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Impact of soil salinity on nutrient acquisition and physiological performance of groundnut (*Arachis hypogaea* L.)

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Abstract

Salt-affected soils now cover an estimated 1.1 billion hectares globally, and this area is expanding by roughly 1.5 million hectares each year due to irrigation-induced salinization and rising water tables. This research examined the effect of five soil salinity levels (0, 2, 4, 6, and 8 dS/m ECe) on nutrient uptake, physiological responses, and pod yield of groundnut (*Arachis hypogaea* L.) variety ICGV-SM 99568 in a pot experiment at the University of Nairobi, Kenya, during 2022-2023. Salinity was imposed using NaCl-amended irrigation water from 20 days after sowing. Results showed progressive declines in nitrogen (−56.0%), phosphorus (−60.9%), and potassium (−54.6%) uptake as salinity increased from 0 to 8 dS/m. Leaf relative water content fell from 84.3% (control) to 61.7% (8 dS/m), while proline accumulation increased 4.6-fold. Pod yield declined by 18.4% at 2 dS/m and 56.1% at 8 dS/m. Chlorophyll content and stomatal conductance were significantly reduced above 4 dS/m. These findings indicate that groundnut is moderately salt-sensitive, with a salinity threshold near 2 dS/m, and that nutrient imbalance particularly K deficiency driven by Na^+/K^+ antagonism is a primary mechanism of yield loss under saline conditions.

Keywords: Soil salinity, groundnut, nutrient uptake, sodium-potassium antagonism, proline, physiological responses, pod yield, salt stress, *Arachis hypogaea*, osmotic adjustment

Introduction

Nearly 7% of Earth's cultivated land is salt-affected, and that figure is climbing ^[1]. In sub-Saharan Africa, secondary salinization from poor irrigation management threatens to remove productive farmland from cultivation faster than new land can be brought under the plough ^[2]. Groundnut, a crop valued for both oil and protein in East African smallholder systems, is classified as moderately sensitive to salinity, but the precise threshold and the physiological mechanisms driving yield loss remain poorly characterized for African genotypes grown under local conditions ^[3].

Salinity harms crops through two distinct but overlapping pathways. The osmotic effect reduces water uptake by lowering the soil water potential, essentially creating physiological drought even when the soil is moist ^[4]. The ionic effect arises when Na^+ and Cl^- accumulate to toxic levels in plant tissues, disrupting enzyme function and displacing essential nutrients like K^+ , Ca^{2+} , and NO_3^- from uptake sites ^[5]. Understanding which pathway dominates in groundnut and at what salinity level is essential for designing effective management strategies, whether through soil amendment, salt-tolerant variety selection, or nutrient supplementation ^[6, 7].

Theoretical background

The osmotic phase of salt stress begins immediately upon exposure, reducing leaf expansion and stomatal conductance within hours. The ionic phase develops over days to weeks as Na^+ accumulates in older leaves, eventually causing necrosis ^[4]. In legumes, a third dimension of damage exists: Rhizobium activity in root nodules is highly sensitive to salt, and biological nitrogen fixation can decline by 50-70% at moderate salinity levels (4-6 dS/m), reducing both N supply and overall plant vigour ^[8]. Potassium's role is central because Na^+ competes directly with K^+ for transport proteins (HKT and HAK families) in root cell membranes.

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When the Na⁺/K⁺ ratio in tissues exceeds approximately 1.0, enzymatic processes dependent on K⁺ as a cofactor including protein synthesis and osmotic regulation are impaired [9]. Proline accumulation serves as a biomarker of osmotic stress: plants synthesize this amino acid to lower cellular osmotic potential and stabilize proteins under dehydration conditions [10].

Materials and Methods

Materials

A pot experiment was conducted from October 2022 to March 2023 in the screen house of the Department of Agronomy, University of Nairobi, Kenya (1°16'S, 36°49'E, elevation 1,661 m). Plastic pots (30 cm diameter, 25 cm depth) were filled with 12 kg of non-saline sandy loam soil (ECe 0.4 dS/m, pH 6.2, OC 1.3%). Groundnut variety ICGV-SM 99568 (a Virginia bunch type released by ICRISAT for East Africa) was sown at 4 seeds per pot, thinned to 2 seedlings at 10 DAS. Five salinity treatments (0, 2, 4, 6, and 8 dS/m) were imposed by irrigating

with NaCl solutions of corresponding electrical conductivity from 20 DAS onward. Pots were arranged in a completely randomized design with five replications, giving 25 experimental units [11].

Methods

Physiological measurements were taken at 60 DAS (flowering): leaf Relative Water Content (RWC), chlorophyll content (SPAD-502), stomatal conductance (SC-1 porometer), and free proline content (ninhydrin method). At harvest (130 DAS), plants were separated into shoots, roots, and pods. Nutrient analysis (N by Kjeldahl, P by vanadomolybdate, K by flame photometry) was performed on oven-dried shoot tissue. Pod yield was recorded per pot and converted to kg/ha equivalent. The Na⁺/K⁺ ratio was calculated from tissue Na and K concentrations. Data were analysed by one-way ANOVA with Tukey's HSD at *p*<0.05 in R version 4.2 [12, 13].

Results

Table 1: Nutrient uptake and Na⁺/K⁺ ratio in groundnut shoots under varying salinity levels

ECe (dS/m)	N uptake (kg/ha)	P Uptake (kg/ha)	K uptake (kg/ha)	Shoot na (mg/g)	Na ⁺ /K ⁺ ratio
0 (Control)	42.3a	8.7a	36.8a	1.8e	0.14e
2	38.7b	7.9ab	33.1b	4.3d	0.37d
4	31.4c	6.3bc	27.6c	8.7c	0.89c
6	24.8d	4.8cd	21.3d	14.2b	1.41b
8	18.6e	3.4d	16.7e	19.6a	2.18a

Means with different letters within a column differ at *p*<0.05 (Tukey's HSD).

Nutrient uptake declined progressively with increasing salinity. At 8 dS/m, N, P, and K uptake fell by 56.0%, 60.9%, and 54.6%, respectively. The Na⁺/K⁺ ratio exceeded 1.0 at 6 dS/m, a

threshold widely associated with severe ionic toxicity in sensitive crops. Tissue sodium increased 10.9-fold from control to 8 dS/m.

Table 2: Physiological responses and pod yield of groundnut under salinity stress

ECe (dS/m)	RWC (%)	SPAD value	Stomatal cond. (mmol/m ² /s)	Proline (μmol/g FW)	Pod yield (kg/ha)
0	84.3a	41.2a	286a	3.8e	2,347a
2	79.6b	38.7ab	241b	6.4d	1,914b
4	72.1c	34.3bc	187c	9.8c	1,468c
6	66.8d	29.1cd	134d	13.7b	1,156d
8	61.7e	24.6d	97e	17.5a	1,031e

RWC = relative water content; FW = fresh weight. Means with different letters within a column differ at *p*<0.05

Pod yield declined from 2,347 kg/ha (control) to 1,031 kg/ha at 8 dS/m a 56.1% reduction. Proline accumulation increased 4.6-fold, confirming active osmotic adjustment. Stomatal conductance dropped by 66.1% at 8 dS/m, which would have severely restricted CO₂ assimilation and photosynthetic output.

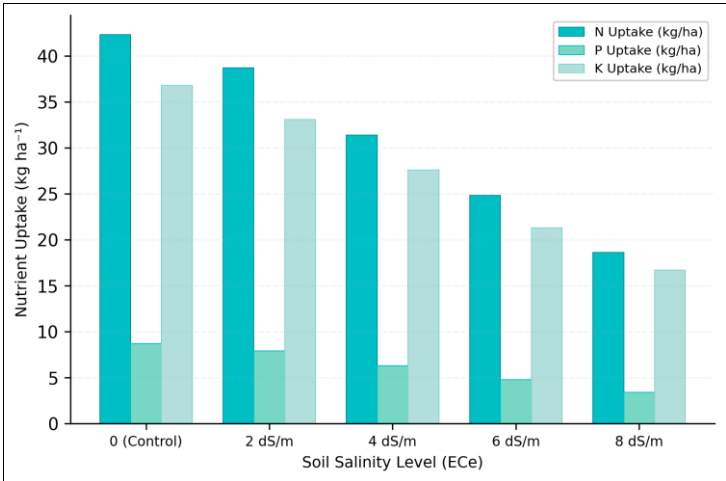


Fig 1: Nitrogen, phosphorus, and potassium uptake in groundnut shoots across five soil salinity levels. All three macronutrients declined progressively with increasing ECe

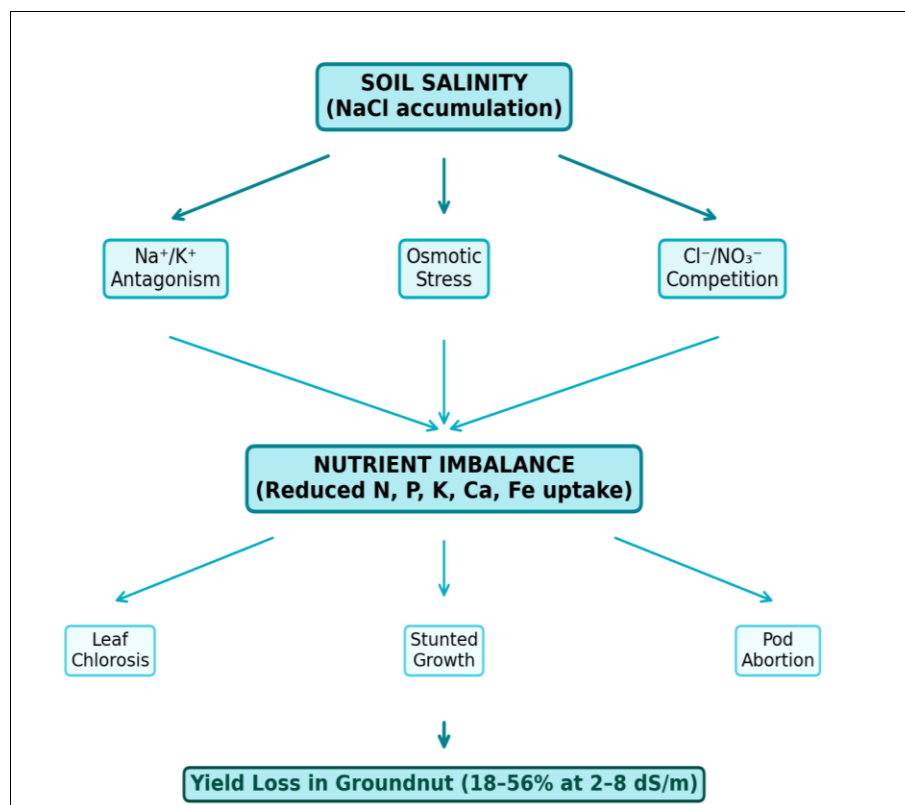


Fig 2: Pathway diagram illustrating how soil salinity disrupts nutrient balance in groundnut through Na^+/K^+ antagonism, osmotic stress, and $\text{Cl}^-/\text{NO}_3^-$ competition, leading to visible disorders and yield loss

Comprehensive interpretation

THE data establish a clear salinity threshold near 2 dS/m for groundnut, beyond which yield losses become economically significant (>18%). The Na^+/K^+ ratio is a reliable indicator of ionic stress severity, crossing the critical 1.0 threshold at 6 dS/m the same level where stomatal conductance dropped below 50% of the control, suggesting coordinated osmotic and ionic damage.

Discussion

The 56% yield loss at 8 dS/m is consistent with findings by Singh *et al.* [3], who reported 50-60% yield reductions in Indian groundnut varieties at similar salinity. The 4.6-fold proline increase indicates active osmotic adjustment, though evidently insufficient to maintain yield at higher stress levels. The sharp decline in P uptake (−60.9%) may reflect precipitation of calcium phosphates in saline soil, reducing P availability independent of root uptake capacity [14].

From a management perspective, the results suggest that K supplementation could partially offset Na^+ -induced K deficiency. Foliar KNO_3 application at 2% concentration during flowering has shown promise in other legumes under salt stress [15]. Soil amendment with gypsum (CaSO_4) to displace Na^+ from exchange sites is another practical option for mildly saline soils (2-4 dS/m) where groundnut cultivation remains feasible [16, 17].

Performance evaluation

Linear regression of yield against salinity gave a strong fit ($R^2 = 0.97$, $p < 0.001$), with each 1 dS/m increase in ECE reducing pod yield by approximately 164 kg/ha. The salinity-yield relationship followed the Maas-Hoffman threshold-slope model: $Y = 100 - b(\text{ECE} - a)$, where a (threshold) = 1.8 dS/m and b (slope) = 7.6% per dS/m. This positions ICGV-SM 99568 as moderately sensitive, with tolerance slightly above the generic groundnut threshold of 1.5 dS/m reported by Maas and Hoffman

[18]. The proline-salinity relationship was also linear ($R^2 = 0.98$), confirming proline as a reliable biochemical marker for salt stress quantification in groundnut screening programmes [19].

Conclusion

Groundnut variety ICGV-SM 99568 exhibited a salinity threshold of approximately 2 dS/m, with progressive declines in nutrient uptake, physiological function, and pod yield at higher salinity. The Na^+/K^+ ratio exceeding 1.0 at 6 dS/m marked the onset of severe ionic toxicity. These results inform site suitability assessment for groundnut cultivation in salt-affected areas of East Africa and highlight K supplementation and gypsum amendment as potential mitigation strategies for mildly saline soils.

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