



Effects of Mineral and Biological Nitrogen on Yields and Nodulation of Two Groundnut (*Arachis hypogaea* L.) Varieties in the Semiarid Region of Sudan

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Abstract

Legumes are widely recognized for improving soil fertility through atmospheric nitrogen fixation. The present study investigates the cultivation of groundnut (*Arachis hypogaea* L.) in the semiarid urban marginal lands of Khartoum, Sudan. A field study was conducted over two seasons to examine the effects of *rhizobium* inoculation (RI), mineral nitrogen (MN, 43 kg N ha⁻¹) fertilizer and a control (C, no addition) on nodulation, yield and its components. Two varieties, *Sodari* and *Kiriz*, were tested in a randomized complete block design (RCBD) with three replicates. The data collected include the number of nodules and the dry weights of nodules, shoots, and roots at 45, 75, and 105 days after sowing (DAS). Data on yield and yield components of seeds and pods were obtained at harvest. The nitrogen (N), phosphorus (P), and potassium (K) contents of the plant samples were analysed in the second season. The dry weights of nodule, shoot, and root of inoculated plants is comparable to that of N-fertilized plants. In the second season, MN increased the number of nodules by 58.6%, 28.4%, and 40.8% compared to RI at 45, 75, and 105 DAS, respectively. In the second season, *Kiriz* significantly outperformed *Sodari* in most parameters. *Kiriz* variety outperformed *Sodari* in pod, seed, and 100-seed weights by 128%, 88%, and 80%, respectively, over the two seasons. Application of RI significantly increased plant phosphorus uptake by 29% compared to C and by 109.5% compared to MN treatments.

Keywords Semiarid · Sodic · Groundnut · *Rhizobium* · Khartoum

1 Introduction

Groundnut (*Arachis hypogaea* L.) is one of the most significant cash crops in Sudan. It comprises 35% of the cultivated area dedicated to cash crops (UNDP 2014) and contributes to 14% of global production (Njoki et al. 2024). Sudan is the second largest producer of groundnut in Africa, after Nigeria, with an average production of 2.04 tons (FAO 2001; Njoki et al. 2024). In 2022, groundnuts were the second most exported crop in Sudan after sesame, generating an estimated revenue of \$423 Million (FAO 2023).

Darfur and Kordofan states account for 60–70% of the country's production, and the remaining is from Gezira, Rahad and New Halfa schemes (UNDP 2014). The continuous conflicts in Darfur and Kordofan states along with drought and rain fluctuations significantly reduce groundnut production. The average production in the rainfed sector dropped from 0.85 t ha⁻¹ in 2022/23 to 0.43 t ha⁻¹ in 2023/24. Whereas, in the irrigated sector, the yield increased from 2.01 in 2022/23 to 2.67 in 2023/24 t ha⁻¹ (FAO 2024).

Urban agriculture has been practiced on fertile lands along the banks of the River Nile in Khartoum city (Abdalla 2018). Fodder, fast-ripening fruits, and leafy vegetables are produced, taking advantage of their proximity to city markets (Abdalla 2018). Recently, urbanization and population growth have changed the use of some fertile lands near cities from agriculture to settlements and recreational areas (Mcgranahan et al. 2020; Schumacher et al. 2009). Consequently, agricultural activities have shifted to marginal lands outside Khartoum city

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¹ ton hectare.⁻¹.

(Mcgranahan et al. 2020; Schumacher et al. 2009). The city of Khartoum, lies within the semiarid climatic zone, which favours the occurrence of saline–sodic soils in Khartoum state (Ali and Szalay 2019; Elagib and Mansell 2000; El–karouri 1979). Low soil fertility, salinity and sodicity are among the production constraints that hamper agricultural activities on the outskirts of the city (El–karouri 1979). The expansion of agriculture in these lands highlights the need to develop sustainable and ecologically safe methods to increase productivity.

The soil in south of Khartoum away from the River Nile banks is saline–sodic, which is the abiotic stress that limits crop growth and production (El–karouri 1979; Mohamed et al. 2015). Previous studies on sorghum, alfalfa, onion, radish, cucumber, and fodder revealed significant ameliorative effects of farmyard manure, gypsum, and green manure on crop yield (El–karouri 1979). Intensive cultivation depletes soil nutrients; moreover, the continuous application of chicken manure may increase the soil pH (Duruigbo et al. 2007). Reclamation of sodic soil with gypsum improves its physical and chemical properties and increases germination and root establishment (Aydemir and Sünger 2011). Leguminous plants improve soil quality by enriching it with nitrogen (N) through the symbiotic N fixation process. Legumes contribute by solubilizing phosphate ions bound to calcium and by increasing soil organic matter content. These contributions offer a sustainable alternative to chemical fertilizers, which can reduce pollution and enhance climate resilience (Abd-Alla et al. 2023). Moreover, legumes stimulate the dissolution of calcium carbonate (CaCO_3) in calcareous soils, releasing Ca^{+2} ions that replace the adsorbed sodium (Na^+). This process reduces the exchangeable sodium percentage (ESP) in the soil (Aydemir and Sünger 2011; Yousif et al. 2019).

Farmers in Sudan generally do not inoculate groundnuts with *rhizobium* bacteria or use N–fertilizer. Tekulu et al. (2020) reported that application of 15 kg N ha^{-1} increased groundnut total biomass yield by 22.5%. The effect of N on legume *rhizobium* symbiosis depends on the time, rate, and N form, in addition to the specific legume species (Abd-Alla et al. 2023).

Adopting profitable legume crops as alternate crops in cropping systems will reduce the need for chemical amendments, sustain soil health and increase productivity. However, little is known about groundnut tolerance and symbiotic activity in saline–sodic soils in Sudan (Elsheikh 1998). The study was conducted to fill the research gap in groundnut growth in semiarid soils and to promote groundnut as an alternative crop in cropping systems. The specific objectives were to perform a comparative analysis of nodule formation, yield, and nutrient uptake, in two groundnut varieties, evaluating their responses to both mineral and biological N–fertilizers.

2 Materials and methods

2.1 Site description

The study was conducted at the demonstration plot of Soba Research Station, Agricultural Research Corporation (ARC), south of Khartoum. The area lies within the semiarid climatic zone, with a mean monthly temperature ranging from 22.1 to 33.7°C and a mean annual rainfall < 200 mm (Elagib and Mansell 2000). The maximum daily temperature average is 29–32°C in March–May, 31–34°C in June–October, and 23–26°C in November–February (Elagib and Mansell 2000). The soil is classified as *Aridisols* from alluvial material derived from the Ethiopian highlands and is labelled calcareous alkaline soil (El–karouri 1979). The activities practiced includes the cultivation of fodder, vegetables, and fruit trees and the raising of livestock. The dominant crop is the salt–resistant fodder crop Sudan grass (*Abu Sbeen*), which is cultivated three times a year and supplemented with chicken manure. The primary source of irrigation water is the Blue Nile and, to a lesser extent, groundwater well (El–karouri 1979).

2.2 Soil sampling and analysis

Six soil samples were taken from the plot corners and the centre at depths of 0–0.25 and 0.25–0.50 m. The samples were air–dried and screened through a 2–mm mesh. The samples were subsequently analysed for soil pH, electrical conductivity (EC), oxidizable organic carbon (%), organic matter (OM), carbon to nitrogen (C/N) ratio, $\text{CaCO}_3\%$, bulk density (BD), particle size distribution, cation exchange capacity (CEC), exchangeable sodium (exch. Na), ESP, N, available phosphorus (Av. P) and exchangeable potassium (exch. K). The pH of a saturated soil paste was measured using standard glass/calomel electrodes in McLean (1982), and the EC of the soil paste extract was determined at 25 °C by a conductivity meter (Rhoades 1982). Oxidizable organic carbon (%) was estimated by dichromate oxidation and titration with ferrous ammonium sulphate (Walkley and Black, 1934). Total organic carbon (TOC) was calculated using a recovery factor of 1.334, and OM was determined using a conversion factor of 1.724 from TOC. The C/N ratio extracted from the TOC and N content. The $\text{CaCO}_3\%$ was estimated following the simple titrimetric procedure (Loeppert and Suarez 1996). The BD was determined using the procedure described by Blake and Hartge (1986). The soil particle size was measured using the pipette method (Day 1965), and textural classes were defined according to the USDA triangle system. The CEC and exchangeable Na were analysed using the method

of Bower et al. (1952), While ESP was calculated, from the results of CEC and exch. Na. The total N was determined by the Kjeldahl method (Bremner and Mulvaney 1982), the soil Av. P was determined according to the sodium bicarbonate procedure (Olsen et al. 1982), and exch. K was measured by a flame photometer.

2.3 Experimental design and field materials

Two-season experiments were conducted to study the response of two groundnut varieties (*Sodari* and *Kiriz*) to mineral nitrogen (MN, urea–46% N), *rhizobium* inoculum (RI) and the control (C, no addition). *Sodari* is a short-maturity variety of 90–120 days from the rainfed sector, and *Kiriz* is a medium-maturity variety of 120–150 days from the irrigated sector. The experiment was arranged in a randomized complete block design (RCBD) with three replicates. The plot size is 12 m² (3m × 4 m), with planting spacing of 0.6m × 0.2m. The seeds (2 seed per hole) were sown on 12th of June 2014 for the first season and on 25th of June 2015 for the second season. The seeds were soaked in aqueous media, dried for 15–20 min under shade, coated with RI and left for 10 min before sowing. The aqueous solution of gum Arabic (50% weight/volume) was used to adhere the inoculum to the seeds (European patent application 1998). The inoculum was obtained from the biofertilization department, Environment and Natural Resources Research Institute (ENRRI) of the National Centre for Research, Khartoum, Sudan. The inoculum is a commercial strain (ENRRI *Bradyrhizobium* sp.), locally isolated from various sites of Sudan (Ahmed et al. 2007). Urea was applied to the respective treatments three weeks after sowing, as recommended, at a rate of 43 kg N ha⁻¹ (95 kg Urea ha⁻¹, FAO 2006). The crop is irrigated every 10 days, and weeding is performed when needed.

2.4 Measurements

Data collected on yield and yield components were; number of pods/plant, pod dry yield (DY)/plant (g), total pod DY (kg ha⁻¹), number of seeds/plant, seed DY/plant (g), total seed DY (kg ha⁻¹), and 100-seed weight (g). Pod and seed yield data were reported based on dry weight. The samples were air-dried until they reached a constant weight. The data were extracted as an average of five plants per plot, while the yield of seeds and pods was taken from a net area of (1m²) and the total yields (kg ha⁻¹) were estimated. The weight of 100-seeds was determined by counting and weighing 100 seeds from each plot. Data on the number of nodules/plants, as well as the dry weights of nodules, shoots, and roots (g), were averaged from five plants per plot, three times during the experimental period, 45, 75, and 105 days after sowing (DAS). The collected fresh nodule, root and shoot samples were dried in an oven at 60 °C for 48 h, and the dry weights

(g) were determined with an electronic balance with 0.01(g) sensitivity. After the harvest of the second season, samples from the whole plant tissue per plot were analysed for their N, P, and K contents (g kg⁻¹). Prior to the analysis, samples were cleaned (dry-wiping), oven dried (75 °C for 24 h) and grinded. The total N content was determined by the Kjeldahl method (Bremner and Mulvaney 1982), and the P and K contents were determined by dry-ash method. The total P concentration was measured with a spectrophotometer, and the K concentration was measured with a flame photometer.

2.5 Statistical analysis

The data from the two seasons were statistically analysed using Statistix Analytical Software Version 10. A two-way analysis of variance (ANOVA) was carried out to determine the main effects of fertilizers, varieties, and their interactions. The means were compared using least significant difference (LSD) tests at the $p < 0.05$ level of probability, with seasons considered as a fixed factor (Gelman 2005).

3 Results and discussion

3.1 Soil status

The soil at the experimental site is alkaline, calcareous ($\text{CaCO}_3 > 50 \text{ g kg}^{-1}$), slightly saline, sodic, and low in OM, N, P, and K (Table 1). The OM and CaCO_3 content are greater in the topsoil (0–0.25 m) than in the subsurface layer (0.25–0.50 m). In contrast, the CEC is 26 cmol kg⁻¹ in the topsoil, increases to 35 cmol kg⁻¹ in the subsurface. The soil texture is clay loam at both sampling depths.

3.2 Nodule numbers

In the first season, treatments and variety has no significant effect on nodule number throughout the growing season (Table 2). However, at 45 DAS, *Kiriz* variety received urea has significantly more nodule than all treatments except in *Sodari* variety treated with urea. After 105 days, in both varieties, nodules number significantly affected by inoculation or application of urea. In the second season treatments and variety significantly affected nodules number (Table 2). In the second season, *Kiriz* produced significantly greater numbers of nodules (Table 2). Application of mineral N increased indigenous strain root nodules number by 190% at 75 DAS and 46.6% at 105 DAS. In both season, variety *Kiriz* is superior to *Sodari* (Table 2).

The experiment was conducted in clay soil, this is likely why *Kiriz* is superior to *Sodari*. The variety *Kiriz* is recommended to the irrigated clay site in Gezira and River Nile states (FAO 2012 and 2022; Mohamad et al. 2018).

Table 1 Descriptive statistics for some soil properties at the experimental site ($n=6$)

Parameter	0–0.25 m		0.25–0.50 m	
	Mean $\pm$ SD	Min. – Max	Mean $\pm$ SD	Min. – Max
pH	8.02 $\pm$ 0.117	7.9–8.2	8.03 $\pm$ 0.175	7.8–8.3
EC (dS m^{-1})	0.97 $\pm$ 0.509	0.3–1.8	1.10 $\pm$ 0.822	0.5–2.7
OC (g kg^{-1})	5.8 $\pm$ 2.21	3.9–9.98	4.7 $\pm$ 2.06	1.09–6.86
OM (g kg^{-1})	10.0 $\pm$ 3.81	6.7–17.2	8.1 $\pm$ 3.56	1.9–11.8
C/N	13.2 $\pm$ 4.54	10–22	12.3 $\pm$ 6.95	02–22
CaCO ₃ (g kg^{-1})	68.0 $\pm$ 24.95	36–92	55.3 $\pm$ 22.51	24–94
ESP	11.0 $\pm$ 2.00	09–14	10.7 $\pm$ 2.34	08–14
Exch. Na (g kg^{-1})	0.8 $\pm$ 0.13	0.64–0.97	0.7 $\pm$ 0.08	0.61–0.81
CEC (cmol kg^{-1})	30.5 $\pm$ 2.66	26–34	29.7 $\pm$ 4.08	24–35
N (g kg^{-1})	1.19 $\pm$ 1.867	0.35–5.0	1.17 $\pm$ 1.880	0.25–5.0
Av. P (g kg^{-1})	0.01 $\pm$ 0.002	0.005–0.010	0.01 $\pm$ 0.001	0.006–0.009
Exch. K (g kg^{-1})	0.07 $\pm$ 0.026	0.04–0.11	0.06 $\pm$ 0.016	0.04–0.08
BD (g cm^{-3})	1.7 $\pm$ 0.06	1.65–1.81	1.9 $\pm$ 0.09	1.74–1.96
Clay (%)	30.5 $\pm$ 2.59	26–33	29.5 $\pm$ 3.15	25–34
Silt (%)	32.5 $\pm$ 6.72	27–45	35.2 $\pm$ 3.49	30–40
Sand (%)	37.0 $\pm$ 6.42	25–43	37.0 $\pm$ 1.67	35–40

SD = standard deviation, min. = minimum, max. = maximum

On the other hand, *Sodari* is recommended to sandy soils in the rainfed areas in western Sudan (FAO 2012 and 2022). Asante et al. (2020) reported that the response of legume crops to rhizobia is specific to variety, which justifies why *Kiriz* is highly responsive to *rhizobium* inoculation. However, the formation of nodules in both varieties under control conditions indicates the presence of indigenous rhizobia in the soil. In Sudan, soils are inhabited by cowpea *rhizobium* strains associated with groundnuts (Hadad et al. 1982).

3.3 Nodule dry weight

In the first season, neither the treatments nor the varieties have a significant difference on nodule dry weight (Table 3). In the second season, the difference between the varieties is significant only at 75 DAS by 125% (Table 3). At 45 DAS, application of MN has no significant effect on the indigenous strain. Whereas at 105 DAS, application of MN increases the nodule dry weight of the indigenous strain by fourfold (Table 3).

This finding highlights the necessity of combining the *rhizobium* inoculum with a starter dose of urea. Adding urea at an early stage will fulfil plant needs and stimulate the activity of microbial bacteria (Anne–Sophie et al. 2002; Mohammad and Alobaidy 2023). At 105 DAS, the results reflected an inconsistent pattern in the dynamics of nodulation over time. The decrease in nodule number (Table 3) at the late growth stage is attributed to a lack of N with no fertilizer addition, and to the stress caused by temperature (Singh et al. 2010). While, the increase in nodules dry weight at the late growth stage attributed to biomass build-up (Hossain et al. 2018).

3.4 Shoot dry weight

In the first season, the shoot dry weight exhibits no significant difference between the treatments, however MN treatment produces higher shoot dry weight than the control and inoculation (Table 4). The effect of variety is significant only at 105 DAS, where shoot dry weight of *Kiriz* is 65% significantly higher than *Sodari*. In the second season, inoculation, and mineral N application significantly increase shoot dry weight at 75 and 105 DAS (Table 4). Mintah et al. (2020) reported that *rhizobium* inoculation and N fertilizer application increased nodulation, and the biomass yield. In the second season, the variety *Kiriz* produces significantly greater shoot dry weights throughout the growing period.

3.5 Root dry weight

In the first season, there are no significant differences in root dry weight due to varieties and treatments throughout the growth period (Table 5). However, in the second season, root dry weight significantly affected by treatment and variety. Unexpectedly, after 45 DAS the root dry weight in the control treatment is significantly higher than the other treatments. This result is likely due higher nodule dry weight in RI and MN treatments (Table 3). Furthermore, the *Kiriz* variety significantly higher than *Sodari* by 60.7% at 45 DAS and 46.6% at 105 DAS (Table 5).

3.6 Pod yield

In the first season, no statistical differences are detected ($p > 0.05$) in number of pods/plant, pod DY/plant (g) and total pod DY (kg ha^{-1} , Table 6). In the second season, application of MN result in 40% and 21.7% significantly higher pod DY/plant (g) and total pod DY (kg ha^{-1}), respectively, over the uninoculated plants (Table 6). On the other hand, inoculation with introduced strain result in 27.3% and 12.9% higher pod DY/plant (g) and total pod DY (kg ha^{-1}), respectively, over the uninoculated plants. *Kiriz* variety produces higher number of pods/plant, pod DY/plant (g) and

Table 2 Effects of treatment and variety on the number of nodules/plant at 45, 75, and 105 DAS for two consecutive seasons

Attribute		Number of nodules/plant					
Interaction		First season (DAS)			Second season (DAS)		
Variety x Treatment		45	75	105	45	75	105
Sodari	C	0.8b	12.2b	49.6a	0.8d	14.9c	40.2b
	RI	9.5ab	27.7ab	32.2a	4.0c	33.0b	20.7c
	MN	1.8b	39.2ab	26.5a	4.4c	62.4a	33.6b
Kiriz	C	4.5b	29.5ab	27.6a	0.7d	26.4b	18.7c
	RI	3.5b	63.9a	64.1a	7.6b	60.6a	40.4b
	MN	21.0a	47.3ab	65.3a	14.0a	57.8a	52.7a
LSD (Interaction)		14.14	43.47	69.21	2.77	11.54	8.58
Treatment							
	C	2.7a	20.9a	38.6a	0.7c	20.7c	29.4b
	RI	6.5a	45.8a	48.2a	5.8b	46.8b	30.6b
	MN	11.4a	43.3a	45.9a	9.2a	60.1a	43.1a
LSD (Treatment)		10.00	30.74	48.94	1.96	8.16	6.07
Variety							
	Sodari	4.1a	26.4a	36.1a	3.1b	36.8b	31.5b
	Kiriz	9.7a	46.9a	52.3a	7.4a	48.3a	37.3a
LSD (Variety)		8.17	25.10	39.96	1.60	6.66	4.95
CV%		113.30	65.19	86.03	29.10	14.92	13.72

Means with different letters are significantly different ($p < 0.05$), DAS = days after sowing, C = control, RI = *rhizobium* inoculum, MN = mineral nitrogen

Table 3 Effects of treatment and variety on nodule dry weight at 45, 75, and 105 DAS for two consecutive seasons

Attribute		Nodules dry weight (g)					
Interaction		First season (DAS)			Second season (DAS)		
Variety x Treatment		45	75	105	45	75	105
Sodari	C	0.00b	0.2a	0.4a	0.00b	0.04c	0.13d
	RI	0.02ab	0.1a	0.2a	0.01b	0.19bc	0.09d
	MN	0.00b	0.2a	0.2a	0.01b	0.14bc	0.58a
Kiriz	C	0.01b	0.2a	0.3a	0.00b	0.05c	0.10d
	RI	0.02ab	0.4a	0.5a	0.11a	0.32ab	0.29c
	MN	0.07a	0.4a	0.3a	0.03b	0.44a	0.39b
LSD (Interaction)		0.050	0.35	0.58	0.065	0.193	0.079
Treatment							
	C	0.01a	0.21a	0.32a	0.00b	0.05b	0.12c
	RI	0.02a	0.26a	0.36a	0.06a	0.26a	0.19b
	MN	0.03a	0.35a	0.23a	0.02ab	0.29a	0.49a
LSD (Treatment)		0.035	0.246	0.410	0.046	0.137	0.056
Variety							
	Sodari	0.01a	0.19a	0.25a	0.01a	0.12b	0.27a
	Kiriz	0.03a	0.35a	0.36a	0.05a	0.27a	0.26a
LSD (Variety)		0.029	0.201	0.335	0.037	0.112	0.046
CV%		143.45	70.45	105.66	125.25	53.59	16.43

Means with different letters are significantly different ($p < 0.05$), DAS = days after sowing, C = control, RI = *rhizobium* inoculum, MN = mineral nitrogen

total pod DY (kg ha^{-1}) than *Sodari* in both seasons. The two seasons average yield (total pod DY) of *Kiriz* was 1.6 t ha^{-1} , which is 30% and 45% lower than the 5-year average of

2.3 t ha^{-1} in Gezira state, (FAO 2024) and 3.1 at the Gezira Research Station (Abu Assar et al. 2004), respectively. The reduction in pod yield could be attributed to soil salinity and

Table 4 Effects of treatment and variety on shoot dry weight at 45, 75, and 105 DAS for two consecutive seasons

Attribute		Shoot dry weight (g)					
Interaction		First season (DAS)			Second season (DAS)		
Variety x Treatment		45	75	105	45	75	105
Sodari	C	3.43ab	9.83a	29.49ab	2.87b	11.98d	27.92c
	RI	3.47ab	8.28a	16.77b	2.99b	14.64cd	29.97c
	MN	1.97b	12.95a	27.50ab	3.21b	15.53c	29.96c
Kiriz	C	3.77ab	14.72a	35.03ab	5.26a	20.37b	38.15b
	RI	2.90ab	16.94a	45.06a	5.78a	27.77a	45.36a
	MN	6.00a	15.82a	41.57a	6.23a	26.93a	45.64a
LSD (Interaction)		3.140	11.8	21.685	1.010	2.887	5.102
Treatment							
	C	3.60a	12.28a	32.26a	4.07a	16.17b	33.04b
	RI	3.18a	12.61a	30.91a	4.39a	21.31a	37.67a
	MN	3.98a	14.39a	34.53a	4.72a	21.23a	37.80a
LSD (Treatment)		2.220	8.344	15.334	0.714	2.041	3.608
Variety							
	Sodari	2.96a	10.36a	24.59b	3.02b	14.12b	29.04b
	Kiriz	4.22a	15.83a	40.55a	5.76a	25.02a	43.05a
LSD (Variety)		1.813	6.813	12.520	0.583	1.667	2.946
CV%		48.09	48.54	36.60	12.65	8.11	7.75

Means with different letters are significantly different ($p < 0.05$), DAS = days after sowing, C = control, RI = *rhizobium* inoculum, MN = mineral nitrogen

Table 5 Effects of treatment and variety on root dry weight at 45, 75, and 105 DAS for two consecutive seasons

Attribute		Root dry weight (g)					
Interaction		First season (DAS)			Second season (DAS)		
Variety x Treatment		45	75	105	45	75	105
Sodari	C	0.24a	0.45a	0.71a	0.22d	0.79a	1.44c
	RI	0.27a	0.60a	0.46a	0.27cd	0.33c	1.20d
	MN	0.30a	0.63a	1.03a	0.33bc	0.81a	1.30cd
Kiriz	C	0.29a	0.70a	0.71a	0.35b	0.85a	2.12a
	RI	0.37a	1.12a	1.01a	0.51a	0.52b	1.96a
	MN	0.20a	0.92a	0.51a	0.48a	0.49b	1.67b
LSD (Interaction)		0.290	0.747	0.660	0.073	0.115	0.204
Treatment							
	C	0.26a	0.57a	0.71a	0.29b	0.82a	1.78a
	RI	0.32a	0.86a	0.74a	0.39a	0.42c	1.58b
	MN	0.25a	0.77a	0.77a	0.41a	0.65b	1.49b
LSD (Treatment)		0.205	0.529	0.467	0.052	0.081	0.144
Variety							
	Sodari	0.27a	0.56a	0.74a	0.28b	0.64a	1.31b
	Kiriz	0.29a	0.91a	0.74a	0.45a	0.62a	1.92a
LSD (Variety)		0.167	0.432	0.381	0.042	0.066	0.118
CV%		57.19	55.81	49.09	11.16	10.05	6.95

Means with different letters are significantly different ($p < 0.05$), DAS = days after sowing, C = control, RI = *rhizobium* inoculum, MN = mineral nitrogen

sodicity stress at the study site. According to Tanji and Kielen (2002) at EC 3.2 dS m⁻¹, groundnut production decreased by 29%. Singh and Abrol (1985) reported a reduction in dry

biomass, straw, and pod yield of groundnut at ESP more than 8. The same author reported reduction in groundnut pod yield by 29% and 50% at ESP 15 and 20, respectively.

Table 6 Effects of treatment and variety on the number of pods/plant, pod DY/plant, and total pod DY for two consecutive seasons

Attribute		Number of Pods/plant		Pod DY/plant (g)		Total pod (DY kg ha ⁻¹)	
Interaction		Season					
Variety x Treatment		First	Second	First	Second	First	Second
Sodari	C	26.10a	18.32c	13.70c	12.22d	828.7bc	519.4b
	RI	20.33a	20.88c	10.97c	14.14d	548.0c	572.3b
	MN	32.30a	22.24bc	19.77bc	18.59cd	981.7bc	735.8b
Kiriz	C	32.27a	27.83abc	28.03ab	25.28bc	1365.3ab	1064.8a
	RI	35.13a	32.59ab	39.67a	33.59ab	1850.0a	1696.3a
	MN	30.93a	37.43a	23.30bc	33.89a	1189.7abc	1849.9a
LSD (Interaction)		19.454	10.726	14.206	8.352	731.07	323.86
Treatment							
	C	29.18a	23.08a	20.87a	18.75b	1097.0a	1062.1b
	RI	27.73a	26.74a	25.32a	23.87ab	1199.0a	1134.3ab
	MN	31.62a	29.84a	21.53a	26.24a	1085.7a	1292.8a
LSD (Treatment)		13.756	7.585	10.045	5.906	516.94	229.0
Variety							
	Sodari	26.24a	20.48b	14.81b	14.98b	786.1b	609.1b
	Kiriz	32.78a	32.62a	30.33a	30.92a	1468.3a	1717.0a
LSD (Variety)		11.232	6.193	8.202	4.822	422.08	186.98
CV%		36.23	22.21	34.59	20.00	35.65	15.31

Means with different letters are significantly different ($p < 0.05$), C = control, RI = *rhizobium* inoculum, MN = mineral nitrogen, DY = dry yield

Table 7 Effects of treatment and variety on the number of seeds/plant, seed DY/plant, total seed DY, and 100–seed weight in two consecutive seasons

Attribute		Number of seeds/plant		Seed DY/plant (g)		Total seed (DY kg ha ⁻¹)		100–seed weight (g)	
Interaction		Season							
Variety x Treatment		First	Second	First	Second	First	Second	First	Second
Sodari	C	23.40b	31.58b	10.50ab	8.28c	567.7ab	412.1c	23.8cd	27.2bc
	RI	23.20b	38.42ab	7.10b	9.18c	355.3b	417.5c	16.4d	22.7c
	MN	27.53ab	38.17ab	12.63ab	10.69c	620.3ab	534.6c	32.6bc	27.7bc
Kiriz	C	27.07ab	43.92ab	15.53ab	16.83b	671.7ab	839.1b	34.1b	42.8ab
	RI	41.33a	52.17a	20.43a	22.31a	984.3a	1117.9a	48.1a	49.5a
	MN	38.67ab	44.83ab	13.50ab	23.35a	691.7ab	1167.5a	39.3ab	57.1a
LSD (Interaction)		16.586	14.790	10.116	4.644	495.77	277.13	9.198	15.65
Treatment									
	C	25.2a	37.8a	13.0a	12.6b	619.7a	625.6b	28.98b	35.0a
	RI	32.3a	45.3a	13.8a	15.7ab	669.8a	767.7ab	32.23ab	36.1a
	MN	33.1a	41.5a	13.1a	17.0a	656.0a	851.1a	35.95a	42.4a
LSD (Treatment)		11.73	10.46	7.15	3.28	350.57	160.60	6.50	11.07
Variety									
	Sodari	24.7b	36.1b	10.1b	9.4b	514.4a	454.8b	24.3b	25.9b
	Kiriz	35.7a	47.0a	16.5a	20.8a	782.6a	1041.5a	40.5a	49.8a
LSD (Variety)		9.58	8.54	5.84	2.68	286.24	131.13	5.31	9.03
CV%		30.19	19.58	41.86	16.90	42.02	16.69	15.61	22.74

Means with different letters are significantly different ($p < 0.05$), C= control, RI=*rhizobium* inoculum, MN= mineral nitrogen, DY= dry yield

3.7 Seed yield

Table 7 shows the effect of treatment and variety on seed parameters. Generally, in the first season treatments have no significant effect on most seed parameters, except 100 seed weight. On contrast, 100–seed weight (g) on the second season is not significantly affected by treatments, it followed the order as $MN > RI > C$. In both seasons, *Kiriz* excelled *Sodari* in all seed parameters (Table 7). However, in the second season addition of urea increases the yield significantly by 35% over the control. The increase in seed yield from inoculation is not significantly different from the control but it is higher by 24.6% (Table 7). The difference between the two variety was statistically significant for all seed parameters except total seed DY in the first season.

In general, *Kiriz* performs better than *Sodari*. HajHussein et al. (2018) noted the genetic superiority of *Kiriz* over eight tested varieties, including *Sodari*, in a similar environment. Akley et al. (2022) found that inoculating soybeans creates a positive correlation between grain yield and soil N level. However, the same authors noted that when inoculation was not applied, the yield decreased in the following year. This accounts for the increase in groundnut seed yield in the second season, which is likely due to the cumulative effects of the *rhizobium* applied over the two seasons.

3.8 Plant nutrient content

The results reveal no significant differences in the N and K contents among the varieties or treatments (Table 8). However, the variety *Kiriz* has higher N and K levels than *Sodari*. The P content of the *Sodari* variety significantly exceeds that of the *Kiriz* variety. In the first and second seasons, root to shoot (R/S) ratio ranges between 0.03 and 0.05 for *Sodari* and between 0.02 and 0.04 for *Kiriz* at 105 DAS. The higher (R/S) ratio for *Sodari* indicates that it has allocated more resources in its root rhizosphere to enhance the acquisition of water and nutrients. This is compatible with the variety trait that suits drought tolerance in rainfed areas (FAO 2022). The treatments differ significantly from one another, with the RI outperforming its counterparts. According to the optimal range defined by Singh et al. (2005), the N content in plant tissue is below the optimum value (20–50 g kg⁻¹), whereas P (2–5 g kg⁻¹) and K (10–50 g kg⁻¹) are at their minimum limits. The low N, P, and K contents in plant tissue are a consequence of low levels in the soil pool, resulting in a lack of P and K applied as mineral or organic fertilizers. According to Horneck et al. (2011), the P and K levels in our soil were low ($K < 0.15$ g kg⁻¹ and $P < 0.01$ g kg⁻¹), but the total N concentration of 1.2 g kg⁻¹ was within the range of 1–1.5 g kg⁻¹. The results of N uptake indicate that either the varieties are more compatible with the indigenous *rhizobium* or that N₂ fixation

Table 8 Effects of treatment and variety on the contents of nitrogen (N), phosphorus (P), and potassium (K) in plants during the second season

Attribute		Nutrient content (g kg ⁻¹)		
Variety x Treatment		N	P	K
Sodari	C	7.2a	3.8a	10.5a
	RI	4.9a	4.4a	15.3a
	MN	7.7a	2.9b	15.6a
Kiriz	C	7.7a	2.9b	14.9a
	RI	6.5a	4.5a	14.5a
	MN	7.2a	1.3c	14.2a
LSD (Interaction)		4.09	0.85	7.21
Treatment				
	C	7.5a	3.4b	12.7a
	RI	5.7a	4.4a	14.9a
	MN	7.5a	2.1c	14.9a
LSD (Treatment)		2.89	0.60	5.10
Variety				
	Sodari	6.6a	3.7a	13.8a
	Kiriz	7.2a	2.9b	14.5a
LSD (Variety)		2.36	0.49	4.16
CV%		32.64	14.12	28.0

Means with different letters are significantly different ($p < 0.05$), C = control, RI = *rhizobium* inoculum, MN = mineral nitrogen

is insufficient for meeting the plant's needs. Similar results were reported by Hadad et al. (1986), who reported that groundnuts presented more progressive growth when MN was added. Adinurani et al. (2021) and Yamamoto et al. (2022) reported that root *rhizobium* can enhance P uptake by plants, due to the organic acids released from phosphate-solubilizing microorganisms. These acids increased P solubility and availability to plants (Silva et al. 2023). Formation and activity of root nodules require increased P, especially when plants obtain N through biological fixation (Adinurani et al. 2021). Although K is not a key element in nodule formation, it plays an essential role in regulating osmotic balance (Weisany 2013). This inhibits the photosynthesis process and the accumulation of carbohydrates, which improves the N₂ fixation process (Singh and Kataria 2012). The N and K contents in the groundnuts follow a similar trend across the different treatments. Singh and Abrol (1985) found that when ESP rose from 8 to 15, the N, P and K content in mature plant tissue decreased by 11.2, 11.6 and 8.3%, respectively. This indicates that the acquisition of N and K is more affected by high ESP than P did. Singh et al. (2010) reported that the highest uptake of K occurred with the application of 30 kg N ha⁻¹ and 30 kg K₂O. The application of mineral K can rise nutrient uptake, particularly in saline soils with high osmotic pressure (Weisany 2013).

4 Conclusion

The results confirm the existence of an indigenous *rhizobium* strain in Soba soil and the adaptability of the variety *Kiriz*. Inoculation and addition of MN increases most of the studied parameter over the control treatment. Additionally, the *rhizobium* colonization increased from the beginning of the growth period and accumulated for the second season. The variety *Sodari* significantly responds to *rhizobium* in P content in plant tissue whereas N and K show no difference within treatments.

The expansion of urban agriculture to the outskirts of Khartoum marginal lands, where soil fertility is obstructed by salinity and sodicity. Cultivating legume crops in such soil will improve their productivity and even minimize the use of chemical fertilizers and amendments. A better use of minerals and biological fertilizers will increase the potential of these soils. It is recommended to investigate the impacts of *rhizobium* on the P uptake variety wise, along with mineral N on groundnut yield and nutrient content. Further research is needed to screen different groundnut varieties and *rhizobium* strains at higher salinity levels. Preliminary information about the performance of groundnuts in this soil could be used for future research.

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Data availability The data that support the findings of this study are openly available in Figshare.com at the following private share link <https://figshare.com/s/db5a6250238adfaf7ca3>

The link contains a folder with 3 files:

1. File named first season support the data from the first season in Tables 2, 3, 4, 5, 6 and 7.
2. File named second season support the data from the second season in Tables 2, 3, 4, 5, 6 and 7.
3. File named plant and soil analysis support the data in Table 1 and 8.

Declarations

Ethical statement Not applicable.

Competing 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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