. However, rice production and its economic potentials to contribute to food security, are not realised due to limited investment in agronomic practices, including soil management for long-term cultivation in SSA [4] [5]. Thus, a need for systematic studies on the impact of cultivation in paddy fields to develop effective soil salinity, sodicity and acidification management strategies in expanding rice production among farmers in the semi-arid seasonal floodplains of SSA.

Soil salinity and sodicity pose significant challenges to rice productivity worldwide, particularly in arid and semi-arid regions [6] [7]. Soil salinity and sodicity conditions arise from the accumulation of soluble salts and exchangeable Na ions, respectively, which impair soil structural stability and development. This ultimately compromises permeability and fertility [8].

In regions where irrigation agriculture is essential, such as southern Africa, understanding the long-term impacts of farming practices, including land preparation, water and fertilizer management, on soil health and crop production is critical [9]. Therefore, a study focusing on irrigated rice long term cultivation of paddy rice, is crucial to investigate the effects of prolonged paddy field cultivation on soil salinity, sodicity and acidification [3].

Globally, environmental impact of paddy cultivation has been extensively studied, particularly its contribution to soil salinization and sodification under irrigation systems [10]-[12]. Excessive water use, poor drainage, and the introduction of saline irrigation water can exacerbate these issues in rice paddy fields [13]-[15].

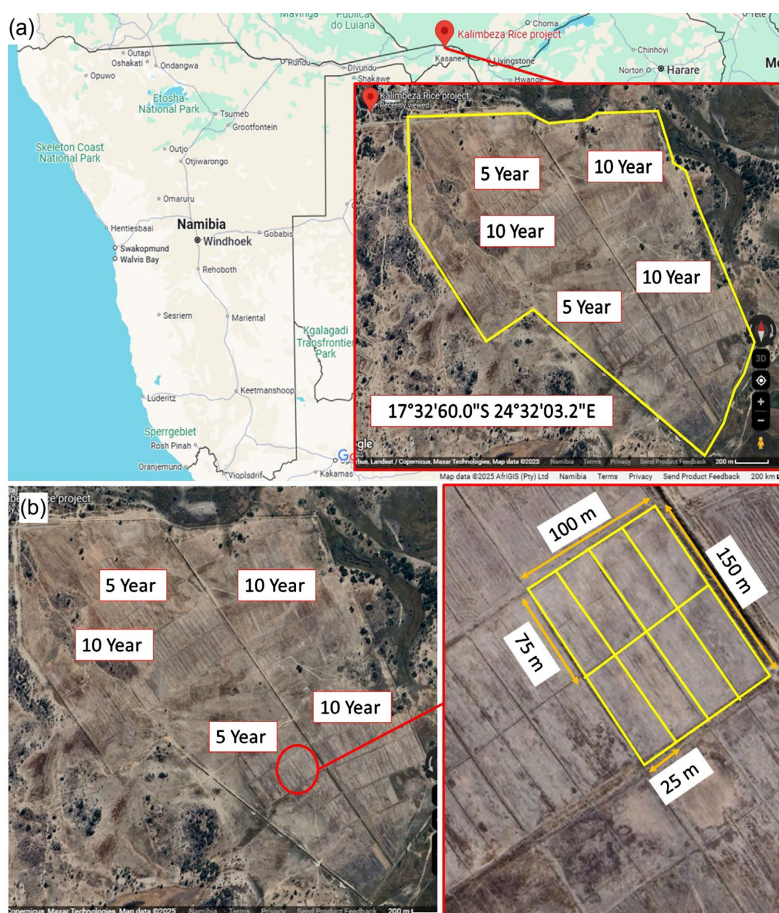
In southern Africa, where water resources are limited and climate variability is pronounced, understanding the interplay between paddy cultivation salinity accumulation and soil health is particularly pressing.

Systematic studies on salinity accumulation and its impact on paddy rice fields are limited in southern Africa. This underscores the need to evaluate salinity and sodicity accumulation and their impact on soil and water management technologies in paddy fields. The objective of this study was to evaluate the impact of cultivation of paddy rice on field salinity and sodicity accumulation in the Zambezi River floodplains of Namibia.

## 2. Materials and Methods

### 2.1. Study Site

The study involved soil sampling from the Kalimbeza Rice Project, situated along the Zambezi River floodplain in Zambezi Region, northeastern Namibia (**Figure 1**). The site is located at latitude  $17^{\circ}32'60.0''S$ , longitude  $24^{\circ}32'03.2''E$  and altitude 797 m above sea level. The land is predominantly flat and low-lying, making it suitable for seasonal floodplain rice cultivation.



**Figure 1.** Namibian map showing the Kalimbeza Rice Project in Zambezi region and paddy fields ( $17^{\circ}32'60.0''S$   $24^{\circ}32'03.2''E$ ).

The soils are mostly sandy and alluvial, with varying fertility levels and pH values ranging from ~5.5~6.5, and high organic matter content suitable for rice cultivation [16]. The Kalimbeza Rice project covers a total area of 222 ha, with 90 ha actively under production as of 2021 [17]. The main paddies are 150 × 100 m and are subdivided into 25 × 75 m sections for better water management (Figure 1).

The region experiences Tropical Savanna Climate (Aw), receiving mean annual rainfall of 600 to 1000 mm, predominantly between November and April. The Project benefits from the high rainfall in the Zambezi Region, compared to other parts of Namibia, which are arid and semi-arid [18]. The mean annual temperature is 26°C, with hot summers exceeding 35°C and mild winters rarely dropping below 10°C. Proximity to the Zambezi River provides a reliable supply for irrigation, supplemented by seasonal flooding that aids in natural irrigation and soil enrichment [18]-[20]. The irrigation water used in the Kalimbeza Rice Project is from the Zambezi River with an average EC<sub>iw</sub> of 0.05 - 0.15 dS·m<sup>-1</sup> and a SAR<sub>iw</sub> of 3 - 5.

## 2.2. Field Soil Sampling

Soil samples were collected from four paddy rice fields, for two cultivation period (5 and 10 years), after harvesting. A paddy fields sized 0.25 ha (25 m × 75 m) were selected for soil analysis (Figure 1). Uncultivated paddies, 25 m away from paddy fields, were sampled as control. The fields were grown predominantly with Supar and IRGA418 rice varieties.

In each paddy field (0.25 ha), five sub-samples were taken at a depth of 0 - 20 cm, using a 100 cm<sup>3</sup> steel core sampler and combined to form a composite sample for analysis. A total of four paddies were randomly selected sampled (replications) per growing period. A total of 12 sampling representing eight paddy fields and four controls were used for soil analysis.

## 2.3. Laboratory Analysis

The soil samples were air-dried, sieved through a 2 mm sieve to remove debris and standardise particle size, and subsequently prepared for physicochemical analysis. Soil texture was analysed using the sodium hexametaphosphate procedure and classified using the USDA system [21]. Soil salinity and sodicity were assessed through measurements of pH, electrical conductivity (EC), sodium (Na<sup>+</sup>), potassium (K<sup>+</sup>), calcium (Ca<sup>2+</sup>), magnesium (Mg<sup>2+</sup>), and sodium adsorption ratio (SAR) [22].

These chemical analyses were done based on the standard methods as outlined in the Non-Affiliated Soil Analysis Work Committee [22]. The pH (in water) was measured using a 1:2.5 soil-to-water suspension (mass-to-volume ratio). Exchangeable Ca, Mg, and K were extracted with 1 mol·L<sup>-1</sup> neutral ammonium acetate and analysed using an Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES; Optima 7000 DV, Perkin Elmer Inc., USA). The soil pH, EC and the concentrations of Ca, K, Mg, and Na as assessed from the saturated paste extract (EC<sub>e</sub>) were used to determine soil salinity and sodicity.

Measurements for pH, EC, and the concentrations of Ca, K, Mg, and Na from the ECe were conducted using a pH-mV meter, conductivity meter (MultiLab 540; WTW Wissenschaftlich-Technische Werkstätten GmbH, Germany) and ICP-OES, respectively. Soil salinity was expressed as the EC of the ECe. Sodicity was represented by the sodium adsorption ratio (SAR), calculated using the formula:

$$\text{SAR} = \text{Na}^+ / \sqrt{(\text{Ca}^{2+} + \text{Mg}^{2+})/2}$$

## 2.4. Data Analysis

Data collected were analysed using the one-way analysis of variance (ANOVA) of R Core Team (2023). Significant means were separated using the Least Significant Difference (LSD) test at  $p < 0.05$  level of significance. Pearson's correlation coefficients were applied to evaluate relationships between soil fertility parameters specific to paddy fields. Correlations were drawn between soil chemical parameters related to saline and sodic build up in irrigated paddy rice systems.

Salinity was determined by the electrical conductivity of the saturated paste extract (ECe), while sodicity was evaluated using the SAR following the guidelines from the Non-Affiliated Soil Analysis Work Committee [22]. Soils were categorized as non-saline when ECe value was  $< 4 \text{ dS}\cdot\text{m}^{-1}$ , and saline when ECe was  $\geq 4 \text{ dS}\cdot\text{m}^{-1}$ . Soils were considered non-sodic when SAR value was  $< 13$ , and sodic when SAR was  $\geq 13$ . These diagnostic class values are critical for understanding the potential long-term effects of paddy rice cultivation on soil properties, thereby providing context for interpreting the observed soil changes.

## 3. Results

### 3.1. Soil Properties

**Table 1** presents analytical data for soil texture. The proportion of sand, silt and clay-sized particles showed no significant variation across paddy fields. Overall, mean values were 58.7% sand, 20.7% silt, and 20.6% clay, classifying the soil as sandy loam. The soil under 5-years and 10-years of cultivation was classified as sandy loam, with sand, silt, and clay contents of 50.8%, 21.6%, and 27.6%, and 51.6%, 23.8%, and 24.7%, respectively. The control soil was classified as loamy sand, consisting of 73.7% sand, 16.8% silt, and 9.6% clay.

**Table 1.** Soil analytical data for paddy fields under three cultivation periods at the Kalimbeza Rice Project, in Namibia.

Years	Sand (%)	Silt (%)	Clay (%)	Textural class	pH	EC mS/m
0	73.700	16.750	9.600	Loamy sand	6.730	17.565
5	50.780	21.570	27.620	Sandy loam	5.795	16.805
10	51.550	23.800	24.650	Sandy loam	5.495	50.530
Mean	58.677	20.707	20.623	Sandy loam		28.300
p-values	0.200	0.368	0.145	-		0.111

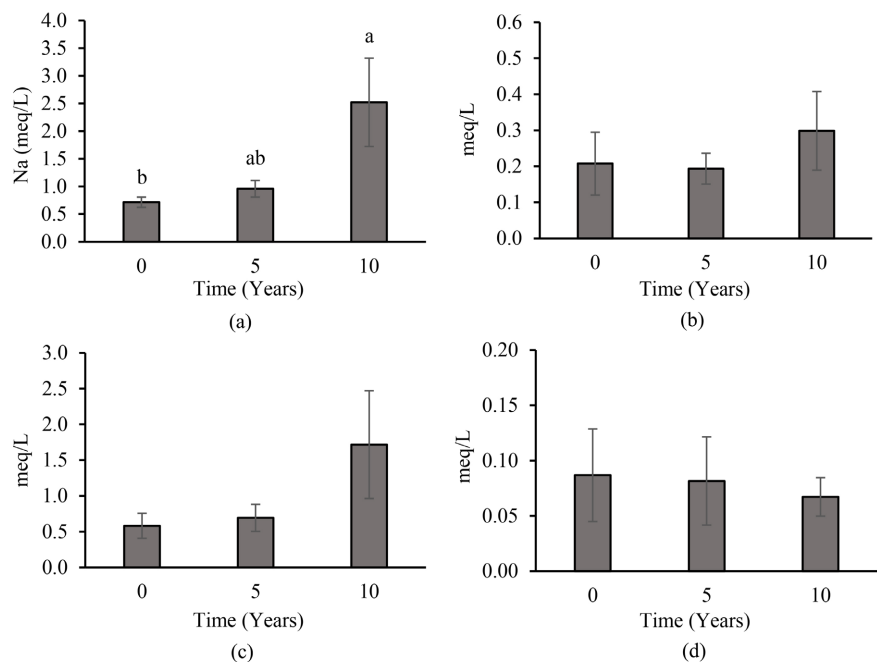
## Continued

s.e.d.	12.613	4.676	8.307	-	15.103
l.s.d.	30.862	11.443	20.327	-	36.956
cv%	30.400	31.900	57.000	-	75.500

EC. = electrical conductivity; p-values = probability value that corresponds to a variance ratio; SED = Standard errors of differences of means; LSD = Least significant differences of means (5% level); cv% = coefficients of variation.

**Table 1** presents results for soil pH and EC. Soil pH varied between the control and the 10-years paddy cultivation. The grand mean pH was 6.0, with the lowest pH (5.5) recorded in the 10-years cultivated paddy fields, followed by 5.8 in the 5-years fields and 6.7 in the control. EC did not vary significantly among the paddy fields (**Table 1**). The overall mean EC was 28.3 mS/m. The highest EC (50.5 mS/m) was observed in the 10-years paddy fields, while the lowest values were recorded in the 5-years (16.8 mS/m) and control (17.6 mS/m) fields. A high coefficient of variation (75.5%) was observed for EC.

The concentration of exchangeable sodium in the cultivated paddy rice soil increased significantly, with duration of cultivation (**Figure 2**). The mean concentration of exchangeable Na in the paddy rice system was 2.52 meq/L in 10-year paddy fields, significantly ( $p \leq 0.05$ ) greater than 0.71 meq/L in the uncultivated control. However, the concentration of exchangeable Na of 1.0 meq/L in 5-year paddy fields, did not differ significantly from the control and the 10-years fields (**Figure 2**).



**Figure 2.** Mean values of chemical properties for paddy fields under rice cultivation for 0-years, 5-years and 10-years at the Kalimbeza Rice Project, Namibia. Na, Sodium (a); Mg, Magnesium (b); Ca, Calcium (c); K, Potassium (d).

The concentration of exchangeable Mg was not significant across paddy fields, with a mean of 0.23 meq/L (**Figure 2**). The highest Mg of 0.30 meq/L was recorded for 10 years was not significantly different with 0.21 and 0.19 meq/L for control and 5 years paddy fields, respectively. A high coefficient of variation of 82.0% was recorded for Mg.

The mean Na concentration across all paddy fields was 1.4 meq/L (**Figure 2**). The Na concentration in the 10-years paddy fields (2.52 meq/L) was significantly higher ( $p \leq 0.05$ ) than in the control fields (0.71 meq/L). The Na concentration in the 5-years paddy fields (1.0 meq/L) was not significantly different from either the control or the 10-years fields. The mean magnesium (Mg) concentration across all paddy fields was 0.23 meq/L (**Figure 2**). The highest Mg concentration (0.30 meq/L) was recorded in the 10-year fields, but this was not significantly different from the control (0.21 meq/L) and the 5-years fields (0.19 meq/L). A high coefficient of variation (82.0%) was observed for Mg.

The mean sodium adsorption ratio (SAR) across all paddy fields was 1.76. The highest SAR was recorded in the 10-year fields (2.5) and was significantly higher than the SAR control (1.3), but not significantly different with the 5-years (1.5) fields.

The mean carbon (C) content across all paddy fields was 0.71%. The highest C content (0.85%) was recorded in the 5-years fields and was not significantly different from the 10-years (0.76%) and control (0.53%) fields. The mean nitrogen (N) content across all paddy fields was 0.06%. The highest N content (0.07%) was recorded in the 5-years and 10-years fields, which was not significantly different from the control fields (0.04%). The mean carbon-to-nitrogen (C:N) ratio across all paddy fields was 11.94:1. The highest C:N ratio (12.60:1) was recorded in the control fields and was significantly different from the 10-years fields (10.90), whereas the 5-years fields (12.31) were not significantly different from either the control or the 10-years fields.

### 3.2. Correlations among Some Soil Chemical Properties

**Table 2** shows the correlations among soil texture and chemical properties. Soil pH was positively related with sand and the C:N ratio ( $r = 0.61$ ), and moderately negatively correlated with clay ( $r = -0.68$ ) and total nitrogen (N) ( $r = -0.65$ ). Electrical conductivity (EC) was strongly and positively correlated with sodium (Na) ( $r = 0.98$ ), calcium (Ca) ( $r = 0.93$ ), sodium adsorption ratio (SAR) ( $r = 0.79$ ), and magnesium (Mg) ( $r = 0.73$ ), and negatively correlated with the C:N ratio ( $r = -0.75$ ). The Na proportion showed a significantly high positive correlation with Ca ( $r = 0.92$ ), SAR ( $r = 0.84$ ), and Mg ( $r = 0.69$ ), and a moderate negative correlation with the C:N ratio ( $r = -0.79$ ). The Mg proportion displayed strong and significant positive correlations with Ca ( $r = 0.88$ ). Ca was positively and significantly correlated with SAR ( $r = 0.58$ ), and significantly and negatively correlated with the C:N ratio ( $r = -0.60$ ). SAR was significantly and negatively correlated with the C:N ratio ( $r = -0.85$ ), whereas carbon (C) was significantly and positively corre-

lated with N ( $r = 0.98$ ). The sand proportion was significantly and negatively correlated with silt ( $r = -0.93$ ) and clay ( $r = -0.97$ ), and silt was significantly and positively correlated with clay ( $r = 0.80$ ).

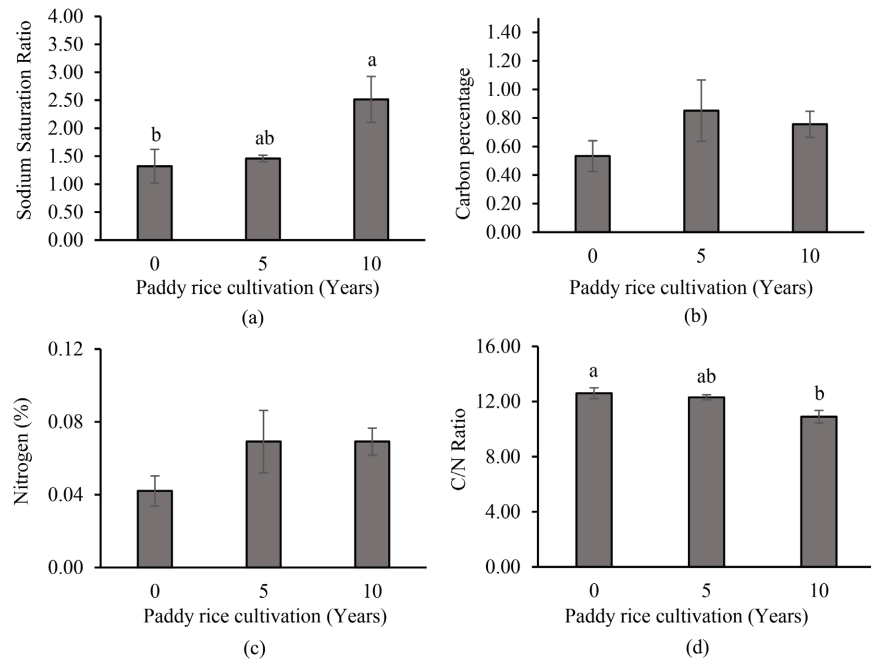
**Table 2.** Pearson's correlations showing pairwise trait associations between chemical properties of paddy fields under t three rice cultivation periods at the Kalimbeza Rice Project, Namibia.

Trait	pH	EC (mS/m)	Na (meq/L)	Mg (meq/L)	Ca (meq/L)	K (meq/L)	SAR	C (%)	N (%)	C:N	Sand (%)	Silt (%)	Clay (%)
pHw	1.000												
EC	-0.481	1.000											
Na	-0.556	0.979 **	1.000										
Mg	-0.172	0.733 **	0.689 *	1.000									
Ca	-0.396	0.932 **	0.923 **	0.876 **	1.000								
K	0.049	-0.116	-0.230	0.300	-0.055	1.000							
SAR	-0.568	0.79 **	0.844 **	0.260	0.578 *	-0.426	1.000						
C	-0.527	-0.048	-0.078	-0.171	-0.129	0.192	-0.072	1.000					
N	-0.645 *	0.108	0.087	-0.092	0.001	0.136	0.102	0.978 **	1.000				
C:N	0.609 *	-0.752 **	-0.786 **	-0.286	-0.594 *	0.338	-0.845 **	0.007	-0.192	1.000			
Sand	0.627 *	-0.361	-0.475	-0.100	-0.360	0.155	-0.473	-0.162	-0.280	0.534	1.000		
Silt	-0.484	0.439	0.529	0.144	0.453	-0.270	0.454	0.126	0.233	-0.507	-0.93 **	1.000	
Clay	-0.675 *	0.275	0.398	0.062	0.265	-0.060	0.446	0.173	0.287	-0.510	-0.966 **	0.804 **	1.000

EC = electrical conductivity; Na = Sodium; Mg = Magnesium; Ca = Calcium; K = Potassium; SAR = Sodium Adsorption Ratio; C = Carbon; N = Nitrogen; C:N = carbon-to-nitrogen ratio; \* significant at  $p \leq 0.05$ ; \*\*significant at  $p \leq 0.01$ .

#### 4. Discussion

Monitoring salinity and sodicity accumulation is important for mitigating negative impacts on rice production in lowland rice paddy fields. The physico-chemical properties showed a relationship with the number of years under cultivation at the Kalimbeza Rice Project. Significant variations ( $p \leq 0.05$ ) were observed in pH (Table 1), sodium (Na), sodium adsorption ratio (SAR), and the carbon-to-nitrogen ratio (C:N ratio) (Figure 2 and Figure 3). The values for EC, Na, and SAR indicated a gradual increase associated with long-term rice cultivation, revealing the need to monitor and adopt soil amendment strategies to avoid salinity and sodicity accumulation. Overall, the soil at the project is sandy loam, with the paddy soil being loamy sand. The soil exhibits favorable characteristics for rice growth, with an electrical conductivity (EC) of less than 4 dS/m and a sodium adsorption ratio (SAR) of less than 13. These values confirm it is neither saline nor sodic, and the study suggests no adverse effects on rice production.



**Figure 3.** Soil chemical analysis results for paddy fields under rice cultivation at the Kalimbeza Rice Project, Namibia. (a) SAR = Sodium Adsorption Ratio, (b) C = Carbon, (c) N = Nitrogen, (d) C:N ratio = Carbon-to-Nitrogen Ratio.

#### Soil texture

Soil texture describes the relative amounts of sand, silt, and clay in a soil sample [23]. These particles are essential physical properties that influence water retention, drainage, aeration, and soil fertility [24]. In the present study, the soil texture of the paddy fields was heterogeneous, consisting of sand (8.3%), clay (8.3%), sandy clay loam (16.7%), sandy loam (16.7%), clay loam (25.0%), and loamy sand (25.0%) (Table 1), revealing the need for varying crop management practices at the project. These results support the study by Abah *et al.* [16], who reported particle size distributions of 62.60% sand, 19.20% clay, and 18.20% silt in paddy fields at the project.

Sandy soils are unsuitable for lowland rice cultivation due to their poor water retention capacity [25] [26]. Lowland rice thrives best in clay or clay loam soils, which are better at holding water and nutrients. The present study revealed that the sand percentage had a significant positive correlation with pH ( $r = 0.63$ ), whereas clay had a significant negative correlation with pH ( $r = -0.68$ ). This suggests that the Zambezi River ideally deposits alluvial sediments and silt as it traverses the floodplain, overlaying the Kalahari sands [19]. Therefore, the soil heterogeneity at the project demands soil amendment and drainage systems to maintain healthy soil.

#### Soil pH

The soil pH in rice paddies is a crucial factor influencing rice crop growth, nutrient accessibility, and overall productivity [27]. The ideal soil pH for rice ranges between 5.5 and 6.5, which is slightly acidic to neutral [28] [29]. Some rice varie-

ties can adapt to a wider pH range, between 4.0 and 7.5, but extreme pH levels affect the growth and yield of sensitive varieties [30] [31]. At the project site, pH ranged between 5.5 and 6.7 (Table 1), indicating varying soil fertility that should be considered when choosing soil amendments and fertilizers. Slightly acidic soils (pH < 5.5) in the project area impact rice growth and production, a common occurrence in many wetland paddy fields [32]. This can lead to aluminum (Al) and iron (Fe) toxicity, as these elements become more soluble and accessible to plants in acidic soils, inhibiting root growth, reducing plant biomass, and disrupting water uptake [33]. Phosphorus (P) availability is also reduced due to fixation by Fe and Al [34]. Thus, the project should focus on applying lime (calcium carbonate) and incorporating organic matter to enhance soil structure and buffering capacity. Selecting acid-tolerant rice varieties should also be considered to mitigate the effects of low soil pH.

#### *Soil electrical conductivity (EC)*

Soil electrical conductivity (EC) is a key factor in lowland rice cultivation, as it measures the level of soluble salts in the soil, which influences crop growth [35]. In rice farming, EC serves as a crucial measure of soil salinity, significantly affecting plant health and productivity [36]. In the present study, the mean EC of 28.3 mS/m falls within the ideal range for most rice varieties, which is between 20.0 and 150 mS/m. However, the control and 5-year paddies had low EC (<20 mS/m), indicating low nutrient availability, which can lead to nutrient deficiencies that affect plant growth [37]. This suggests that the project may need to use fertilizers during production to increase the EC to between 20.0 and 150.0 mS/m to ensure adequate nutrient availability without causing osmotic stress. However, fertilizer application should be monitored to avoid high EC (>150 mS/m), which signals saline soil conditions. High EC can cause osmotic stress, reducing water uptake by plants. Furthermore, elevated EC can signify ion toxicity caused by the buildup of sodium ions (Na<sup>+</sup>) and chloride ions (Cl<sup>-</sup>), which disrupts nutrient balance and reduces the availability of essential nutrients like calcium (Ca), potassium (K), and magnesium (Mg) for plants [38].

#### *Sodium (Na)*

The optimal sodium ion (Na<sup>+</sup>) concentration in paddy fields varies based on rice variety, salinity tolerance, soil texture, and water conditions [39] [40]. Generally, rice is considered moderately sensitive to salinity [41]. High Na<sup>+</sup> levels can negatively affect rice growth by disrupting water uptake, nutrient balance, and overall plant health [42]. The threshold Na<sup>+</sup> concentration in irrigation water or soil solution should ideally remain below 30 mS/m to avoid yield reduction in most rice varieties [43]. Rice begins to experience stress at EC levels of about 40 mS/m or 920 mg/L sodium chloride in water [44]. In the present study, variations in Na<sup>+</sup> concentrations were strongly associated with EC, Mg, Ca, SAR, and the C:N ratio. This reveals that the paddy fields under cultivation for 10 years have accumulated Na<sup>+</sup> compare to control. Therefore, there is a need to monitor Na<sup>+</sup> levels and regularly flush paddy fields with fresh water to reduce excess Na<sup>+</sup>. More-

over, the application of calcium sulphate (gypsum) can displace  $\text{Na}^+$  from soil colloids, improving soil structure and reducing  $\text{Na}^+$  toxicity. Additionally, selecting salt-tolerant varieties is an important strategy to maintain productivity.

#### *Magnesium (Mg)*

Magnesium (Mg) is an essential plant nutrient that plays a vital role in crop growth, including rice, particularly in wetland conditions [45]. The interaction of Mg with salinity, sodicity, and wetland conditions is important for understanding its availability and the impact of long-term rice cultivation [46] [47]. In saline conditions, high concentrations of  $\text{Na}^+$  and  $\text{Cl}^-$  ions compete with  $\text{Mg}^{2+}$  for uptake by rice roots [38]. In the present study, the mean Mg concentration of 0.23 meq/L, with a highest value of 0.30 meq/L and a lowest of 0.19 meq/L, is lower than the critical level of 1.0 - 2.0 cmol (+)/kg soil. Levels below 1.0 cmol (+)/kg are considered deficient and may negatively affect rice growth [48]. Although soil samples from the Kalimbeza Rice Project showed very low Mg levels, these values may reflect methodological differences rather than true deficiencies, as critical Mg thresholds vary depending on soil type, crop species, and the analytical method used [16]. Moreover, while visual Mg deficiency symptoms in rice are typically observed when leaf Mg content falls below 0.1% of dry weight, irrigated systems like Kalimbeza often receive sufficient Mg through irrigation water, reducing the likelihood of widespread deficiency affecting yield [49].

#### *Calcium (Ca)*

Optimal calcium (Ca) levels play a critical role in soil structure and plant health, particularly in balancing soil pH and aiding nutrient absorption [50]. The ideal Ca range for rice paddy fields is between 200 and 400 ppm [51]. Ca helps reduce soil acidity, which is common in flooded paddy fields [52]. In the present study, the mean pH is 4.9, which is slightly acidic, and the mean Ca concentration was 0.8 meq/L, indicating the need for fertilizer strategies involving the application of agricultural lime (calcium carbonate), gypsum, and organic amendments. Incorporating organic matter such as compost, farmyard manure, and biochar can help maintain nutrient balance [53].

#### *Potassium (K)*

The ideal potassium (K) levels in paddy fields depend on soil type, climate, and the specific growth stage of the rice crop [54]. Potassium is essential for various physiological functions, including water regulation, enzyme activation, and disease resistance [55]. The ideal K levels for most paddy fields are between 110 and 160 ppm of exchangeable K, which is considered sufficient [56]. In the present study, the mean K concentration of 0.08 meq/L reveals the need for K application during production. The observed low K levels, relative to commonly accepted critical thresholds for rice cultivation, may partly reflect methodological differences in K extraction from soils with specific clay mineralogy. Therefore, further studies focusing on K levels are recommended. Moreover, the recommended K fertilizer rate of between 40 and 60 kg  $\text{K}_2\text{O}$ /ha is needed for healthy rice plants that can resist pests, diseases, and environmental stresses [54].

#### *Sodium Adsorption Ratio (SAR)*

The Sodium Adsorption Ratio (SAR) is an important indicator of soil sodicity, which affects water infiltration, soil permeability, and overall soil structure [57] [58]. Maintaining an appropriate SAR is critical in rice paddy fields since rice is grown in flooded conditions that can exacerbate sodicity issues. The ideal SAR for paddy fields is <13, indicating low Na<sup>+</sup> levels relative to Ca<sup>2+</sup> and Mg<sup>2+</sup>, which is favourable for soil health and crop growth [43]. In the present study, the highest SAR was 2.5, which is low and may indicate low nutrient content. Thus, there is a need for fertilizers and soil conditioning, involving the application of agricultural lime, gypsum, and organic amendments, to improve fertility without leading to salinity and sodicity.

#### *Carbon (C)*

Soil carbon (C) percentage plays a vital role in rice growth and production, especially in saline and sodic soils [59]. The ideal soil organic carbon (SOC) percentage for paddy fields can vary depending on several factors, including soil type, climate, and specific rice variety [60]. Recommended SOC is at least 3% to >5% to improve water holding capacity, nutrient availability, and overall soil structure [61]. In the current study, the 0.53%, 0.85%, and 0.76% carbon in the control, 5-year, and 10-year paddy fields, respectively, show lower levels. This is closely linked to soil health, influencing key factors such as structure, aeration, and microbial activity. Therefore, there is a need to increase organic carbon levels to enhance nutrient availability and water retention to promote healthier rice growth. Additionally, soil carbon sequestration helps mitigate the adverse effects of salinity and sodicity by improving soil buffering capacity and cation exchange capacity (CEC) [62]. Incorporating organic amendments such as compost, biochar, and green manure can further enhance soil structure, reduce salinity stress, and improve water retention. Overall, increasing organic carbon levels contributes to better soil quality, resilience against stress conditions, and higher rice yields.

#### *Nitrogen (N)*

Nitrogen (N) is a crucial nutrient for rice growth, significantly influenced by soil salinity and sodicity [63]. In the present study, N percentages were 0.04% for the control and 0.07% for both the 5-year and 10-year paddy fields. The higher level of N in the control compared with the 5-year and 10-year paddy fields suggests residual N fertilizer in the soil. Rice requires optimal nitrogen levels for tillering, leaf expansion, and grain filling [64]. However, high soil salinity and sodicity can reduce nitrogen uptake efficiency [65]. Under moderate nitrogen application, rice plants develop better root and shoot systems, even in stressed conditions, improving overall biomass [66]. Moderate to high nitrogen application (100 - 150 kg N/ha) can partially mitigate salinity stress by promoting plant vigor, chlorophyll synthesis, and enzyme activity [67].

#### *Carbon-to-Nitrogen (C:N) ratio*

The carbon-to-nitrogen (C:N) ratio is a key indicator of soil health, influencing organic matter breakdown and nitrogen availability for rice cultivation [68]. This

ratio, representing the balance between organic carbon and total nitrogen, is particularly important in saline and sodic soils, where it significantly affects soil structure, microbial activity, and nutrient cycling, ultimately impacting rice growth and yield [59]. A low C:N ratio (<10:1) suggests abundant nitrogen but can result in rapid decomposition and nitrogen loss [69]. Conversely, a high C:N ratio (>25:1) slows decomposition, potentially causing nitrogen deficiency due to immobilization [70]. Ideally, productive rice soils maintain a C:N ratio between 12:1 and 20:1. In this study, the control and 5-year paddies exhibited higher C:N ratios (12.6:1 and 12.3:1, respectively) compared to the 10-year paddies (10.9:1), suggesting an influence of long-term management practices. The C:N ratio showed strong correlations with pH, electrical conductivity (EC), sodium (Na), calcium (Ca), sodium adsorption ratio (SAR), and silt and clay content, highlighting its relevance to the study of soil salinity and sodicity (Table 2). Salinity can hinder microbial activity and organic matter decomposition, thus affecting the C:N ratio [62]. While a low C:N ratio (excess N) can increase osmotic stress due to excessive plant growth, a high C:N ratio (limited nitrogen) can slow decomposition and nitrogen mineralization, leading to nitrogen deficiency and poor rice growth. Maintaining a balanced C:N ratio (12:1 to 20:1) promotes optimal organic matter decomposition, microbial activity, and nitrogen retention, thereby mitigating the negative impacts of salinity stress.

## 5. Conclusion

This study underscores the progressive accumulation of salinity and sodicity in the Kalimbeza Rice Project fields, particularly in relation to the duration of rice cultivation. Significant increases in soil pH, sodium (Na), sodium adsorption ratio (SAR), and the carbon-to-nitrogen (C:N) ratio were observed, with the highest Na concentration (2.52 meq/L) and SAR value (2.5) recorded in fields cultivated continuously for 10 years. These findings indicate that prolonged rice cultivation without appropriate soil management contributes to the gradual degradation of soil quality through increased salinity and sodicity. The association between extended cultivation periods and elevated Na and SAR levels highlights the urgent need for the adoption of sustainable soil management practices. To preserve the long-term productivity of lowland rice systems, regular monitoring of salinity and sodicity should be institutionalized. In addition, the application of soil amendments such as agricultural lime, gypsum, and organic matter is recommended to improve soil structure, enhance nutrient availability, and mitigate sodium-induced degradation. Future research should also investigate the potential of crop rotation and improved water management strategies to promote sustainable soil health in irrigated rice ecosystems.

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### Data Availability Statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

### Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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