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Toward the replacement of conventional fertilizer with polyhalite in eastern China to improve peanut growth and soil quality

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Abstract

Background: Polyhalite fertilizer application is an effective way to alleviate a shortage of potassium. This study explored the effects of polyhalite fertilizer application as a total or partial replacement for conventional potassium fertilizer to improve peanut growth and soil quality.

Results: The index of peanut yield and its economic benefits, the content and distribution of mineral nutrients in different organs, soil chemical properties, and rhizosphere microbial diversity in response to the treatments were examined. The results show that the M4P6T treatment (60% polyhalite fertilizer replacing potassium chloride as the base fertilizer, and 40% potassium chloride fertilizer applied as a topdressing) increased profit by 7.2% without affecting the yield. The M4P6T treatment significantly improved the accumulation and distribution of potassium, calcium and magnesium in the kernels compared with the M10B treatment (no polyhalite fertilizer; potassium chloride fertilizer only as the base fertilizer). Soil treated with polyhalite fertilizer had higher alpha-diversity values and greater relative abundance of microbes at the phylum and genus levels.

Conclusions: Partial substitution of polyhalite for potassium chloride improved soil quality and peanut growth more than did single applications of polyhalite and potassium chloride.

Keywords: Peanut, Polyhalite, Potassium chloride, Yield, Soil

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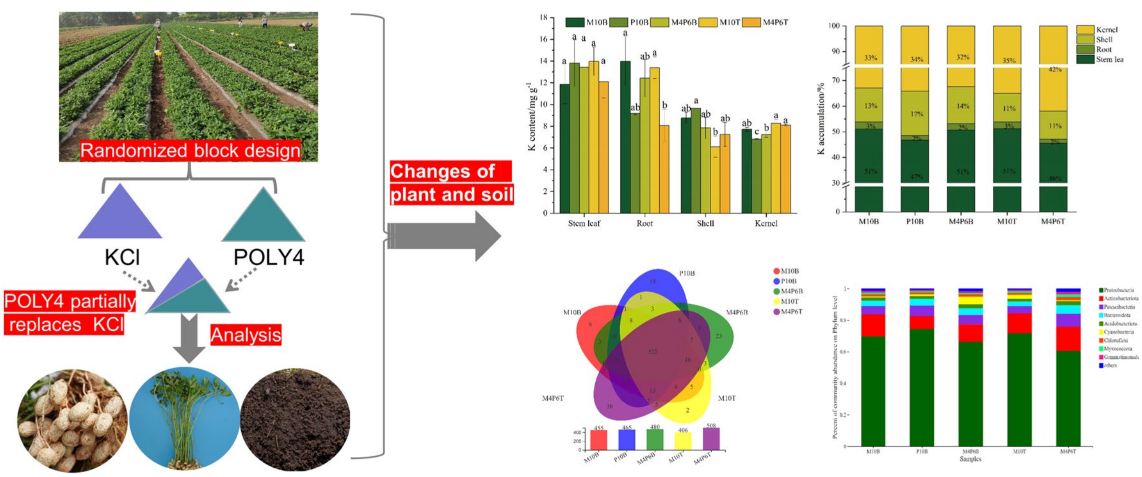
Graphical Abstract



Background

Peanut (*Arachis hypogaea* L.) is grown worldwide and is produced primarily for edible oil and seeds rich in protein, lipids, and minerals [1, 2]. It is grown widely in the semi-arid tropics. China contributes the largest proportion of the global crop (36.31%), followed by India (13.52%) [3]. Potassium [4] is the most abundant cation in plants, in which plays vital roles in growth and almost all related functions. Peanut is a typical potassium-loving crop. Thus, conventional potassium fertilizers, such as potassium chloride (MOP) and potassium sulfate (SOP) have been used for years to supply nutrients to this crop. MOP is a natural mineral mined from deep deposits. Potassium sulfate and potassium nitrate are byproducts of MOP mining, and are more expensive than MOP. As peanut is not sensitive to chloride, the less-expensive MOP has become the preferred fertilizer for peanut farmers.

World population growth, the increasing demand for protein-rich diets, and a decrease in arable land have driven fertilizer prices higher with the greater global demand for potash [5]. K fertilizer application is mandatory in intensive agriculture to ensure and sustain an adequate supply for crops [6]. Thus, the seeking of alternative potassium sources is an important measure to promote the sustainable development of global agriculture. Polyhalite (POLY4) is an evaporated mineral composed of potassium (K), magnesium (Mg), and calcium (Ca) in the form of sulfate (S) with the chemical formula $K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$ [7]. POLY4 extraction and use are difficult and limited because of the mineral's complex composition, deep location (< 1000 m), and relatively low purity in some countries, such as China [8]. North Yorkshire, UK, has the highest quality POLY4 (85.7% pure) [5]. J.S.H proposed the use of polyhalite as a K fertilizer [9]. High-grade polyhalite can be mined and marketed with no processing except crushing and sizing, which has sparked interest in its use as a low-chloride potassium fertilizer [10, 11].

The literature on polyhalite fertilizer application to agronomic crops is very limited. Polyhalite has been shown to perform well as a fertilizer of rice [12], ramie [13], peanut [14], potato [15], and corn [16], with equal or greater yields and improved quality compared to the use of MOP or SOP as a K source. Tiwari et al. [17] demonstrated that application of polyhalite fertilizers increased mustard and sesame yields and significantly increased the absorption of potassium by plants compared with other potassium fertilizers. Mello et al. [18] reported that soils treated with polyhalite fertilizer had higher Ca and Mg contents compared to those treated with other K fertilizer. These results indicate that POLY4 could serve as a K fertilizer in agriculture. Crop responses to K fertilizer depend on the soil fertility, climate, and the variety grown [19]. In China, most research on polyhalite has been carried out on acidified soils; relatively little has been performed on neutral soils. Microorganisms play important roles in soil quality and in plant growth and development [20]. However, no study has explored the effects of polyhalite application on soil microorganisms. In addition, the K content of polyhalite is very low compared with those of MOP and SOP [21]. Thus, polyhalite cannot completely replace traditional potassium fertilizers. Given the high sulfur and calcium contents of POLY4, this mineral might be used in the future together with other potassium fertilizers [8]. The combined use of polyhalite and a traditional potassium fertilizer for slow release is more beneficial to crop growth and meets the nutrient demand.

We hypothesized that polyhalite fertilizer would be well suited for use on peanut plantations in eastern China, because its nutrient-release profile is relatively slow and nutrient absorption improves with soil quality. A field trial was set up in northern China to investigate whether polyhalite fertilizers would improve peanut growth and soil quality. Different K-based fertilizers were applied to peanuts on plantations. The objectives of this study were to: (1) investigate the response of peanut yields to different treatments, and the economic benefits; (2) assess the effects of mineral nutrient absorption by peanut organs under different fertilization treatments; and (3) determine whether polyhalite fertilizer affects the basic chemical properties and composition of the soil rhizosphere microbial community.

Materials and methods

Experimental site and material

The experiment was carried out in Houhuayuan Village, Huashan Town, Qingdao City, Shandong Province, China (36°34′N, 120°30′E) from May 16 to September 21, 2019. This region has a warm-temperate monsoon continental climate. During the experimental period, rainfall was highest in early August (146.31 mm) and the average temperature was highest in late July (28.63 °C) (Additional file 1: Fig. S1). The test soil was classified as a vertisol according to the US soil taxonomy, and the basic chemical properties of the topsoil (0–30 cm) were: pH, 6.63; electrical conductivity (EC), 88.90 μs cm^{-1}; available nitrogen, 52.50 mg kg^{-1}; available phosphorus, 103.30 mg kg^{-1}; available potassium, 119 mg kg^{-1}; exchangeable calcium, 2370 mg kg^{-1}; exchangeable magnesium, 200 mg kg^{-1}; and available sulfur, 32.30 mg kg^{-1}.

The Huayu 22 peanut variety, the main variety grown in Shandong Province since 2010, was used [22]. This variety is widely cultivated locally due to its high quality and yield. The polyhalite fertilizer used in the experiment was granular (Sirius Minerals Plc, Scarborough, UK). It was composed of polyhalite powder, with the composition 14% K_2O, 17% CaO, 6% MgO, and 48% SO_3. The other fertilizers applied were urea (46% N), diammonium phosphate (18% N and 46% P_2O_5), and potash muriate (62.7% K_2O), supplied by Tianjin Hengxing Chemical Co. (Tianjin, China).

Experimental design

All treatments had the same contents of N (156 kg N hm^{-2}), P_2O_5 (117 kg P_2O_5 hm^{-2}), and K_2O (185 kg K_2O hm^{-2}) to ensure that consistent amounts of nutrients were applied. Five treatments were applied (Table 1): (1) M10B, no polyhalite, MOP only applied as the base fertilizer; (2) P10B, 100% polyhalite replacing MOP as the base fertilizer; (3) M4P6B, 60% polyhalite replacing MOP as the base fertilizer; (4) M10T, no polyhalite, 60% MOP applied as the base fertilizer and the remaining 40% MOP applied as a topdressing; and (5) M4P6T, 60% polyhalite replacing MOP as the base fertilizer, and 40% MOP applied as a topdressing. The total amounts of the different potassium fertilizers applied to the soil were calculated according to their K_2O contents. Nitrogen and P fertilizers were applied once as base fertilizer at 239.61 kg hm^{-2} and 254.35 kg hm^{-2}, respectively. The base fertilizer was usually supplied at sowing and the topdressing was applied at the flowering-pegging stage.

Peanut sampling and analysis

To avoid border effects and deviation of the results based on plant positions in the plots, 30 non-border peanut plants were collected randomly at the same positions in each plot to determine yields. The plants were separated into roots, stem leaves, shells, and kernels, which were dried in an oven (101-3AB; Tianjin Test Instrument Co., Ltd. Tianjin, China) at 105 °C for 30 min, and then at 60 °C to constant weight. The dried samples were ground to pass through a 40-mesh sieve (particle size 0.42 mm) and digested in a mixture of concentrated nitric acid

Table 1 Test settings

Treatment	K-fertilizer (K_2O kg hm^{-2})				K_2O/kg hm^{-2}	N/kg hm^{-2}	P_2O_5/kg hm^{-2}
	Applied as base fertilizer		Applied as top dressing fertilizer				
	MOP	Polyhalite	MOP	Polyhalite			
M10B	185	–	–	–	185	156	117
P10B	–	185	–	–	185	156	117
M4P6B	–	111	74	–	185	156	117
M10T	111	–	74	–	185	156	117
M4P6T	–	111	74	–	185	156	117

(HNO_3) and concentrated perchloric acid ($HClO_4$; 5:1, *v*/*v*) [23, 24]. The total K, Ca, and Mg contents of each part of the peanut plant were measured by inductively coupled plasma atomic emission spectroscopy (ICP-AES).

Soil chemical property index

Tillage-layer (0–30 cm) soil samples were collected randomly during harvest from subplots designed based on the grid-layout method. After the removal of visible stones and plant debris, the soil was air dried in the shade at room temperature for approximately 15 days, homogenized, and passed through a 10-mesh sieve (particle size, 2 mm). The basic chemical properties of the soil (available N, P, and S contents; exchangeable K, Ca, and Mg contents; and EC and pH) were analyzed [25]. Available N was determined by the alkali solution diffusion method; available P was extracted with 0.5 mol L^{-1} $NaHCO_3$ and determined by ammonium molybdate colorimetry, and available S was extracted with a $CaCl_2$ solution and determined by the barium sulfate turbidimetric method. The homogenized soil was suspended in 1 mol L^{-1} CH_3COONH_4; the suspension was passed through a 0.45 mm filter, and the exchangeable K, Ca, and Mg contents of the filtrate were determined by ICP-AES using an Avio 200 instrument (PerkinElmer, Waltham, MA, USA). Soil pH (soil:water ratio, 1:2.5) was measured using a PHS-3E pH meter, and soil EC (soil:water ratio, 1:5) was measured using a DDSJ-308F electrical conductivity meter.

Rhizosphere soil sampling and high-throughput sequencing

The peanut rhizosphere soil was collected using a multipoint mixed sample collection method. Soil that was attached tightly to the roots was collected with a sterile brush and mixed with other samples from the plot. Three rhizosphere soil samples were mixed as a replicate of the biological sample. The samples were placed in sterile bags, sealed, brought back to the laboratory in an ice box, and stored at − 80 °C for DNA extraction. The soil microbial community structure was analyzed by high-throughput sequencing. DNA was extracted from the soil samples using an OMEGA Soil Kit according to the manufacturer's instructions. The concentration and purity of the DNA were determined spectrophotometrically by measuring the absorbance of each sample at 230, 260, and 280 nm [26]. DNA quality was further checked by amplifying a portion of the 16S rDNA using the primer combination 340F (5′-CCTACGGGNBGC ASCAG-3′) and 805R (5′-GACTACNVGGGTAT CTAATCC-3′). PE250 sequencing was performed on the HiSeq2500 platform. The relevant tests were performed by Shanghai Meiji Biomedical Technology Co. (Shanghai, China).

Bioinformatics and statistical analyses

Sequencing quality for the peanut rhizosphere soil samples was analyzed using plotting of Venn diagrams and rarefaction curves at the operational taxonomic unit (OTU) level. The diversity and structure of the rhizosphere bacterial communities were analyzed using the alpha diversity index and the bacterial composition at the phylum and genus levels, respectively. Functional annotation of the OTUs was performed using PICRUSt for analysis of the metabolic functions of the microorganisms. Finally, the correlations between rhizosphere microorganisms and soil environmental factors were analyzed.

The statistical analysis was performed using Excel 2003 (Microsof Inc., Redmond, WA, USA) and SPSS 25.0 (IBM SPSS Inc., Chicago, IL, USA) software. All data were subjected to one-way analysis of variance. Means were compared using Duncan's multiple range test, and *p* values < 0.05 were considered significant. All figures were created using Meguiar's Cloud platform and Origin 2019. The figures showed means and standard deviations.

Results

Yield and profit

The peanut yield and profit gained from POLY4 use will primarily determine whether POLY4 is a candidate for partial or total replacement of MOP as a traditional K fertilizer. The analysis did not show a significant effect of the applied experimental variants on peanut yield (Fig. 1); however, a difference in profit was observed (Table 2). Peanut yield ranged from 6100.95 to 7326.81 kg hm^{-2}.

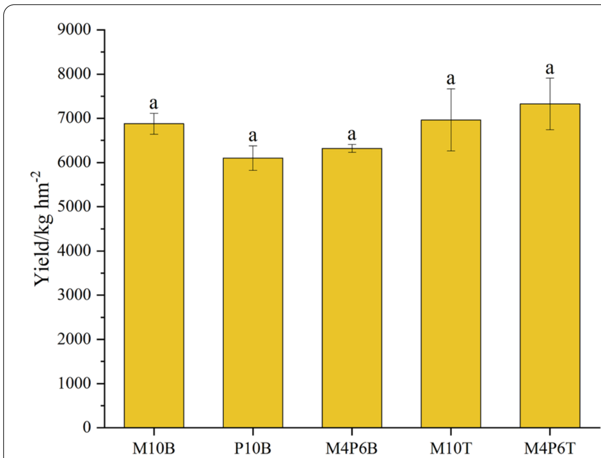


Fig. 1 Yield of peanut. The values are means ± standard deviation of the replications ($n = 3$). Different letters show statistically significant differences among treatments at $p < 0.05$

Table 2 Economic benefits analysis of different treatments

Treatment	Income/¥ hm^{-2}	K fertilizer cost/¥ hm^{-2}	N, P fertilizer cost/¥ hm^{-2}	Other production cost/¥	Net income/¥ hm^{-2}
M10B	68,775.57	1121.21	1307.22	9600	56747.14
P10B	61,009.47	1717.86	1307.22	9600	48384.39
M4P6B	63,200.17	1479.22	1307.22	9600	50813.73
M10T	69,637.40	1121.21	1307.22	9600	57608.97
M4P6T	73,268.07	1479.22	1307.22	9600	60881.63

Income = yield × peanut price; The price of peanut was ¥10 kg^{-1}

The yield increased by 1.25–6.53% under the M10T and M4P6T treatments compared with that under the M10B treatment. The yield was the highest (7326.81 kg hm^{-2}) under the M4P6T treatment. Many factors, including the costs of fertilizer, labor, pesticides, and other production aspects, are involved in the net income from peanut production. We compared the relative increase in net revenue obtained with POLY4 and MOP fertilization. To account for all other costs, such as those of seeds and N and P fertilizers, other production activities were equal for all treatments. Differences were observed only in the cost and yield of the K fertilizer. Net incomes for all treatments were ¥48,384.39–60,881.63 hm^{-2}. Among all treatments, M4P6T was associated with the highest net revenue, followed by M10T.

K fertilizer cost = K fertilizer price × K fertilizer product dose (The all treatments were 185 kg hm^{-2} in K_2O); The fertilizer prices of urea (46% N), diammonium phosphate (18% N and 46% P_2O_5), and muriate of potash (62.7% K_2O) were ¥2.08 kg^{-1}, ¥3.18 kg^{-1}, and ¥3.8 kg^{-1}, respectively. The price of POLY4 (14% K_2O) was ¥1.3 kg^{-1}, according to one manager of Sirius Minerals Plc [8].

Other production cost included peanut seeds (1950 ¥ hm^{-2}), pesticides (300 ¥ hm^{-2}), machine tillage (1350 ¥ hm^{-2}), and labor cost (6000 ¥ hm^{-2}).

Net income = (income—K fertilizer cost—other fertilizer cost—other production cost).

K, Ca, and Mg contents in peanut organs

The K content was highest in the stem leaves and lowest in kernels (Fig. 2a). The root and shell K contents were lower under M10T and M4P6T than under M10B, whereas the kernel K content was higher under M10T and M4P6T than under M10B. The shell K content did not differ significantly under the M10T and M4P6T treatments. The Ca content was also highest in stem leaves and lowest in kernels (Fig. 2b). Among all fertilization treatments, the root and shell Ca contents were lower under M10T and M4P6T than under the M10B treatment. The kernel Ca content was significantly higher under the M10T and M4P6T treatments than under M10B. However, no significant difference in the shell Ca content was detected between the M10T and M4P6T treatments. The Mg content was highest in stem leaves and lowest in shells (Fig. 2c). There was no significant difference in Mg content between all treatments in each peanut organ. Notably, the root and shell Mg contents were lower under the M10T and M4P6T treatments than under the M10B treatment. However, the kernel Mg content was higher under M10T and M4P6T than under M10B. These results indicate that topdressing was more conducive to the absorption and migration of minerals into the kernel, which improved peanut quality. Thus, the partial substitution of POLY4 for MOP is feasible.

Accumulation of K, Ca, and Mg peanut organs

K accumulation was highest in the stem leaves, and lowest in the roots (Fig. 3a). Less K accumulated in the stem leaves and roots under P10B and M4P6T than under M10B. However, more K accumulated in the shells under P10B and M4P6B than under M10B. More K accumulated in the kernels under M4P6T than under M10B. Ca accumulation was highest in stem leaves and lowest in roots (Fig. 3b). Among all fertilization treatments, P10B and M10T resulted in less Ca accumulation in stem leaves than did M10B. More Ca accumulated in the stem leaves under M4P6B than under M10B. However, more Ca accumulated in the shells under P10B than under M10B. More Ca accumulated in the kernels under M4P6T and M10T than under M10B. The Mg accumulation was highest in stem leaves and lowest in roots (Fig. 3c). Less Mg accumulated in the stem leaves and more Mg accumulated in the kernels under all treatments compared with the M10B treatment. In addition, more Mg accumulated in the shells under P10B and M4P6B than under M10B.

K, Ca, and Mg distribution ratios in kernels

Significant differences in K distribution ratios in kernels were observed among the fertilization treatments (Fig. 4a). This ratio was lower under M10B than under all other treatments. The M4P6T treatment resulted in

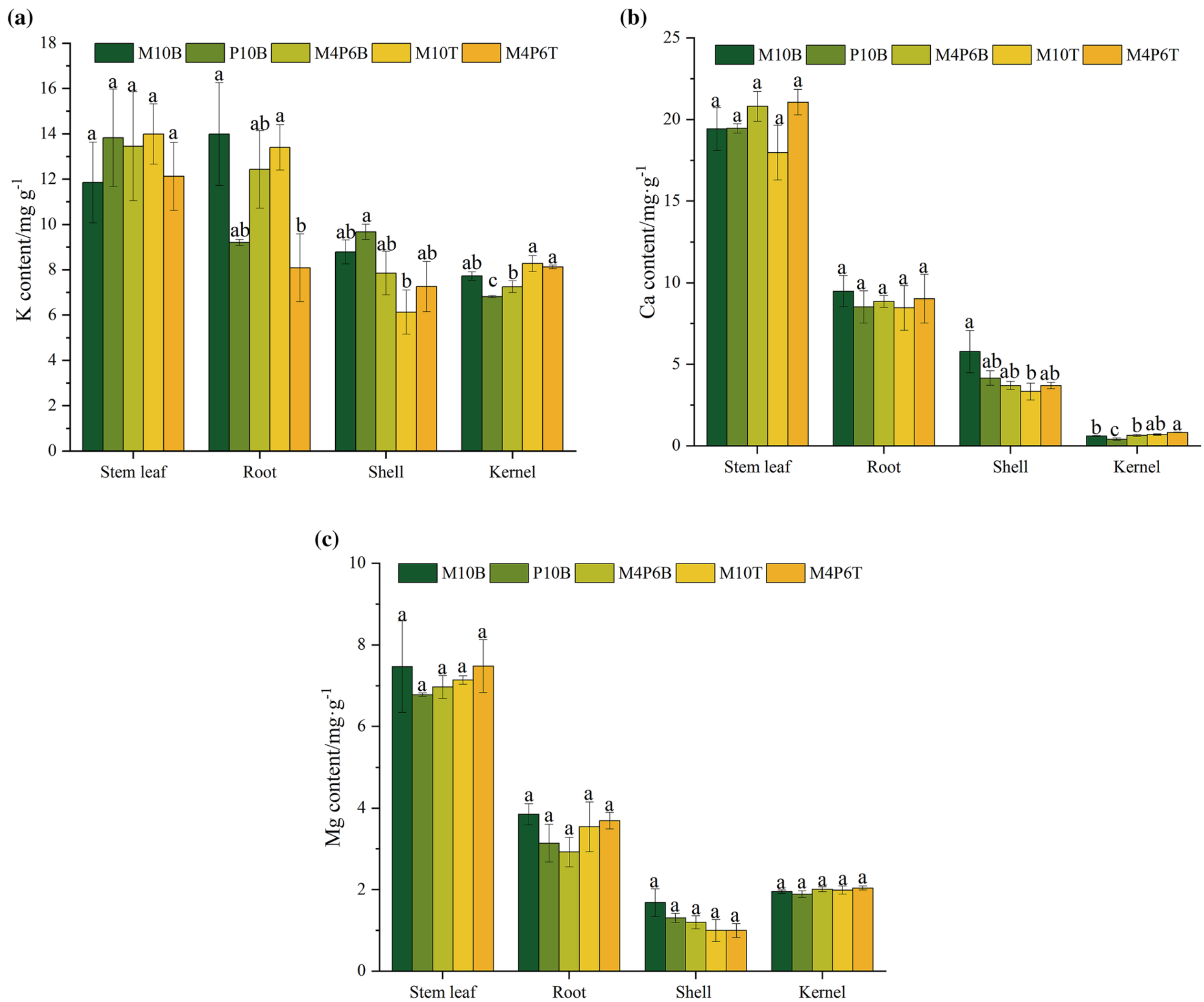


Fig. 2 Content of K, Ca and Mg in organs of peanut. **a** K content, **b** Ca content, **c** Mg content. The values are means ± standard deviation of the replications ($n = 3$). Different letters show statistically significant differences among treatments at $p < 0.05$

the highest K distribution ratio in kernels, but this ratio did not differ significantly from those resulting from the P10B and M10T treatments. The Ca distribution ratio in kernels was highest under the M4P6T treatment (Fig. 4b). The M10B treatment resulted in a lower Mg distribution ratio in kernels than other treatments (Fig. 4c). The P10B and M4P6T treatments showed significant differences compared to M10B.

Basic soil chemical properties

The fertilization treatments affected the basic soil chemical properties at harvest differently. Soil pH values ranged from 5.88 to 6.53, and those resulting from the P10B and M4P6B treatments were 0.12–0.28 higher than that observed with M10B (Fig. 5a). The M10T and M4P6T treatments increased soil pH by 0.55–0.65 compared with M10B. The pH of the soil under the M10T treatment differed significantly from that of the soil under the M10B treatment. The soil EC ranged from 80.30 to 314.67 μs cm^{-1} (Fig. 5b). Compared with M10B treatment, treated with polyhalite fertilizer had lower soil EC. Among all treatments, M4P6T resulted in the lowest soil EC, followed by M10T. The available N content ranged from 51.92 to 79.33 mg kg^{-1} (Fig. 5c). It was highest under M10B, with no significant difference among the other fertilization treatments. The exchangeable K content ranged from 0.86 to 1.22 cmol kg^{-1} (Fig. 5e). The available P content ranged from 105.14 to 252.33 mg kg^{-1}

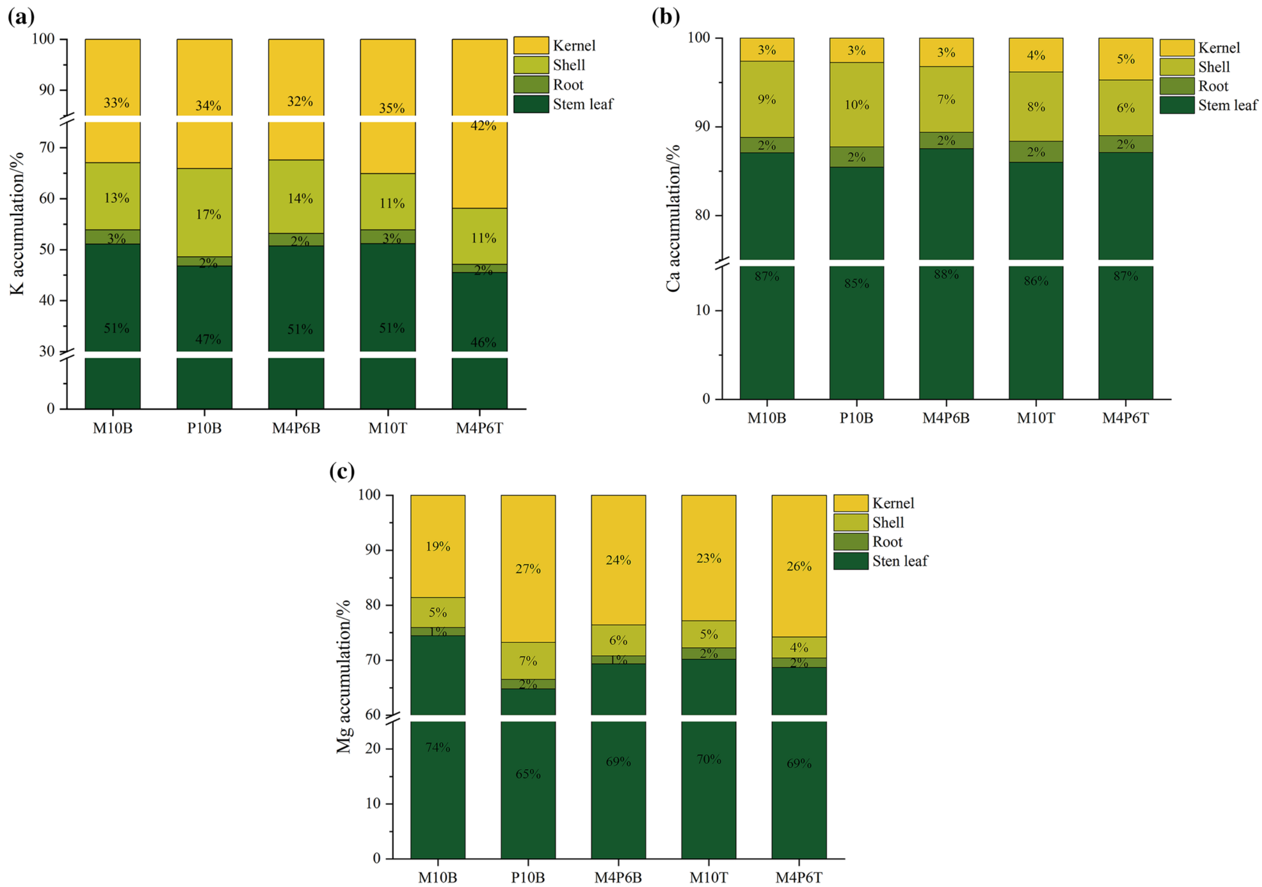


Fig. 3 Accumulation of K, Ca and Mg in organs of peanut. **a** K accumulation, **b** Ca accumulation, **c** Mg accumulation. K accumulation = the organ biomass × the organ K content. Ca or Mg accumulation was calculated in the same way as K accumulation

(Fig. 5d). It was higher under M10B than under all other treatments. The significantly lowest available P content was found for the M4P6T treatment, followed by M10T. Relative to the available N content, the exchangeable Ca and Mg contents showed opposite changes (Fig. 5f, g). They were lower under M10B than under all other fertilization treatments. The highest exchangeable Ca and Mg contents were found for the M4P6T treatment, followed by P10B.

Quality of peanut rhizosphere soil bacterial community sequencing

OTUs are taxon markers (strain, species, genus, or grouping) used in phylogenetic and population genetics research [27]. They are defined by > 97% (species-level) similarity between sequences, representing species. In total, 2314 OTUs were detected in the rhizosphere soil; the numbers of OTUs in soils under the M10B, P10B, M4P6B, M10T, and M4P6T treatments were 455, 465, 480, 406, and 508, respectively. The microbial community-specific OTU of all fertilization treatments was 322, and those of M10B, P10B, M4P6B, M10T and M4P6T were 9, 18, 23, 2, and 36, respectively (Fig. 6). All sequences were selected randomly, and rarefaction curves were constructed according to the numbers of extracted sequences and corresponding OTUs. The rarefaction curves were evaluated to determine whether the number of sequences was sufficient to cover all taxa and to evaluate species richness in the samples. When the number of sequences reached 8000, the rarefaction curve for each sample tended to flatten (Additional file 1: Fig. S2). As the number of sequences increased, the number of corresponding OTUs increased only slightly, indicating that the sequencing depth covered all species and the amount of sequencing data was sufficient to reflect the species diversity in the sample.

Alpha diversity analysis of the soil rhizosphere bacteria

Microbial community coverage for all treatments was > 0.975, indicating that the sequencing results were

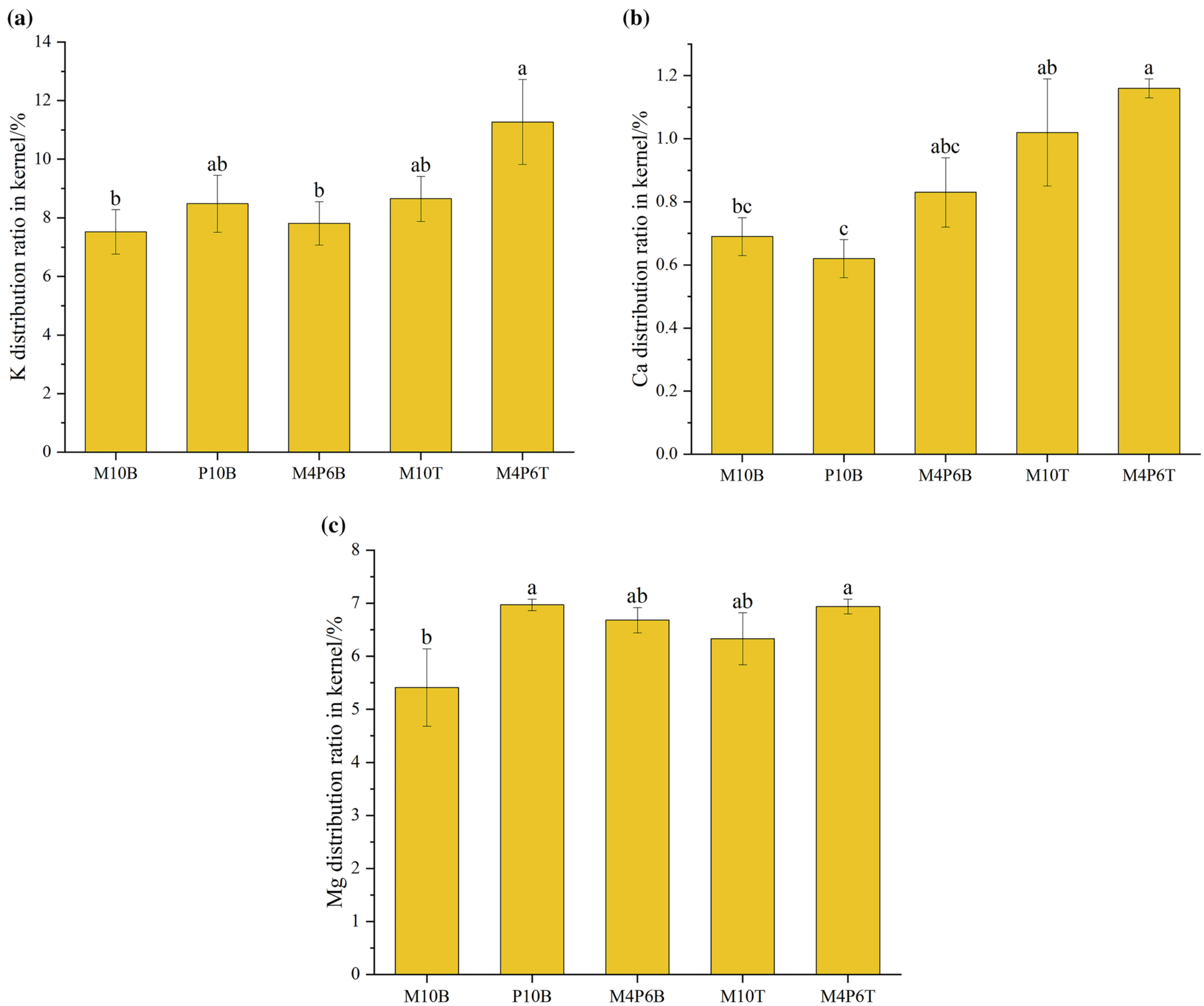


Fig.4 Distribution ratio of K, Ca and Mg in kernel. **a** K distribution ratio, **b** Ca distribution ratio, **c** Mg distribution ratio. K distribution ratio in kernel = K accumulation in kernel/K accumulation of the plant. Ca or Mg distribution ratio was calculated in the same way as K distribution ratio

reliable and representative and that the richness and diversity of the rhizosphere soil microbial communities were affected mainly by the fertilization treatments (Table 3). The Sobs, Ace, and Chao1 indices reflected the bacterial richness in the peanut rhizosphere soil, with values ranging from 895.50 to 1201.00, 1262.20 to 1582.80, and 1223.59 to 1553.61, respectively. The Shannon index reflected the bacterial diversity in the soil rhizosphere and ranged from 4.15 to 5.14. The Simpson index, which reflects the bacterial diversity in the soil rhizosphere, had the opposite trend to the Shannon index, ranging from 0.028 to 0.101. The Sobs and Shannon indices revealed that the M4P6B and M4P6T treatments resulted in greater bacterial diversity than did the M10B treatment. P10B, M4P6B, and M4P6T resulted in higher Ace and Chao1 indices than observed for M10B. The lowest Sobs, Ace, and Chao1 indices were observed for the M10T treatment.

Composition of the microbial communities in the soil rhizosphere at the phylum and genus levels

The composition of the bacterial communities was studied at the phylum and genus levels to investigate differences in the soil rhizosphere microbial structure under the fertilization treatments. The dominant bacteria at the phylum level in all samples were Proteobacteria, Actinobacteriota, Patescibacteria, Bacteroidota, Acidobacteriota, Cyanobacteria, Chloroflexi, Myxococcota, and Gemmatimonadota (Fig. 7a). The relative abundance

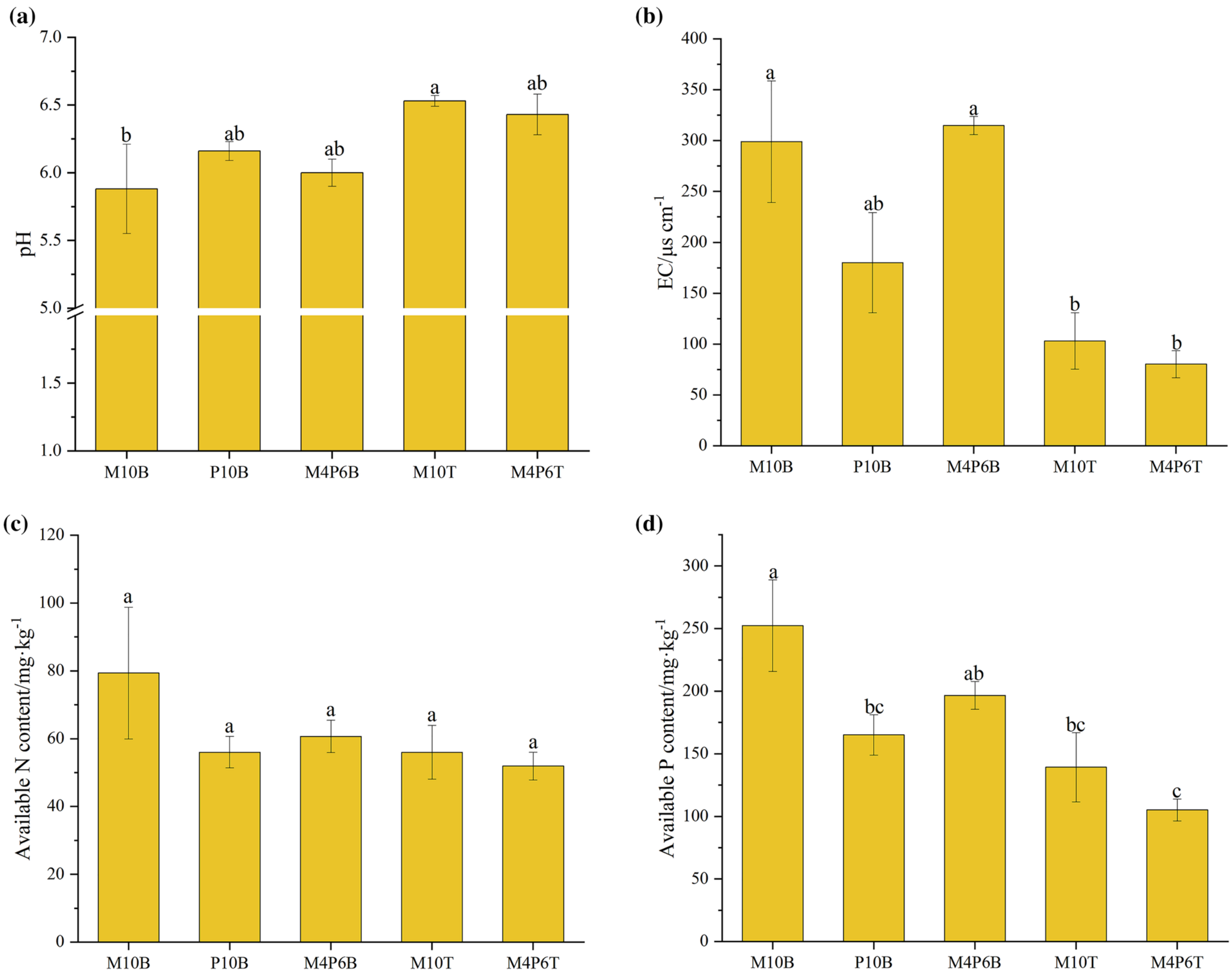


Fig. 5 Basic chemical properties. **a** Soil pH, **b** soil EC, **c** available N, **d** available P, **e** exchangeable K, **f** exchangeable Ca, **g** exchangeable Mg. The values are means ± standard deviation of the replications ($n = 3$). Different letters show statistically significant differences among treatments at $p < 0.05$

was greatest for Proteobacteria, followed by Actinobacteriota, Patescibacteria, and Bacteroidota. The P10B and M10T treatments resulted in greater relative abundances of Proteobacteria than did M10B. The greatest relative abundance of Actinobacteriota was found under the M4P6T treatment. P10B, M4P6B, and M4P6T resulted in greater relative abundances of Patescibacteria and Bacteroidota than did M10B. This finding indicates POLY4 treatment enhanced the relative abundance of dominant soil bacteria at the phylum level. At the genus level, the relative abundance of Bradyrhizobium was the highest, followed by those of Burkholderia–Caballeronia–Paraburkholderia and Sphingomonas (Fig. 7b). Unnamed bacteria comprised large proportions of the samples. The P10B and M4P6B treatments resulted in greater relative abundances of Bradyrhizobium than did M10B. No difference in the relative abundance of Burkholderia–Caballeronia–Paraburkholderia or Sphingomonas was detected among the fertilization treatments.

Metabolic functional characteristics of the bacterial community

Functional annotation of the OTUs was performed using PICRUSt for the analysis of the metabolic functions of the microorganisms. No significant difference in metabolic functional characteristics was detected among the fertilization treatments (Fig. 8a). The main metabolic functional characteristics were amino acid transport and metabolism, general function prediction only, transcription, energy production and conversion, carbohydrate

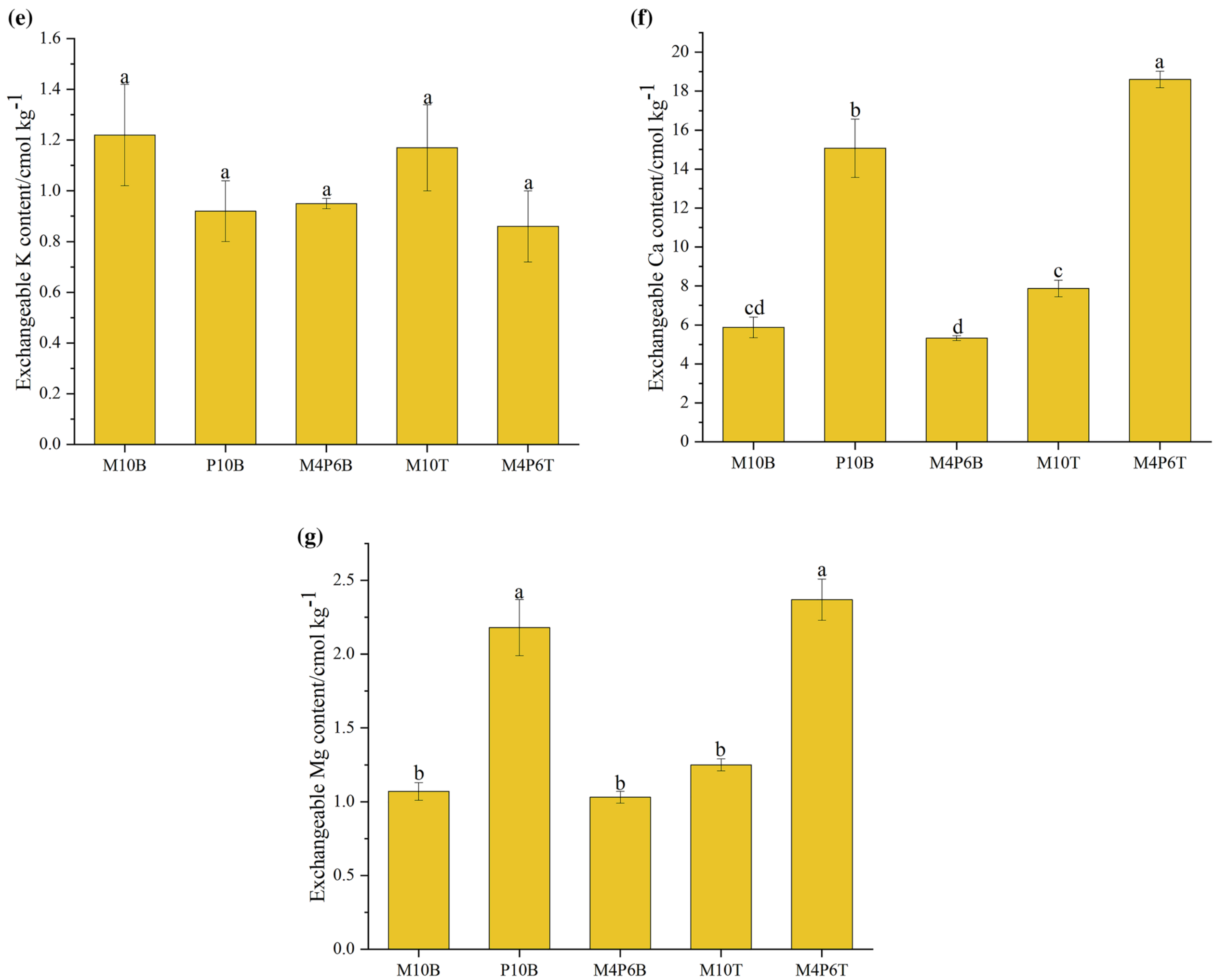


Fig. 5 continued

transport and metabolism, and inorganic ion transport and biogenesis (Fig. 8b). Large proportions of the samples had unknown functional characteristics.

Correlations of soil rhizosphere bacterial communities with soil chemical factors

Spearman's correlation heatmaps showed that most bacteria at the phylum level correlated significantly or extremely significantly with soil chemical factors, including the soil EC, available P, and exchangeable Ca and Mg (Fig. 9). The soil EC correlated positively with Sumerlaeota and Firmicutes. The available P correlated negatively with RCP2-54, Entotheonellaeota, MBNT15, and Methylomirabilota. The exchangeable Ca showed significant and extremely significant positive correlations with RCP2-54 and Deinococcota, and a negative correlation with Sumeriaeota. In addition, the exchangeable Mg correlated positively with RCP2-54 and MBNT15.

Discussion

Effects of fertilization practice on peanut yield and profit

The primary purpose of peanut production is to improve the yield and profit gain. Peanut growth and pod yield can be increased with the proper use of potassium fertilizer [28]. In this study, we found that yield did not differ significantly among fertilization treatments, in contrast to the findings of Tam et al. [29] and Li et al. [30]. The polyhalite fertilization treatments, such as P10B and M4P6B, did not affect the yield compared with M10B. Huang et al. [12] reported that polyhalite is more suitable for use in regions with relatively high rainfall and low available K, due to its slow release. Hence, the lack of difference in yield may be attributed to the higher available soil K content in our experiment. Notably, the management practice of topdressing in the M10T and M4P6T treatments resulted in higher yields than under M10B, although this difference was not significant. The pegging

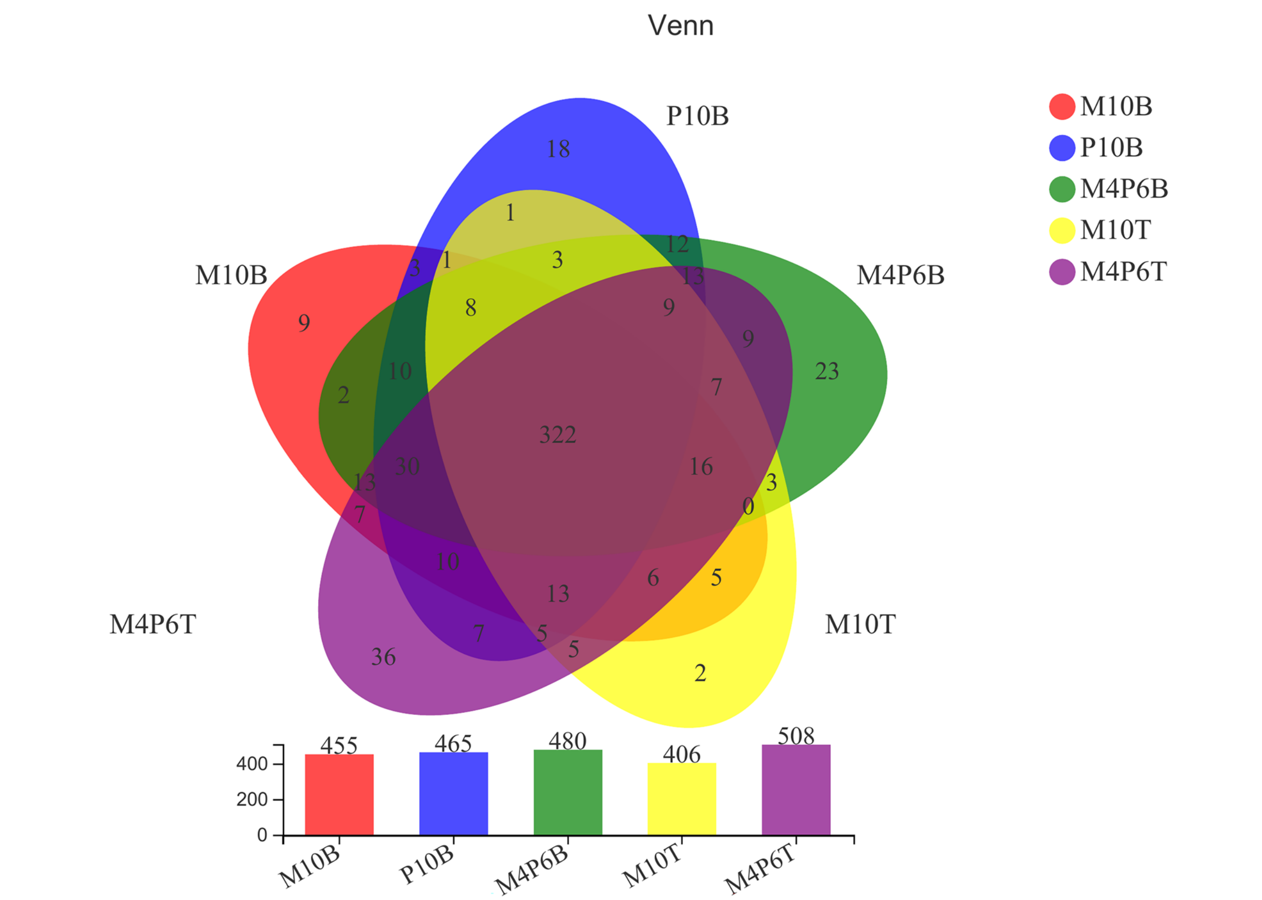


Fig. 6 Venn diagram of OTU levels

Table 3 Alpha diversity index of rhizosphere soil samples

Treatment	Coverage	Sobs	Ace	Chao1	Shannon	Simpson
M10B	0.978 ± 0.0016 ab	984.00 ± 89.00 a	1356.44 ± 104.78 a	1345.40 ± 121.36 a	4.45 ± 0.17 a	0.059 ± 0.025 a
P10B	0.976 ± 0.0008 b	977.50 ± 40.50 a	1582.80 ± 168.65 a	1430.28 ± 43.17 a	4.15 ± 0.21 a	0.101 ± 0.0485 a
M4P6B	0.978 ± 0.0003 ab	1066.50 ± 73.50 a	1433.38 ± 36.19 a	1407.97 ± 49.96 a	4.54 ± 0.49 a	0.069 ± 0.0430 a
M10T	0.980 ± 0.0012 a	895.50 ± 132.50 a	1262.20 ± 115.66 a	1223.59 ± 132.55 a	4.24 ± 0.33 a	0.065 ± 0.0061 a
M4P6T	0.977 ± 0.0004 ab	1201.00 ± 2.00 a	1533.16 ± 12.72 a	1553.61 ± 28.39 a	5.14 ± 0.08 a	0.028 ± 0.0085 a

stage is a critical period for topdressing fertilization [31], indicating that topdressing with K can reduce K fixation in the soil and meet the K demand for plant growth. Net income is affected mainly by differences in the peanut yields and K fertilizer costs. Polyhalite fertilizer is less expensive due to its lower K content. The P10B potassium fertilizer cost more than did the fertilizers for the other treatments under application of the same amount of K. Hence, the M4P6T treatment resulted in the highest yield and profit, which is conducive to alleviation of the pressure of the potash shortage. However, polyhalite is not sold widely as a commercial-grade potash fertilizer. Its price is set according to existing information records, and may change if its Ca and Mg contents are considered.

Effects of the fertilization practice on the absorption of potassium, calcium, and magnesium by different organs

Ca and Mg are important nutrients that affect plant growth and development, in addition to potassium [32]. Calcium deficiency hinders photosynthate translocation and distribution, pod development, and yield [33]. Mg is an activator of various enzymes and plays

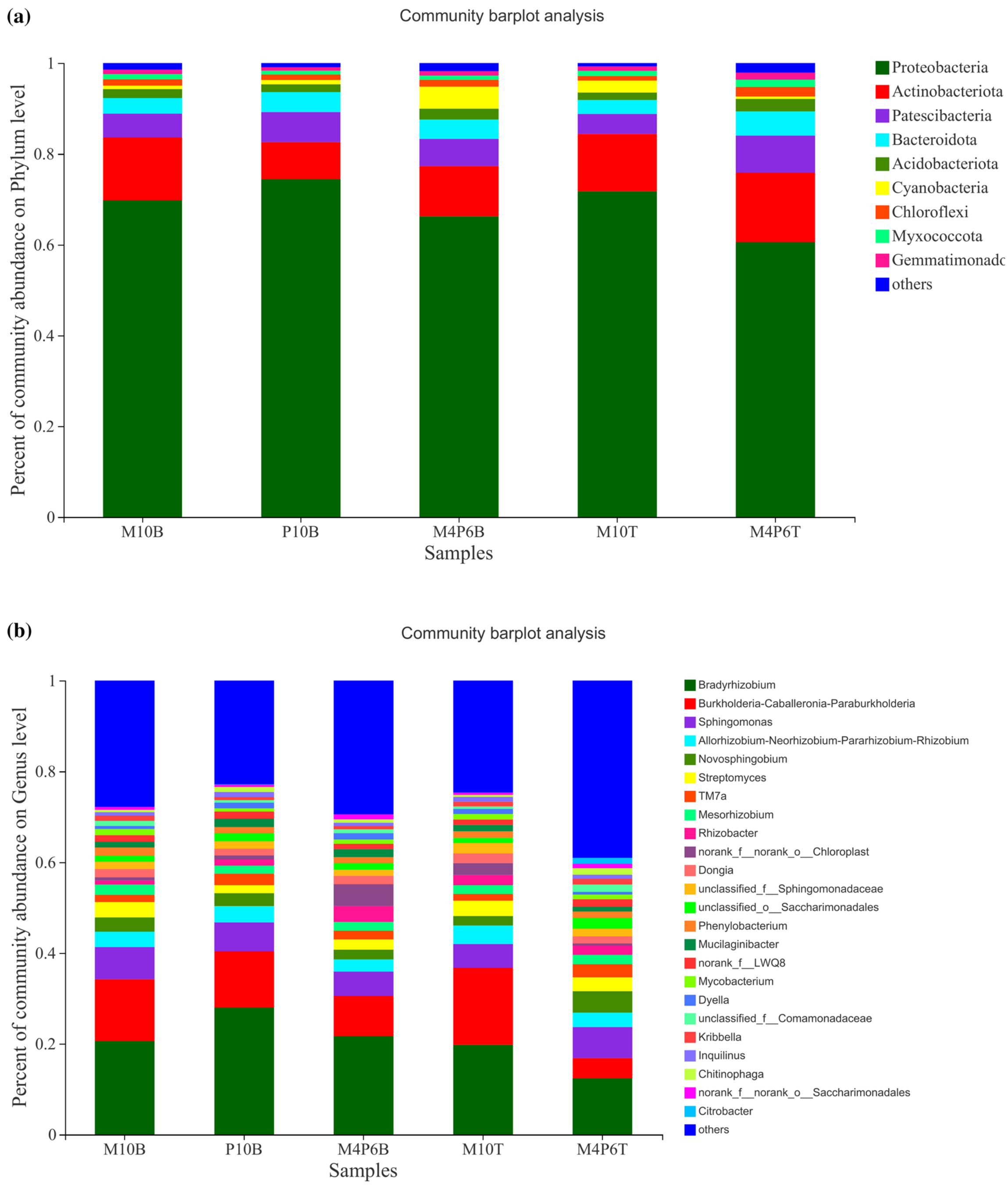


Fig. 7 Abundance analysis of microbial community at the phylum and genus levels. **a** Abundance analysis of microbial community at the phylum, **b** abundance analysis of microbial community at the genus levels

key roles in the formation of carbohydrates, proteins, and fats [34, 35]. Sun et al. [36], Si et al. [37], and Wang et al. [38] reported that fertilization significantly increased nutrient accumulation in the peanut plant, and that K and Ca are located mainly in the stem leaves. Similar results were observed in this study. In addition, we found that the M10T and M4P6T treatments increased the K, Ca, and Mg contents of kernels, but decreased those of roots and shells. We observed that P10B or M4P6B resulted in more accumulation of K and Mg in shells, and that the M4P6T treatment resulted in the greatest accumulation of K, Ca, and Mg

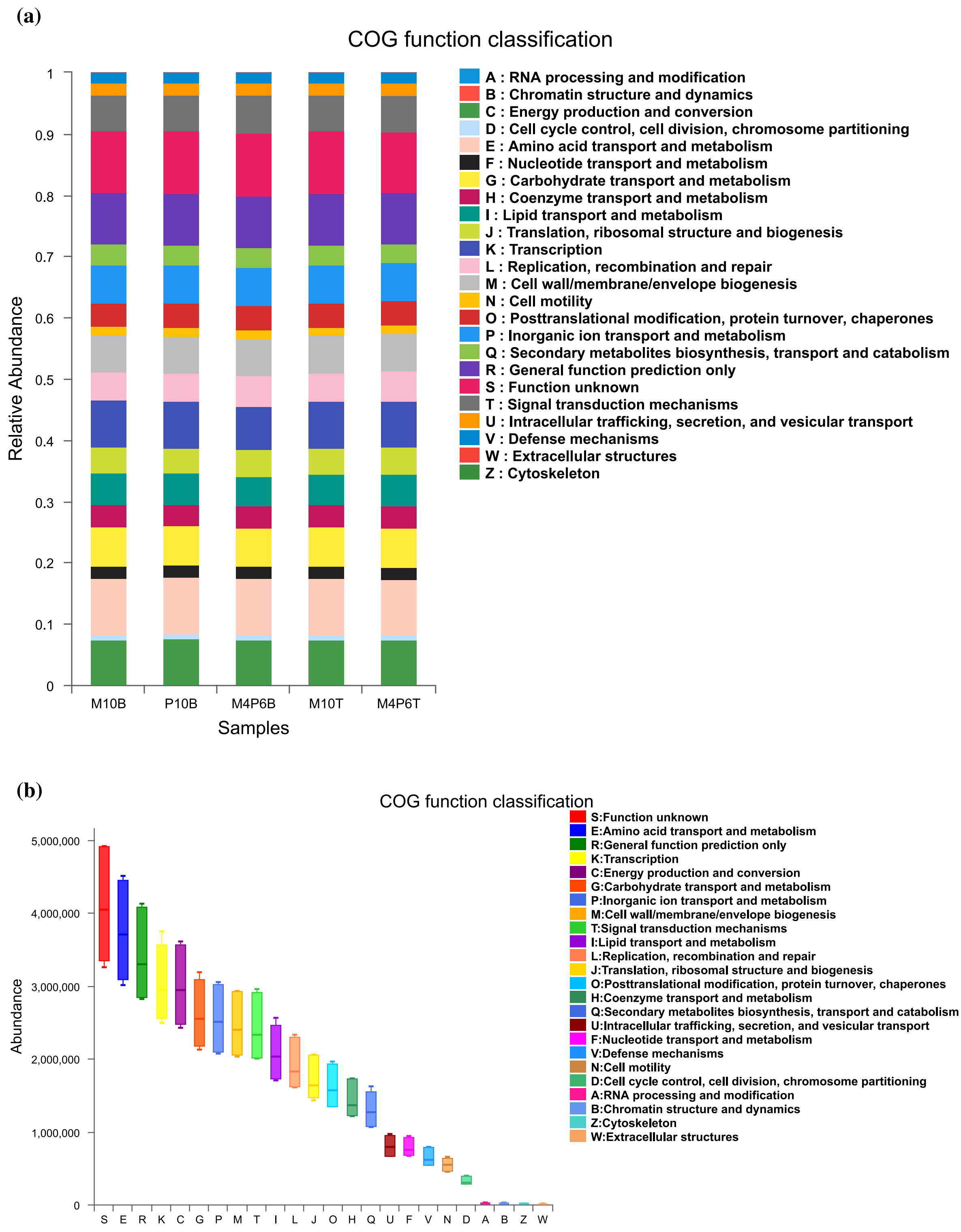


Fig. 8 Microbe functional characteristics analysis based on COG. **a** Metabolic functional characteristic of different fertilization treatments, **b** abundance of microbe functional characteristics

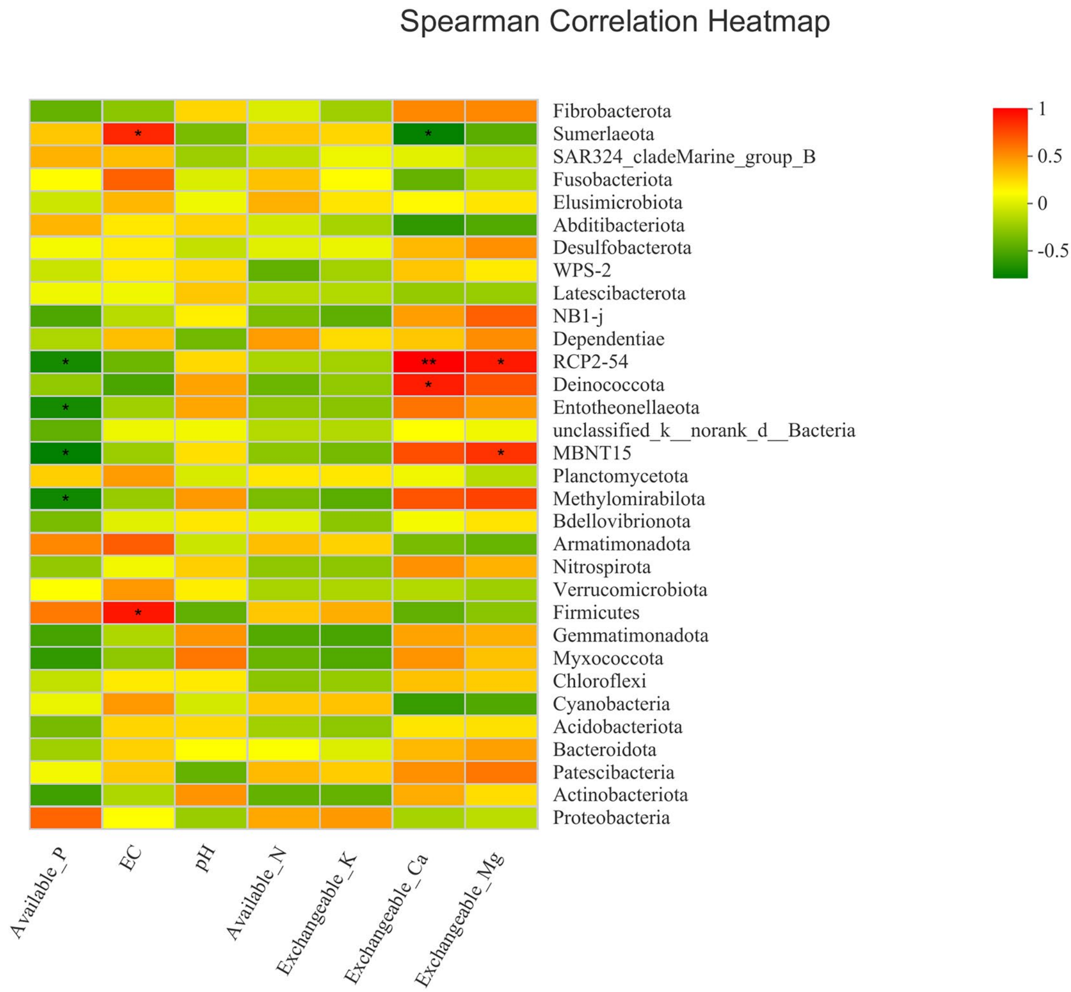


Fig. 9 Spearman correlation heatmap. Statistical significance is considered as * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$. Green or red colors represent a significant negative or positive correlation. The darker the color, the stronger the correlation

in kernels. These results indicate that polyhalite fertilizer application promoted the movement of K, Ca, and Mg to pods, thereby resulting in high-quality peanut production. The uptake of K, Ca, and Mg by crops is affected by many factors, and the interaction among them also affects nutrient absorption [39]. Li et al. [40] confirmed that the interaction between K, Ca, and Mg in tobacco leaves is not a single antagonism, as K has a strong inhibitory effect on Ca and Mg. However, among all of the treatments, polyhalite application was advantageous in terms of the absorption and accumulation of K, Ca, and Mg in the reproductive organs and further expansion of the sink source. These findings agree with those reported by Wang et al. [41]. The main reason was that the antagonism of K, Ca, and Mg occurred predominantly at high concentration levels. Polyhalite was applied as a partial substitute, and its supply of Ca and Mg was low. When the content of calcium and magnesium is low, the interaction between potassium, calcium and magnesium is mainly a synergistic reaction. However, the human dietary intake of K is often too low, about one-third of the evolutionary intake [42]. In this study, the M4P6T treatment increased the distribution rates of K, Ca, and Mg in kernels. The benefits of increasing the intake of minerals in the human diet may be achieved by enhancing minerals in crops [43, 44], which also indirectly indicates the feasibility of the partial substitution of polyhalite for MOP.

Effects of the fertilization practice on soil basic chemical properties

Soil quality indicators consist of the basic chemical properties and microbial biodiversity, which are associated with key soil ecosystem functions [45]. Rational fertilization is key to increase the agricultural yields and improve soil quality [46, 47]. Many studies have shown that long-term use of chemical fertilizers acidifies and compacts the soil, among other hazards [48, 49]. The use of polyhalite fertilizer is considered harmless, with the development of green agriculture. Previous research has shown that polyhalite fertilizer application improves the soil quality, including reduced soil acidity and enriched K, Ca, and Mg contents [18]. Similar results were obtained in our study; the treatments based on polyhalite fertilizer resulted in higher soil pH than did the MOP treatments. Polyhalite is rich in Ca, Mg, S, and other mineral elements. The cations, of these minerals, such as Ca^{2+}, Mg^{2+}, and K^{+}, replace Al^{3+} on soil colloids and neutralize H^{+} in the soil solution, thereby improving the soil pH [50]. The M10T treatment resulted in higher soil pH values than did M10B. Soil properties are affected greatly by the fertilization mode [51]; the M10T treatment reduced nutrient leaching, which decreased soil acidity. The polyhalite fertilizer treatments resulted in lower soil EC and exchangeable K content, but higher exchangeable Ca and Mg contents, in this study. The soil EC reflects the content of salt ions in the soil. Barbier et al. [52] reported that polyhalite has a lower salt index and lower solubility than does MOP muriate. Topdressing fertilizer application is more favorable for nutrient absorption, as it reduces the soil EC. Zhao et al. [14] reported a significantly higher residual K content with the use of MOP fertilizer than with the use of POLY4 fertilizer. Polyhalite fertilizer application effectively increased the soil Ca and Mg contents [18].

Effects of the fertilization practice on soil rhizosphere microorganisms

The composition and activity of the soil microbial community largely determine the soil biogeochemical cycles, fertility, and quality [53, 54]. The most important effects of fertilization for soil microorganisms are those on the soil physical and chemical properties and nutrient contents [55]. The Sobs, Ace, Chao1, and Shannon indices were higher after polyhalite fertilizer application. This practice increased the proportions of beneficial bacteria, such as Proteobacteria and Actinobacteriota, in the soil compared with MOP fertilizer application. This may have occurred, because polyhalite maintained the loose state of the soil aggregates, avoided soil hardening and salinization [12], and provided multiple minerals [52]. Bacteria tend to prefer nutrient-rich soil environments, which are favorable for their growth [53, 54]. Beneficial bacteria improve the soil quality and promote crop growth. In addition, significant correlations were observed between some soil chemical factors and bacteria in this experiment. For example, the soil EC correlated positively with Firmicutes, and the exchangeable Ca content correlated with Deinococcota. We demonstrated that fertilizer application changed the bacterial diversity in the soil rhizosphere by changing the nutrient structure of the soil [55]. The composition and diversity of soil microbial communities are influenced by many factors, such as the method and type of fertilization [56, 57]. Long-term positioning tests should be performed to further explore the effect of fertilization on soil microorganisms.

Conclusions

Plant nutrient absorption, soil chemical properties, bacterial diversity indices, and bacterial community composition changed significantly after the application of different proportions of polyhalite fertilizer as a substitute for KCl fertilizer. Polyhalite fertilizer application increased K, Ca, and Mg uptake by peanut kernels, reduced soil acidification, supplemented soil nutrients, and increased the abundance of beneficial microorganisms. The soil chemical characteristics were related closely to the bacterial community composition. The soil EC and exchangeable Ca and Mg contents were the main factors correlated with the bacterial communities. The peanut yield under the 60% polyhalite fertilizer substitution treatment did not differ significantly from, but was slightly higher than, that under the KCl treatment, and profits were largest under the former. Thus, we recommend substitution with 60% polyhalite fertilizer to improve peanut yields and agricultural sustainability.

Abbreviations

MOP: Potassium chloride; SOP: Potassium sulfate; K: Potassium; Ca: Calcium; Mg: Magnesium; sulphate: S; POLY4: Polyhalite; N: Urea; P: Phosphorus; M10B: No polyhalite fertilizer and only MOP fertilizer applied as base fertilizer; P10B: The proportion of polyhalite fertilizer replacing MOP fertilizer being 100% applied as base fertilizer; M4P6B: The proportion of polyhalite fertilizer replacing MOP fertilizer being 60% applied as base fertilizer; M10T: No polyhalite fertilizer and only MOP fertilizer, and 60% MOP fertilizer was applied as base fertilizer and the remaining 40% MOP fertilizer was applied as topdressing fertilizer; M4P6T: The proportion of polyhalite fertilizer replacing MOP fertilizer being 60% applied as base fertilizer, and 40% MOP fertilizer was applied as topdressing fertilizer; ICP-AES: Plasma atomic emission spectroscopy; soil EC: Soil electrical conductivity; DNA: Deoxyribose nucleic acid; EC: Electrical conductivity.

Supplementary Information

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Additional file 1: Fig. S1 Mean temperature and precipitation every half-month during the field experiment in 2019. **Fig. S2** Rarefaction curve.

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Author contributions
HT: investigation, data analysis, writing original draft. YC: investigation, data curation. CL: methodology, project administration. FZ: software. CH: resources, supervision. HZ: software. XF: resources, validation. DY: validation, writing review and editing, supervision. DZ: reviewing and editing. All authors read and approved the final manuscript.

Availability of data and materials
All data were presented in the manuscript.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All authors listed have read the complete manuscript and have approved submission of the paper.

Competing interests
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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References

1. Toomer OT. Nutritional chemistry of the peanut (Arachis hypogaea). Crit Rev Food Sci Nutr. 2018;58(17):3042–53.
2. Settaluri VS, Kandala CVK, Puppala N, Sundaram J. Peanuts and their nutritional aspects-a review. Food Nutr Sci. 2012;3:1644–50.
3. United States Department of Agriculture (USDA). World Agricultural Production. March 2022. https://downloads.usda.library.cornell.edu/usda-esmis/files/5q47rn72z/vx022j10w/j0990g31m/production.pdf.
4. Zahoor R, Dong HR, Abid M, Zhao WQ, Wang YH, Zhou ZG. Potassium fertilizer improves drought stress alleviation potential in cotton by enhancing photosynthesis and carbohydrate metabolism. Environ Exp Bot. 2017;137:73–83.
5. Kemp SJ, Smith FW, Wagner D, Mounteney I, Bell CP, Milne CJ, Gowing CJB, Pottas TL. An improved approach to characterize potash-bearing evaporite deposits, evidenced in North Yorkshire. UK Econ Geol. 2016;111(3):719–42.
6. Zörba C, Senbayram M, Peiter E. Potassium in agriculture-status and perspectives. J Plant Physiol. 2014;171(9):656–69.
7. Albadarin AB, Lewis TD, Walker GM. Granulated polyhalite fertilizer caking propensity. Powder Technol. 2017;308:193–9.
8. Zhou Z, Chen K, Yu H, Chen QR, Wu FC, Zeng XZ, Tu SH, Qin YS, Meakin R, Fan XH. Changes in tea performance and soil properties after three years of polyhalite application. Agron J. 2019;111:1967–76.
9. S HJ. Polyhalite as a source of potash to plants. J Franklin I. 1933;215(2):168.
10. Yuan JQ. Brief introduction of foreign polyhalite materials. Ind Miner Process. 1974;06:47–58.
11. Tan HT, Sun W, Cui YZ, Wei QQ, Li TS, Yan DY. Present situation of potash resources and analysis of development and application of polyhalite. Inorg Chem Ind. 2022;54(06):23–30.
12. Huang XZ, Chen BY. Agricultural fertilizer efficiency test of Nongle polyhalite rock (mine). China Non-metallic Min Ind. 1990;02:26–31.
13. Ding YX. Brief report on application of polyhalite mineral powder to ramie. Plant Fiber Sci China. 1992;03:40.
14. Zhao LY. Study on the effect of polyhalite on crop growth. Tai'an: Shandong Agricultural University; 2015.
15. Mello SDC, Pierce FJ, Tonhati R, Almeida GS, Neto DD, Pavuluri K. Potato response to polyhalite as a potassium source fertilizer in Brazil: yield and quality. HortSci. 2018;53(3):373–9.
16. Wang Y, Li WQ, Zhao LY, Li HH. Effect of polyhalite on corn growth and nutrient uptake. Soil Fert Sci China. 2018;06:166–73.
17. Tiwari DD, Pandey SB, Katiyar NK. Effects of polyhalite as a fertilizer on yield and quality of the oilseed crops mustard and sesame. Int Potash Inst. 2015;42:10–7.
18. Mello SDC, Tonhati R, Neto DD, Darapuneni M, Pavuluri K. Response of tomato to polyhalite as a multi-nutrient fertilizer in southeast Brazil. J Plant Nutr. 2018;41(16):2126–40.
19. Bansal SK, Kumar S. Effect of SOP on yield and quality of potato. Fertil News. 1998;43:43–6.
20. Song WF, Shu AP, Liu JA, Shi WC, Li MC, Zhang WX, Li ZZ, Liu GR, Yuan FS, Zhang SX, Liu ZB, Gao Z. Effects of long-term fertilization with different substitution ratios of organic fertilizer on paddy soil. Pedosphere. 2022;32(4):637–48.
21. Lin YT, Yin SM. Distribution, genesis and significance of shallow-seated polyhalite ore in Quxian Sichuan. Acta Geol Sichuan. 1998;18(02):121–5.
22. Wu ZF, Sun XW, Wang CB, Zheng YP, Wang SB, Liu JH, Zheng YM, Wu JX, Feng H, Yu TY. Effects of low light stress on rubisco activity and the ultrastructure of chloroplast in functional leaves of peanut. Chin J Plant Ecol. 2014;38(7):740–8.
23. Lu LK. Analytical methods of soil and agricultural chemistry. Beijing: Chinese Agricultural Science and Technology Press; 1999.
24. Yang SJ, Shi PB, Wang HQ, Liu YW, Zheng L, Li TS, Cong HL, Yu B. Research on aging and acidification performance of commercial archival paper. Ferroelectrics. 2022;593:158–65.
25. Bao SD. Soil and agrochemical analysis. 3rd ed. Beijing: China Agriculture Press; 2007.
26. Pii Y, Borruso L, Brusetti L, Crecchio C, Cesco S, Mimmo T. The interaction between iron nutrition, plant species and soil type shapes the rhizosphere microbiome. Plant Physiol Bioch. 2016;99:39–48.
27. Chen YL, Tu PF, Yang YB, Xue XH, Feng ZH, Dan CX, Cheng FX, Yang YF, Deng LS. Diversity of rice rhizosphere microorganisms under different fertilization modes of slow-release fertilizer. Sci Rep. 2022;12:2694.
28. Wang YF, Kang YJ, Wang ML, Zhao CX. Effects of potassium application on the accumulated nitrogen source and yield of peanut. J Nucl Agric Sci. 2013;27(01):126–31.
29. Tam HM, Manh DM, Thuan TT, Cuong HH, Bao PV. Agronomic efficiency of polyhalite application on peanut yield and quality in Vietnam. Int Potash Inst. 2016;47:3–11.
30. Li HH, Li WQ, Wang Y, Zhao LY. Effect of polyhalite on peanut growth and nutrient uptake. J Agric Resour Environ. 2019;36(2):169–75.
31. Wu QH, Wang Y, Zhao YN, Li RK, Si YK, Huang YF, Ye YL, Zhang FS. Effects of NPK ratio on yield, nutrient absorption and economic benefit of high-yielding summer peanut in a fluvo-aquic soil. Soil Fert Sci China. 2019;2:98–104.
32. Tränkner M, Tavakol E, Jákli B. Functioning of potassium and magnesium in photosynthesis, photosynthate translocation and photoprotection. Physiol Plant. 2018;163:414–31.
33. Dang XS, Jiang CJ, Li JL, Zhao KN, Qu SN, Liu N, Wang J, Wang XG. Effects of calcium fertilizer on yield and physiological characteristics of peanut. J Shenyang Agric Univ. 2018;49(6):717–23.
34. Nishizawa Y, Morii H, Durlach J. New perspectives in magnesium research. London: Spring-Verlag; 2007.
35. Zheng YP, Wu ZF, Wang CX, Wang CB, Shen P, Zhao HJ, Feng H, Sun XS. Response of peanut magnesium nutrient characteristics to various tillage measures in brown soils. J Nucl Agric Sci. 2018;32(12):2406–13.
36. Sun YH, Liang YY, Yu MY, Qu XM. Study on the absorption and translocation of N, P, and K in peanut. Soil Fert Sci China. 1979;05:40–3.

37. Si XZ, Zhang X, Suo YY, Mao JW, Li L, Li GP, Yu H. Differences of peanut genotype on NPK uptake, distribution and utilization on vertisol soil. Chin J Oil Crop Sci. 2017;39(3):380–5.
38. Wang JG, Zhang H, Li L, Liu DW, Wan SB, Wang F, Lu S, Guo F. Effects of calcium application and plastic film mulching cultivation on accumulation, distribution and utilization efficiency of Ca in peanut in red soil under Ca deficiency. Acta Agric Boreali-Sinica. 2017;32(6):205–12.
39. Ma JM, Li HX, Zhang XK. Effects of different potassium application amounts on the growth and uptake of calcium and magnesium in tomato under facility condition. Soil Fert Sci China. 2021;3:90–5.
40. Li J, Zhang MQ, Lin Q, Chen ZC, Xie GQ, Peng JG, Xiong DZ. Effects of interaction of potassium, calcium and magnesium on flue-cured tobacco growth and nutrient absorption. J Anhui Agric Univ. 2005;32(4):529–33.
41. Wang YL, Li DX, Lu DJ, Xu XY, Chen XQ, Zhao ZX, Wang HY, Fan XH, Meakin R. Effect of root-zone application of polyhalite on yield, quality and nutrient absorption of flue-cured tobacco in Kunming. Soil Fert Sci China. 2021;3:199–206.
42. He FJ, MacGregor GA. Beneficial effects of potassium on human health. Physiol Plant. 2008;133(4):725–35.
43. Demingé C, Sabboh H, Rémésy C, Meneton P. Protective effects of high dietary potassium: nutritional and metabolic aspects. J Nutr. 2004;134(11):2903–6.
44. Römheld V, Kirkby EA. Research on potassium in agriculture: needs and prospects. Plant Soil. 2010;335:155–80.
45. Muñoz-Rojas M. Soil quality indicators: critical tools in ecosystem restoration. Curr Opin Environ Sci Health. 2018;5:47–52.
46. Ju XT, Zhang C. Nitrogen cycling and environmental impacts in upland agricultural soils in north china: a review. J Integr Agric. 2017;16(12):2848–62.
47. Zhao R, Wu J, Jiang C, Liu F. Effects of biochar particle size and concomitant nitrogen fertilization on soil microbial community structure during the maize seedling stage. Environ Sci Pollut Res. 2020;27:13095–104.
48. Guo JH, Liu XJ, Zhang Y, Shen JL, Han WX, Zhang WF, Christie P, Goulding KWT, Vitousek PM, Zhang FS. Significant acidification in major Chinese croplands. Sci. 2010;327:1008–10.
49. Liu EK, Yan CG, Mei XR, He WQ, Bing SH, Ding LP, Liu Q, Liu S, Fan TL. Long-term effect of chemical fertilizer, straw, and manure on soil chemical and biological properties in northwest China. Geoderma. 2010;158:173–80.
50. Zhao LF, Huang PW, Chen H, Lu QG. Effects of soil conditioner and organic fertilizer on soil acidification and fertility cultivation in red soil tea garden. J Zhejiang Agric Sci. 2022. https://doi.org/10.16178/j.issn.0528-9017.20220535.(Preprint).
51. Zhang X, Davidson EA, Mauzerall DL, Searchinger TD, Dumas P, Shen Y. Managing nitrogen for sustainable development. Nat. 2015;528:51–9.
52. Barbier M, Li YC, Liu GD, He ZL, Mylavarapu R, Zhang SA. Characterizing polyhalite plant nutritional properties. Agric Res Technol Open Access J. 2017;6(3):65–73.
53. Xu Y, Zhang GC, Ding H, Ci DW, Qin FF, Zhang ZM, Dai LX. Effects of salt and drought stresses on rhizosphere soil bacterial community structure and peanut yield. Chin J Appl Ecol. 2010;31(4):1305–13.
54. Tian PY. Bacterial diversity in rhizospheres of salt-tolerant plants, PGPR screening and microflora construction. Yinchuan: Ningxia University; 2019.
55. Kong X, Jin D, Tai X, Yu H, Duan G, Yan XL, Pan JG, Song JH, Deng Y. Bioremediation of dibutyl phthalate in a simulated agricultural ecosystem by Gordonia sp. strain QH-11 and the microbial ecological effects in soil. Sci Total Environ. 2019;667:691–700.
56. Zhou J, Lei T. Review and prospects on methodology and affecting factors of soil microbial diversity. Biodiversity Sci. 2007;15(3):306–11.
57. Denef K, Roobroeck D, Manimel-Wadu MCW, Lootens P, Boeckx P. Microbial community composition and rhizodeposit-carbon assimilation in differently managed temperate grassland soils. Soil Biol Biochem. 2009;41(1):144–53.

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