Effects of Mineral and Particle-Size Composition on Nutrient and Salt Contents of Farmland Soils in the Hotan Region

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Abstract

This study analyzed the causes of low soil nutrient content in the Hotan region from the perspectives of soil mineral and particle composition. Using the grid sampling method, 255 sampling points were established in cultivated and garden land to analyze the correlations of soil mineral composition and particle composition with nutrients and salinity. The results showed that soil particles in the Hotan region were dominated by sand (50.30% by mass) and silt (41.40%), while clay accounted for only 8.30%. Sand content was significantly negatively correlated with organic carbon, total nitrogen, alkali-hydrolyzable nitrogen, total phosphorus, available phosphorus, total potassium, total salt, and available iron, manganese, copper, and zinc contents (P<0.05), whereas silt content was significantly positively correlated with all the above indicators (P<0.05). However, the low content of clay minerals made a limited contribution to nutrient accumulation. Feldspar (4.6%) and mica (5.1%) were extremely significantly positively correlated with total potassium (P<0.05). Low clay mineral content and high sand content are the reasons for the low soil nutrient content in the Hotan region. Accordingly, increasing the application of organic fertilizer and clay minerals to provide nutrients and promote aggregate formation is an effective measure for improving farmland soil fertility in the Hotan region.

Full Text

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Abstract: To identify the reasons for the low soil nutrient contents in the Hotan region from the perspective of soil mineral and particle-size composition, 255 sampling points were arranged in cultivated garden land using the grid-point method. The correlations of soil mineral composition and particle-size composition with nutrients and salts were analyzed. The results showed that soil particles in the Hotan region were dominated by sand (50.30% by mass) and silt (41.40%), whereas clay accounted for only 8.30%. Sand content was significantly negatively correlated with organic carbon, total nitrogen, alkali-hydrolyzable nitrogen, total phosphorus, available phosphorus, total potassium, total salt, and the contents of available iron, manganese, copper, and zinc ($P < 0.05$); in contrast, silt content was significantly positively correlated with all of the above indicators ($P < 0.05$). The relatively high sand content accelerated mineralization and decomposition, increased porosity and permeability, and weakened adsorption capacity, resulting in a low soil organic carbon content (5.55 g · kg−1), moderately low levels of total nitrogen (0.76 g · kg−1), total potassium (16.24 g · kg−1), and available potassium (182.71 mg · kg−1), and a moderate degree of salinization (total salt content of 2.99 g · kg−1). Available iron (28.4 mg · kg−1) and zinc (1.6 mg · kg−1) were at high and extremely high levels, respectively, while available manganese (9.1 mg · kg−1) and copper (0.7 mg · kg−1) were at medium levels, which may be related to the abundant adsorption sites provided by silt. The mineral composition was dominated by primary minerals such as quartz (73.4%); among secondary minerals, calcite content was relatively high (12.1%), whereas clay mineral content was low (10.2%). Clay mineral content was significantly positively correlated with the contents of total potassium, organic carbon, and available iron, manganese, copper, and zinc ($P < 0.05$), but the low clay mineral content made only a limited contribution to nutrient accumulation. Feldspar (4.6%) and mica (5.1%) were extremely significantly positively correlated with total potassium ($P < 0.05$); mica, as an important source of structural magnesium, was positively correlated with available magnesium (104.9 mg · kg−1) ($P < 0.05$). Low clay mineral content and high sand content are the reasons for the low soil nutrient contents in the Hotan region. On this basis, increasing the application of organic fertilizer and clay minerals to supply nutrients and promote aggregate formation is an effective measure for improving farmland soil fertility in the Hotan region.

Keywords: clay minerals; particle-size composition; soil nutrients; soil salinity; Hotan region

Soil fertility refers to the capacity of soil to supply the water, nutrients, air, and heat required for plant growth. The level of soil fertility is closely related to natural processes, such as mineral composition, particle size, and biological accumulation, as well as to human activities. The types and contents of soil minerals play a role in nutrient retention[1]. According to their origin, minerals can be divided into primary minerals and secondary minerals. Primary minerals such as feldspar and mica are important sources of potassium; feldspar is also rich in silicon, sodium, and calcium, as well as small amounts of manganese and copper, while mica contains magnesium, iron, calcium, sodium, and various trace elements. Secondary minerals such as montmorillonite, chlorite, kaolinite, and illite are formed by recrystallization after chemical alteration or decomposition of primary minerals. Their surfaces generate negatively charged exchange sites, which adsorb and retain various nutrients by forming outer-sphere complexes[2–3]. Accordingly, the application of clay minerals to farmland can enhance soil fertility. For example, Li Min et al.[4] showed that the application of phosphogypsum and potassium feldspar can effectively increase the contents of macro-and medium-quantity nutrients such as phosphorus, potassium, calcium, magnesium, and silicon in farmland soil. Zhao Zhirui et al.[5] reported that applying clay minerals such as bentonite and sepiolite can inhibit the formation of calcium phosphate precipitates in soil and prolong nitrogen retention time by adsorbing NH4+, thereby improving soil fertility.

Particles are the basic constituent units of soil structural bodies. Their composition, distribution, particle size, combination ratio, and arrangement have significant effects on nutrient and salt contents[6]. Because clay and silt have small particle sizes, large specific surface areas, and carry abundant and relatively large amounts of nutrients, soils with higher proportions of clay and silt often have higher nutrient contents. In addition, as an inorganic cementing material, clay can promote particle flocculation and aggregation,

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By adsorbing organic matter and cations, they form organic–inorganic complexes, thereby enhancing aggregate stability and improving the soil’ s nutrient-retention capacity. In contrast, sand particles have large particle sizes, small specific surface areas, weak nutrient-adsorption capacity, and no colloidal properties, which is unfavorable for aggregate formation; therefore, soils with high sand content have lower nutrient contents[7-10]. With respect to salts, soils with high clay and silt contents, owing to their fewer macropores and larger specific surface areas, have stronger adsorption of salts, leading to salt accumulation; sand particles, by contrast, are relatively dispersed and have difficulty retaining water, so salts are leached with water, reducing salt accumulation[11-12]. Therefore, salt content is negatively correlated with sand content and positively correlated with silt and clay contents[13-14].

Hotan Prefecture is located at the southernmost end of Xinjiang. Because it is affected by wind-blown sand, the ecological environment is harsh; moreover, with a large population and limited land, the per capita cultivated land area is only 0.086 hm^2. The fertility of cultivated soils is poor, and local soil salinization is relatively severe, resulting in low local grain yields, high production costs, and great difficulty in increasing farmers’ income[15-16]. Therefore, it is highly necessary to systematically determine the current status of soil nutrients and salts in farmland soils of Hotan Prefecture and their influencing factors. Accordingly, this study adopted a grid-based sampling method and established 255 sampling points in cropland and orchard land. The contents of soil pH, organic carbon, total nitrogen, alkali-hydrolyzable nitrogen, total phosphorus, available phosphorus, total potassium, rapidly available potassium, total salts, available iron, available manganese, available copper, and available zinc, as well as mineral composition and particle composition, were analyzed to determine the current status of soil salinity and nutrients in farmland soils of the region. Through correlation analysis between mineral composition, particle composition, and nutrient contents, the effects of minerals and particles on farmland nutrient and salt contents were revealed, with the aim of providing basic data and reference for soil improvement and land productivity enhancement in Hotan Prefecture.

1 Data and Methods

1.1 Overview of the Study Area

Hotan Prefecture is located in the southernmost part of Xinjiang (78°17′–82°38′E, 36°52′–37°19′N), on the northern slope of the Kunlun Mountains and adjacent to the Taklimakan Desert, with an area of 24.78×10^4 km^2. Administratively, it comprises seven counties and one city: Hotan City, Hotan County, Moyu County, Pishan County, Lop County, Qira County, Yutian County, and Minfeng County. The region has a typical extremely arid desert climate, with annual precipitation of 28.9-47.1 mm, evaporation as high as 2198-2790 mm, a mean annual temperature of 12.5 °C, and more than 220 days of dusty weather per year[15]. The terrain is higher in the south and lower in the north. In the southern Kunlun Mountains, elevations range from 3000 to 6000 m, with the highest point exceeding 7000 m. Northward from the foothills of the Kunlun Mountains are, in sequence, the Gobi belt, the river alluvial-fan oasis belt, and finally the Taklimakan Desert, which extends to the center of the Tarim Basin[15]. The cultivated land area of Hotan Prefecture is 2.16×10^3 km^2, and the orchard land area is 1.45×10^3 km^2. The main crops include wheat, maize, and cotton, while the main fruit trees are jujube and walnut[17]. Soil types include aeolian sandy soil, brown desert soil, meadow soil, and solonchak, among others[18].

1.2 Sampling-Point Layout

A grid-based sampling method was adopted. In combination with factors such as soil type, crop type, and years of cultivation, a 3 km × 3 km grid generated using the ArcGIS fishnet tool was used to set up 255 sampling points within cropland and orchard land; the soil samples collected were used for nutrient and salt determination. In addition, a 30 km × 30 km grid was generated, and 27 points were further selected from among the 255 sampling points; the samples collected from these points were used to determine medium and trace elements as well as mineral composition (Fig. 1).

1.3 Sample Collection

From July to August 2022, soil was collected at each sampling point using the five-point sampling method. The collected samples were thoroughly mixed, and then soil samples were taken by the "quartering method" for physicochemical analysis. At the same time, information such as the longitude and latitude, elevation, soil type, and land-use type of each sampling point was recorded.

1.4 Sample Determination

Soil organic carbon was determined by the potassium dichromate oxidation-volumetric method[19], inorganic carbon by the gasometric method[20]; total nitrogen was determined using an elemental analyzer (Italy

Left map legend: national boundary; undetermined boundary; provincial/autonomous-region boundary.
Right map legend: sampling point; elevation/m; 6929; 1039.

Note: The base map was prepared using the standard map from the National Platform for Common Geospatial Information Services, with approval number GS(2024)0650; no modifications were made to the base-map boundaries.

Fig. 1 Diagram of sampling point distribution

Euro Vector EA3000); alkali-hydrolyzed nitrogen was determined by the alkali diffusion method[20]; total phosphorus was determined by acid dissolution-molybdenum antimony colorimetry[21], and available phosphorus by sodium bicarbonate extraction-molybdenum antimony colorimetry[19]; total potassium was determined by acid dissolution-atomic absorption spectrophotometry, and available potassium by ammonium acetate extraction-flame photometry[22]; medium and trace elements were determined by diethylenetriaminepentaacetic acid (DTPA) extraction-inductively coupled plasma emission spectrometry[23]; pH was determined by the electrode method, and total salt by the gravimetric method[19]; particle composition was determined by the hydrometer method[20], and according to the USDA standard, particles were divided by particle size into three fractions: sand (2–0.05 mm), silt (0.05–0.002 mm), and clay (<0.002 mm); mineral composition was determined by X-ray diffraction[24].

1.5 Data analysis

Based on the classification standards specified in the Technical Regulations for the Second National Soil Survey[25] and relevant literature[26], soil nutrients (Table 1) and trace elements (Table 2) were classified.

SPSS 26.0 was used for statistical analysis, and Pearson correlation coefficients were used to analyze the correlations between soil particle composition and soil nutrients and salts.

Table 1 Soil nutrient and salt classification standards
Tab. 1 Soil nutrient and salt classification standards

Indicator	High	Relatively high	Medium	Relatively low	Low
pH	$ $8.5	8.0–8.5	7.5–8.0	7.2–7.5	$ $7.2
Salinization degree /(g · kg−1)	>6.0	4.0–6.0	2.0–4.0	1.0–2.0	$ $1.0
Organic carbon /(g · kg−1)	>15.0	12.0–15.0	9.0–12.0	6.0–9.0	$ $6.0
Total nitrogen /(g · kg−1)	>1.50	1.00–1.50	0.75–1.00	0.50–0.75	$ $0.50
Alkali-hydrolyzed nitrogen /(mg · kg−1)	>60.0	45.0–60.0	35.0–45.0	25.0–35.0	$ $25.0
Total phosphorus /(g · kg−1)	>1.00	0.80–1.00	0.60–0.80	0.40–0.60	$ $0.40
Available phosphorus /(mg · kg−1)	>30.0	30.0–20.0	15.0–20.0	8.0–15.0	$ $8.0
Total potassium /(g · kg−1)	>25.0	20.0–25.0	15.0–20.0	10.0–15.0	$ $10.0
Available potassium /(mg · kg−1)	>250	200–250	150–200	100–150	$ $100

Table 2 Soil micronutrient content classification standards
Tab. 2 Standards for classification of soil micronutrient content /(mg · kg−1)

Micronutrient	Extremely high	High	Medium	Low	Extremely low
Available iron	>20.0	10.0–20.0	4.5–10.0	2.5–4.5	<2.5
Available manganese	>30.0	15.0–30.0	5.0–15.0	1.0–5.0	<1.0
Available copper	>1.8	1.0–1.8	0.2–1.0	0.1–0.2	<0.1
Available zinc	>3.0	1.0–3.0	0.5–1.0	0.3–0.5	<0.3

2 Results and analysis

2.1 Organic carbon and inorganic carbon

Organic carbon improves soil structure, enhances its capacity for water and fertilizer retention, increases fertility, and optimizes structure[27]. Inorganic carbon mainly exists in the form of carbonate salts and plays an important role in carbon sequestration, maintaining soil quality and a stable carbon balance, and soil fertility[28]. The mean organic carbon content of farmland soil in the Hetao area was 5.55 g · kg−1, with a coefficient of variation of 48.64%, showing moderate variability; the mean inorganic carbon content was 14.54 g · kg−1, with a coefficient of variation of 9.99%, showing weak variability (Table 3).

Table 3 Descriptive statistics of soil organic and inorganic carbon content
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<table>
<tr><th>Indicator</th><th>Minimum</th><th>Maximum</th><th>Mean ± standard deviation</th><th>Coefficient of variation</th></tr>
<tr><td>Organic carbon /(g · kg−1)</td><td>0.74</td><td>13.43</td><td>5.55$±2.70|48.64±$1.45</td><td>9.99%</td></tr>
</table>

2.2 Total nitrogen and alkali-hydrolyzed nitrogen

Nitrogen is an essential element for crop growth and development; it participates in the formation of many important organic compounds in crops and has an extremely important influence on crop yield and quality[1]. Total nitrogen is an indicator for measuring the total reserve of soil nitrogen[29]. Alkali-hydrolyzed nitrogen refers to inorganic nitrogen and readily hydrolyzable organic nitrogen that can be absorbed and utilized by crops; it is an important indicator for measuring the soil' s recent nitrogen supply capacity and reflecting nitrogen availability[30]. The mean total nitrogen content in the study area was 0.76 g · kg−1, with a coefficient of variation of 72.61%, indicating moderate variability; the mean alkali-hydrolyzed nitrogen content was 50.11 mg · kg−1, with a coefficient of variation of 49.45%, also indicating moderate variability (Table 4).

Table 4 Descriptive statistics of soil total nitrogen and alkali-hydrolyzed nitrogen content

Tab. 4 Descriptive statistics of soil total nitrogen and alkali-hydrolyzed nitrogen content

Indicator	Minimum	Maximum	Mean ± standard deviation	Coefficient of variation
Total nitrogen /(g・kg−1)	0.15	4.85	0.76\$±0.55|72.61±\$24.78	49.45%

2.3 Total phosphorus and available phosphorus

Phosphorus is one of the important nutrient elements required by crops. It participates in photosynthesis and various metabolic processes in crops and has effects in promoting growth, increasing yield, and improving quality[31–32]. Total phosphorus includes inorganic phosphorus and organic phosphorus; available phosphorus refers to phosphorus that can be absorbed and utilized by crops, including water-soluble phosphorus, some adsorbed phosphorus, and organic phosphorus[1]. Total phosphorus and available phosphorus respectively characterize the soil' s phosphorus-supply potential and phosphorus-supply level[33]. The mean total phosphorus content was

0.67 $g \cdot kg^{-1}$, with a coefficient of variation of 25.58%, indicating moderate variation; the available phosphorus content was 17.77 $mg \cdot kg^{-1}$, with a coefficient of variation of 103.39%, indicating strong variation (Table 5).

Tab. 5 Descriptive statistics of total and available phosphorus contents in soil

Indicator	Minimum	Maximum	Mean ± standard deviation	Coefficient of variation
Total phosphorus / ($g \cdot kg^{-1}$)	0.40	2.81	0.67\$±0.17|25.58±\$18.3[illegible]	103.39%

2.4 Total potassium and available potassium

Potassium is a key factor affecting crop quality [34]. Total potassium reflects the total reserves of potassium in soil, while available potassium refers to potassium that can be readily absorbed and utilized by crops, directly reflecting the soil' s potassium-supply level for crop growth [35]. The average total potassium content was 16.24 $g \cdot kg^{-1}$, with a coefficient of variation of 7.39%, indicating weak variation; the available potassium content was 182.71 $mg \cdot kg^{-1}$, with a coefficient of variation of 61.96%, indicating moderate variation (Table 6).

Tab. 6 Descriptive statistics of soil total potassium and available potassium content

<table>
<tr><th>Indicator</th><th>Minimum</th><th>Maximum</th><th>Mean ± standard deviation</th><th>Coefficient of variation</th></tr>
<tr><td>Total potassium / ($g \cdot kg^{-1}$)</td><td>12.81</td><td>21.85</td><td>16.24$±1.20|7.39±$113.21</td><td>61.96%</td></tr>
</table>

2.5 Macro and trace elements

Macro elements (Ca, Mg) and trace elements (Fe, Mn, Cu, Zn) are important components of soil fertility and are important sources of enzymes, growth hormones, activators, and vitamins in crops. They have strong specificity, and either deficiency or excess can prevent normal crop growth [1]. The average contents of available calcium and magnesium among macro elements were 381.4 $mg \cdot kg^{-1}$ and 104.9 $mg \cdot kg^{-1}$, respectively, with coefficients of variation of 12.93% and 58.58%, both indicating moderate variation. The average contents of available iron, manganese, copper, and zinc among trace elements were 28.4 $mg \cdot kg^{-1}$, 9.1 $mg \cdot kg^{-1}$, 0.7 $mg \cdot kg^{-1}$, and 1.6 $mg \cdot kg^{-1}$, respectively, with coefficients of variation of 94.80%, 58.56%, 76.23%, and 60.85%. The contents of available iron and zinc were at extremely high and high levels, respectively, while the contents of available manganese and available copper were both at moderate levels (Table 7).

Tab. 7 Content of macro and trace elements in soil

<table>
<tr><th>Indicator</th><th>Minimum</th><th>Maximum</th><th>Mean ± standard deviation</th><th>Coefficient of variation</th><th>Grade</th></tr>
<tr><td>Available calcium / ($mg \cdot kg^{-1}$)</td><td>290.8</td><td>513.0</td><td>381.4$±49.3|12.93±61.5|58.58±27.0|94.80±5.3|58.56±0.6|76.23±$1.0</td><td>60.85%</td><td>High</td></tr>
</table>

2.6 pH and total salt

pH is a key indicator for measuring soil acidity and alkalinity; it affects crop nutrient absorption and growth, and determines the chemical forms and solubility of nutrient substances [36]. Salinity is an important indicator for measuring the degree of salinization. An appropriate amount of salt can meet the needs of normal crop growth, whereas excessive salt inhibits crop water uptake and reduces fertility and productivity [37]. The soil in the study area was weakly alkaline, with an average pH of 8.38 and a coefficient of variation of 5.81%, indicating weak variation; the average total salt content was 2.99 $g \cdot kg^{-1}$, with a coefficient of variation of 111.32%, indicating strong variation (Table 8).

Tab. 8 Descriptive statistics of soil pH and total salt

<table>
<tr><th>Indicator</th><th>Minimum</th><th>Maximum</th><th>Mean ± standard deviation</th><th>Coefficient of variation</th></tr>
<tr><td>pH</td><td>6.87</td><td>9.86</td><td>8.38$±0.49|5.81±$3.33</td><td>111.32%</td></tr>
</table>

2.7 Particle composition

Particle composition has important effects on the physical properties, chemical properties, and fertility of soil. Its size and compositional proportion directly affect soil structure and nutrient contents [1]. In the Hetian area, sand particles, with a mass proportion of 50.30%, and silt particles, with a mass proportion of 41.40%, were the main components, while the clay content, with a mass proportion of 8.30%, was relatively low (Table 9).

Tab. 9 Descriptive statistics of soil particle composition /%

<table>
<tr><th>Soil particle grade</th><th>Minimum</th><th>Maximum</th><th>Mean ± standard deviation</th><th>Coefficient of variation</th></tr>
<tr><td>Sand (>0.05 mm)</td><td>20.73</td><td>87.95</td><td>50.30$±12.94|25.71||Silt(0.05–0.002mm)|4.09|69.68|41.40±12.5 0.002mm)|2.13|15.01|8.30±$1.80</td><td>20.64</td></tr>
</table>

Sand content was significantly negatively correlated with the contents of organic carbon, total nitrogen, alkali-hydrolyzable nitrogen, total phosphorus, available phosphorus, total potassium, available iron, manganese, copper, zinc, and total salt ($P < 0.05$); silt content was significantly positively correlated with organic carbon, total nitrogen, alkali-hydrolyzable nitrogen, total phosphorus, available phosphorus, total potassium, available iron, manganese, copper, zinc, and total salt ($P < 0.05$), and significantly negatively correlated with available potassium ($P < 0.05$); whereas clay content showed no significant correlation with nutrient contents ($P > 0.05$) (Table 10).

2.8 Mineral composition

The primary mineral content in soils of the Hetian area was 73.4%; quartz was dominant, accounting for 36.4%, followed by plagioclase (25.4%) and mica.

Tab. 10 Correlations between soil particle composition and nutrients

Indicator	Sand	Silt	Clay
Organic carbon	−0.468**	0.468**	0.102
Total nitrogen	−0.178**	0.170**	0.098
Alkali-hydrolyzable nitrogen	−0.345**	0.347**	0.073
Total phosphorus	−0.198**	0.193**	0.08
Available phosphorus	−0.267**	0.267**	0.088
Total potassium	−0.459**	0.458**	0.109
Rapidly available potassium	0.114	−0.128*	0.104
Total salt	−0.148*	0.140*	0.072
Available magnesium	−0.488**	0.488**	0.195
Available manganese	−0.538**	0.537**	0.265
Available copper	−0.556**	0.571**	0.171
Available zinc	−0.516**	0.506**	0.243

Note: * indicates a significant correlation at the 0.05 level (two-tailed); ** indicates a highly significant correlation at the 0.01 level (two-tailed).

(5.1%), K-feldspar (4.6%), and amphibole (1.9%). The secondary mineral content was 26.6%; calcite had the highest content, at 12.1%, followed by illite (5.6%), chlorite (4.6%), dolomite (4.2%), and gypsum (0.9%). Among them, illite and chlorite, as the main clay minerals, accounted for 10.2% of the secondary minerals (Tab. 11).

Tab. 11 Descriptive statistics of soil mineral content /%

Mineral type	Mineral	Minimum	Maximum	Mean ± standard deviation	Coefficient of variation
Primary minerals	Quartz	31.5	42.5	36.4$±2.7|7.36||Primaryminerals|Plagioclase|15.1|31.4|2 feldspar|2.1|10.9|4.6±2.3|51.09||Primaryminerals|Amph	239.88

Primary minerals are the "reservoir" of soil mineral nutrients and gradually release nutrients during weathering[38]. Feldspar and mica are the main sources of potassium[39–40]; therefore, both mica and K-feldspar showed highly significant positive correlations with total potassium. In addition, the layered structure and abundant adsorption sites of mica enable it to adsorb and store phosphorus[41], and it is also an important source of structural magnesium[42]. During weathering, elements such as magnesium and aluminum in mica undergo substitution reactions with calcium, thereby reducing the available calcium content[43]. Therefore, mica was significantly positively correlated with total phosphorus and available magnesium, but significantly negatively correlated with available calcium (Fig. 2).

Plagioclase is a calcium–sodium aluminosilicate mineral; it contains no potassium itself and has a weak capacity to retain potassium[1]. Meanwhile, the quartz content was as high as 36.4%, indicating that the degree of soil mineral weathering in the Hotan region is relatively weak. This is closely related to the local extremely arid climate and strong-wind environment, and these environmental factors also dominate the large-scale accumulation of aeolian sandy parent materials and the formation of aeolian sandy soils[44]. Because quartz also contains no potassium, a higher quartz content dilutes the potassium content in soil; therefore, both plagioclase and quartz were significantly negatively correlated with total potassium. The reason amphibole was significantly negatively correlated with total phosphorus is that amphibole is a chemically unstable mineral and is readily weathered; calcium released during its weathering reacts with phosphorus to form sparingly soluble calcium phosphate compounds, thereby reducing phosphorus solubility[45–46] (Fig. 2).

Secondary minerals are important carriers of soil nutrients. Magnesium can inhibit the precipitation of calcite and its diagenetic transformation through lattice distortion[47]. When the available magnesium content in soil is relatively high, the crystallization rate and crystal quality of calcite are significantly reduced; therefore, calcite was significantly negatively correlated with available magnesium ($P < 0.05$). Dolomite can immobilize Cu^{2+} through surface adsorption or by forming basic copper carbonate precipitates, and this adsorption and precipitation reduce the available copper content[48]. Therefore, dolomite was significantly negatively correlated with available copper ($P < 0.05$). Gypsum dissolves and releases Ca^{2+} and SO_4^{2-}, thereby increasing salinity. In turn, Ca^{2+} can react with phosphorus and reduce phosphorus availability[45]. Therefore, gypsum was significantly positively correlated with salinity ($P < 0.05$), but highly significantly negatively correlated with total phosphorus ($P < 0.01$) (Fig. 2).

[Heatmap panel: rows include total salt, total phosphorus, total potassium, alkali-hydrolyzable nitrogen, available phosphorus, rapidly available potassium, organic carbon, available calcium, available magnesium, available iron, available manganese, available copper, and available zinc; columns include mica, amphibole, quartz, K-feldspar, plagioclase, calcite, dolomite, gypsum, illite, chlorite, and total clay; the color legend is the correlation coefficient from −1.0 to 1.0.]

Note: $*$ indicates that the correlation is significant at the 0.05 level (two-tailed) ($P < 0.05$); $**$ indicates that the correlation is highly significant at the 0.01 level (two-tailed) ($P < 0.01$).

Fig. 2 Heatmap of correlation between soil minerals and nutrients and salts and medium and trace elements

Clay minerals have a large specific surface area, numerous charges, and abundant active functional groups, and can adsorb nutrients and water through physical and chemical mechanisms. After absorbing water, their interlayer structure changes, causing nutrients originally adsorbed between layers to be released, thereby increasing nutrient availability[3]. In this study, the total amount of clay minerals was significantly positively correlated with total potassium, organic carbon, and the contents of available iron, manganese, copper, and zinc ($P < 0.05$). Illite has a strong adsorption capacity for Zn^{2+}, and this adsorption capacity increases with rising pH[49]. In addition, illite can adsorb NH_4^+ through ion exchange[50], which may explain why illite was significantly positively correlated with both available zinc and alkali-hydrolyzable nitrogen. Chlorite not only contains abundant nutrient elements (such as Si, Mg, Al, Ca, Fe, P, and K), but can also adsorb available nutrients through the negative surface charges and ion-exchange effects of its interlayer structure. Therefore, chlorite was positively correlated with the contents of total phosphorus and total potassium, as well as the contents of available magnesium, zinc, iron, manganese, and copper ($P < 0.05$) (Figure 2).

3 Discussion

The Hotan region is located on the edge of the Taklimakan Desert in southern Xinjiang. Strong winds transport large amounts of sand and dust to this area, resulting in a relatively high sand content in the soil[51]. In addition, intense evaporation causes rapid loss of soil water, reduces aggregate stability, and accelerates soil desertification[52–53]. The soils in this region are dominated by primary minerals, which account for 73.4%, whereas secondary minerals account for 26.6%, among which clay minerals account for only 10.2%. In addition to the dominance of physical weathering under arid climatic conditions and the slow and limited process of chemical weathering, which makes it difficult for primary minerals to further decompose and form clay minerals, the alkaline soil environment (mean pH of 8.38) further inhibits the chemical weathering of minerals[54]. Parent-material type also significantly affects mineral composition. The soil parent materials in the Hotan region mainly include aeolian parent material, alluvial-proluvial parent material, and loess-like parent material. Aeolian parent material is dominated by quartz, with a coarse texture and poor nutrient status; alluvial-proluvial parent material contains some fine particles, but its degree of chemical weathering remains low; although loess-like parent material is rich in clay minerals, its chemical weathering is likewise inhibited under arid climatic conditions[18]. Among primary minerals, quartz has the strongest resistance to weathering, followed by feldspar and mica; these three constitute the main components of sand and coarse silt (physical sand particles). Minerals with weaker weathering resistance, such as plagioclase, pyroxene, and amphibole, are transformed into secondary minerals through chemical weathering[1].

The organic carbon content of farmland soils in the Hotan region is at a low level, mainly due to weak biological activity and insufficient input of exogenous organic materials[55]. In addition, the soil particles are dominated by sand and silt (92%), resulting in high porosity and strong aeration, which promote aerobic microbial activity and accelerate the decomposition of organic carbon[56]. Sand particles have a small specific surface area and few adsorption sites, making it difficult to effectively stabilize organic carbon[57]. By contrast, clay minerals can effectively adsorb organic carbon through their relatively large specific surface area and high charge density, forming stable organic–inorganic complexes[58]. This study showed that clay minerals were significantly positively correlated with organic carbon, indicating that they play an important role in the accumulation of soil organic carbon. However, the clay mineral content in this region is only 10.2%, and its contribution to the formation of relatively stable organic–inorganic complexes with macromolecular organic matter (especially humus) is limited[59], making it difficult to effectively promote organic carbon accumulation.

The contents of total nitrogen, total potassium, and available potassium in farmland soils of the Hotan region are at moderately low levels, whereas the content of alkali-hydrolyzable nitrogen is relatively high. The high sand content increases soil porosity and permeability, making soluble nutrients such as nitrogen and potassium prone to loss with water flow, thereby reducing their contents[44]. Sand particles have a small specific surface area and weak adsorption capacity[60]; although this is unfavorable for nutrient retention, it benefits microbial activity. Good aeration conditions promote the mineralization and nitrification of organic nitrogen, thereby increasing available nitrogen content[56,61]. During leaching, the dissolution and hydrolysis of some nitrogen-containing compounds also convert part of the fixed nitrogen into available nitrogen that can be absorbed and utilized by plants[62]. In addition, the edge sites and outer siloxane surfaces of illite have a certain adsorption capacity for NH_4^+[50]. Both mica and potassium feldspar are positively proportional to total potassium content, but their contents are only 4.6% and 5.1%, respectively. By contrast, plagioclase, with a content as high as 25.4%, contains relatively little potassium, and its structural "openness" is small, making it difficult for potassium to enter its crystal lattice[1]; thus it is negatively correlated with total potassium content. Meanwhile, the low contents of clay particles and clay minerals result in no significant correlation with soil available potassium, which is also one of the reasons why potassium content is at a moderately low level.

The contents of total phosphorus and available phosphorus in the soils of the Hotan region are at moderately high levels. Although mica and clay minerals can fix phosphorus through surface functional groups (such as hydroxyl and oxy groups) and abundant surface-active sites[41,63], their contents in this region are both low; they show no significant correlation with available phosphorus, and their "phosphorus-retention" effect is limited. The relatively high calcium content (available calcium content of 381.4 mg·kg−1, a moderately high level) may react with phosphorus to form poorly soluble calcium phosphate compounds, which may explain the moderately high phosphorus content. The weathering of amphibole (mean content 1.9%) and the dissolution of gypsum (mean content 0.2%) are important sources of Ca^{2+}. These results indicate that the chemical precipitation of calcium and phosphorus is far stronger than the physical adsorption by soil particles and minerals. Even when the contents of clay particles and clay minerals are low, Ca^{2+} in the soil can still fix phosphorus through ionic reactions in solution, thereby increasing phosphorus content[64].

Fine particles have a stronger capacity to adsorb salts, whereas in soils with more coarse particles, salts are readily lost with water flow, thereby reducing salt accumulation in the soil. Therefore, salt content is significantly negatively correlated with sand particles and significantly positively correlated with silt particles[65]. However, the degree of soil salinization in the Hotan region is not

not at a low level but at a medium-to-low level; the reason may be that the groundwater table is relatively high in some areas[66], and strong evaporation brings salts to the surface, where they accumulate. In this study, gypsum was significantly positively correlated with total salts, indicating that gypsum increases surface-layer salinity. This may be because its dissolution releases Ca^{2+}, increasing the content of salt ions in the soil solution. At the same time, the released Ca^{2+} may exchange with Na^{+} on colloids, leading to the accumulation of Na^{+} in the solution[67].

In the Hotan region, the contents of available Fe and Zn in the soil are at extremely high and high levels, respectively, whereas the contents of available Mn and Cu are at moderate levels. In this study, the contents of trace elements were extremely significantly positively correlated with silt. Because the soils in the study area are dominated by sand and silt and have relatively low clay contents, silt plays an important role in retaining trace nutrients. Although the specific surface area of silt is smaller than that of clay, it is larger than that of sand, can provide abundant adsorption sites, and has various functional groups distributed on its surface, such as hydroxyl and carboxyl groups; these functional groups can adsorb trace elements through ion exchange and complexation[8]. In addition, clay minerals also contain certain amounts of trace elements and, by virtue of their large specific surface area, high charge density, and abundant active groups, can adsorb and fix trace elements through physical and chemical processes[3].

In summary, the high sand content and low clay-mineral content in the Hotan region are important reasons affecting soil fertility there. The surfaces and interiors of aggregates can adsorb nutrients and retain dissolved nutrients in water within pores, thereby preventing leaching losses[68]. Therefore, promoting aggregate formation is the key to enhancing nutrient-storage and retention capacity in the Hotan region. Increasing organic fertilizer application is an important measure for promoting aggregate formation. Organic fertilizer not only directly increases the content of soil organic matter; the humic substances, polysaccharides, and other cementing materials produced during its decomposition can also bind dispersed sand or clay particles into aggregates. Organic fertilizer can also provide carbon sources for microorganisms and promote their secretion of sticky metabolic products, further stabilizing aggregates[69]. In addition, adding clay minerals may also be an effective measure for improving farmland soils in the Hotan region. Besides adsorbing soil nutrients, clay minerals can also help form aggregates[70–71]. However, excessive use of clay minerals may lead to the accumulation of heavy metals in soil, thereby posing potential risks to the soil ecological environment[70]. Therefore, when clay minerals are applied to improve soil, further consideration is still required.

4 Conclusion

Soil minerals indirectly affect nutrient accumulation by establishing the background conditions and regulating adsorption and fixation processes, whereas soil particles directly affect nutrient content and availability by altering adsorption capacity, pore connectivity, and microbial habitats. The nutrient contents of farmland soils in the Hotan region are generally low, with the core cause being the low clay-mineral content and relatively high sand content. In addition, mineral composition and particle-size distribution differ significantly in their degree of influence, contribution, and mechanisms of action on nutrient retention in farmland soils of the Hotan region, resulting in differences among the content grades of different nutrients. In the Hotan region, soil aggregates can be promoted and soil nutrient-storage and capacity-enhancement ability can be improved by increasing organic fertilizer application and adding clay-mineral amendments such as bentonite.

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Effects of mineral and particle composition on the nutrient and salt content of farmland soil in the Hotan region

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Abstract: In this study, we analyze the soil mineral and particle composition as well as the reasons for the low soil nutrient content in the Hotan region. A grid sampling method was used to set up 255 sampling points in a cultivated land, and the correlations among soil mineral composition, particle composition, nutrients, and salts were analyzed. The soil particles in the Hotan region were mainly sand (50.30% by mass) and silt (41.40%), with only 8.30% clay. The sand content was significantly negatively correlated with organic carbon, total nitrogen, available nitrogen, total phosphorus, available phosphorus, total potassium, total salt, available iron, available manganese, available copper, and available zinc ($P < 0.05$), whereas the silt content was significantly positively correlated with the above indicators ($P < 0.05$). The high sand content accelerated mineralization and decomposition, increased porosity and permeability, and weakened adsorption capacity, resulting in low soil organic carbon content (5.55 g・kg−1), medium to low levels of total nitrogen (0.76 g・kg−1), total potassium (16.24 g・kg−1), and available potassium (182.71 mg・kg−1); the salinization degree (total salt content 2.99 g・kg−1) was moderate; the available iron (28.4 mg・kg−1) and zinc (1.6 mg・kg−1) contents were at high and extremely high levels, and the available manganese (9.1 mg・kg−1) and copper (0.7 mg・kg−1) contents were at medium levels, which might be related to the rich adsorption sites provided by silt. The mineral composition mainly comprised primary minerals, such as quartz (73.4%), with a relatively high calcite content (12.1%) in secondary minerals, whereas the clay mineral content was low (10.2%). The clay mineral content was significantly positively correlated with total potassium, organic carbon, available iron, available manganese, available copper, and available zinc ($P < 0.05$), but the low clay mineral content contributed little to nutrient accumulation. Feldspar (4.6%) and mica (5.1%) were significantly positively correlated with total potassium ($P < 0.05$); mica, as a key source of structural magnesium, was positively correlated with available magnesium (104.9 mg・kg−1) ($P < 0.05$). The low clay mineral content and high sand content are the reasons for the low soil nutrient content in the Hotan region. Therefore, increasing the application of organic fertilizers and clay minerals to provide nutrients and promote aggregate formation may be an effective measure for improving the fertility of farmland soil in the Hotan region.

Keywords: clay minerals; particle composition; soil nutrients; soil salinity; Hotan region

Note: Figure translations are in progress. See original paper for figures.