**Effects of straw returning and nitrogen addition on soil quality and physicochemical characteristics of coastal saline soil: A field study of 4 consecutive wheat-maize cycles**

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**Abstract**: The effects of different straw returning and nitrogen addition levels on soil quality are important for proper coastal saline soil remediation. Two maize/wheat straw returning levels (1.0 × 104 kg ha-1 (2S) and 5.0 × 103 kg ha-1 (S)) and three inorganic nitrogen addition levels (300 kg ha-1 (N2), 150 kg ha-1 (N) and 75 kg ha-1 (N1/2))—were studied, with 150 kg ha-1 inorganic nitrogen and without straw addition treatment as the control (CK), to elucidate the response of soil physical and chemical properties to the two factors. Dry-sieving technique was applied to fractionate the soils into silt-plus-clay particles (< 0.053 mm, CS), microaggregates (0.053–0.25 mm, MI), small macroaggregates (0.25–2.0 mm, SM), and large macroaggregates (> 2 mm, LM). After four consecutive wheat-maize cycles, different straw and N fertilizer treatments obviously decreased the salinity contents, increased the total nutrient contents, and optimized the soil structure of the saline soil. The saline soil reclamation effects showed significant distinctions among the different straw and N fertilizer treatments. The 2SN2 treatment displayed the greatest effects in regard to decreasing salinity, increasing the total soil nutrient contents and optimizing the soil structure, which resulted in the best remediation effect. Straw returning play a major role in decreasing soil salinity and enhancing saline soil aggregate formation. N fertilizer addition supplies rich nutrients for straw decomposition, and promotes soil microbial growth and reproduction, which brought about C sequestration in coastal saline soil. During the coastal saline soil remediation process in the Yellow River Delta, it is suggested to prioritize straw returning and moderate N fertilizer addition, and live together with moderate P fertilizer application.

**Keywords:** Soil quality, Soil physicochemical properties, soil aggregate, nitrogen addition, straw returning

1. **INTRODUCTION**

Nowadays, agricultural production and environment are under increasing threat from soil salinization. The influence area by salinization of agricultural soil are up 6% all over the world. (Zhang et al., 2010). According to statistics, the saline soil areas of China there are about 99.13 million hectares, with great potential for development and utilization. The Yellow River Delta (YRD) is located in the southwest of the Bohai Bay, north of the Yangtze River Delta and south of Beijing and Tianjin, which is the last river delta in China that has great development potential (Mao et al., 2016). The State Council officially announced the Development Plan of YRD Eco-efficient Economic Zone, and it becomes a national strategy on November 23rd, 2009. Given the shallow groundwater and marine water intrusion, high salt concentration and macronutrient deficiencies have become two significant factors that limit the agricultural production (Yang et al., 2021; Li et al., 2019; Zhang, et al., 2014). There are 442,900 hectares of saline soil, which accounts for more than 50% of the whole region area (Bai, 2020). Desalinization and fertilization is an important way to develop efficient agriculture and improve ecological environment. It is a good way to enhance the implementation of "grain storage in land and technology" strategy and to boost the "ecological protection and high-quality development of the Yellow River basin" strategy (Cui et al., 2018; Zhao, 2016a).

Crop straw is an ample, renewable and cheap resource in China, which contains abundant organic carbon and various nutrients needed by crops (Yan et al., 2019). However, large quantities of straw resources go to waste, such as throwing away or open-air burning (Yin et al., 2018; Wang et al., 2018). These all lead to ecological environmental pollution (Li et al., 2017). Currently, Straw returning has been widely used because the Chinese government has banned straw burning. It has been extensively certified that straw returning could not only enhance the soil fertility levels, soil microbial biomass, and soil aggregate, but also decrease soil salinity and soil bulk density (Berhane et al., 2020; Seglah et al., 2020; Wang et al., 2019; Kim et al., 2017; Bandyopadhyay et al., 2010). By contrast, straw could interfere with plants, harbor insect pests or pathogens, immobilize nutrients, and accumulate heavy metals (Xie et al., 2020; Kerdraon et al., 2019; Chi et al., 2016). Nitrogen is a key restricted nutrient in coastal saline soil of the YRD (Li et al., 2018). The wheat-maize cycles cropping system is the chief farming system in the area. However, relatively little is understood concerning effects of nitrogen addition and straw returning on saline soil quality and physicochemical characteristics of coastal saline soil, especially, on long-term effects and mineral composition and microstructures of coastal saline soil.

Therefore, in this paper, a field experiment of 4 successive wheat-maize cycles was employed to estimate the influence of different nitrogen addition and straw returning levels on 1) bulk saline soil quality, 2) coastal saline soil aggregate distribution and formation, 3) C, N, P, K and salt distribution in soil aggregates. 4) mineral composition and microstructures. It is aimed to better comprehend the basic processes of coastal saline soil improvement and enhance the improvement efficiency of crop straw in combination with nitrogen fertilizer.

**2. MATERIALS AND METHODS**

**2.1 Experimental site**

The research coastal test field is situated in Wudi county (37°53'N, 117°44'E), Binzhou city, Shandong Province, China (Fig. 1). The research site is situated in the warm temperate zone of the East Asia monsoon in the YRD region of China, in the southwest of the Bohai Bay. The climate of the test field is semi-humid, continental climate. The average sunshine duration is 2800 h, the mean annual temperature is 12.5 °C. The mean annual evaporation is 1800 mm, and the mean yearly precipitation is about 600 mm. This region soil type belonged to coastal saline soil. Farmers traditionally used long-term rotations of winter wheat and summer maize, which is the main farming system. The initial soil physicochemical characteristics were obtained with the conventional method of agrochemistry (Bao, 2008) (Table 1).

**2.2 Experimental design and sampling**

The whole test, which adopt a randomized integral sub-plots with different wheat/maize straw (S) and inorganic nitrogen (N) fertilizer levels, has been employed since October 2014, including six different treatments (Fig. 1). Treatment with 150 kg ha-1 inorganic N fertilizer and without straw addition was regarded as the control treatment (CK). In each harvest season, The maize (or wheat) straw was cut into pieces in size about 5-15 cm long with farm machinery, and mixed uniformly with the soil. In each growing season, urea was employed as inorganic nitrogen fertilizer, half of which was applied as base fertilizer, and the residual as after fertilizer. Superphosphate was used by 35.0 kg P ha-1 in each experimental field. Each test was applied three times using 6 × 8 m2 plotsrandomly. Samples were collected separately from the topsoil (0-20 cm) layer, and each plot was sampled three times in June 2018. Five points method in each plot were used in accordance with the S shape, then mixed homogeneously and air dried naturally for bulk soil and soil aggregate analysis. Soil aggregates were separated into four sections measured by the sequential method of dry-sieving division (Savinov, 1936). Shortly, dried soil samples (100 g) was sifted through a series of soil sieves (0.053, 0.25, and 2.0 mm). Subsequently, four fractions were obtained: silt-plus-clay particles (< 0.053 mm, CS), microaggregate (0.053-0.25 mm, MI), small macroaggregate (0.25-2.0 mm, SM) and large macroaggregate (> 2 mm, LM). The dry soil aggregate contents were calculated by the weight of each aggregate fraction.

**2.3 Sample analysis**

The soil physicochemical characters were determined with common methods used previously in Lu (Lu, 1999). The detailed description could be found in Supporting Information part of this manuscript.

**2.4 Statistical analyses**

All experimental data were processed and plotted using Excel software and following were performed with SPSS 20.0. ANOVA and Pearson correlation analysis were employed to soil physicochemical indicators analysis and correlation analysis, respectively. The saline soil-improving effects were evaluated objectively by principal component analysis (PCA) in different straw and N fertilizer treatments. Comprehensive evaluations were carried out with fuzzy membership function, which has been described in our previous research (Yang et al., 2021).

**3. RESULTS**

**3.1 Soil aggregate fractions content, BET surface area and pore width**

The proportions of four soil aggregate fractions in different straw and N fertilizer treatments after four consecutive wheat-maize cycles are shown in Fig. 2. The fractions of maroaggregate (LM+SM) were the predominant fractions in different straw and N fertilizer treatments. The proportions of (LM+SM) in straw treatments were all above 85.1%, which obviously increased by 10.9-14.1% compared with CK (*p* ＜ 0.05). It was ranked in the following order: SN > 2SN > SN2 > 2SN2 > SN1/2 >CK. The percentage of SM in treatment 2SN2 were higher than that in others. The proportions of CS and MI were different, but the differences was inapparent. The largest proportion of CS and the lowest proportion of LM appeared in treatment CK.

In order to research the specific surface area and the adsorption properties of the soil aggregate fractions, the N2 adsorption and desorption experiments were applied to measure the surface area (BET) and pore size distribution of the aggregate fractions (Fig. 3 and Fig. 4). The N2 sorption isotherm at 77.3 K showed that soil aggregate fractions all displayed IUPAC-Ⅱ sorption behaviour, which belonged to a typical type of porous medium multilayer adsorption. The BET surface area of MI and SM were significantly larger than other aggregate fractions (*p* ＜ 0.05), except 2SN2. The lowest BET surface area were observed in the CS aggregate fractions, while most of the largest one were shown in the MI or SM fractions. The BJH adsorption average pore width (4V/A) of soil aggregate fractions has a narrow range in size, ranging from 6.8～8.3 nm. The values among the different fractions have no obviously difference.

**3.2 Soil N, P, K and C of aggregate fractions in different treatments**

Fig. 5 shows that different straw and N fertilizer treatments obviously enhanced the saline soil total N contents, total P contents, and total K contents (P < 0.05) and there were significantly differences among the four aggregate fractions (P < 0.05). The maximal soil total N in LM, SM, CS and MI aggregate sections were found in the treatments SN, SN2, SN2 and SN, respectively; while the minimal values appeared in CK, SN, SN1/2 and SN1/2, respectively. The soil total N contents of MI and SM were higher than other aggregate fractions (*p* ＜ 0.05). The rank of saline soil total P content was MI＞SM＞LM＞CS in the treatments 2SN2, SN2, SN, and CK, while there were no obviously difference among aggregate fractions in 2SN and SN1/2. The lowest total K contents in LM were observed in all soil aggregate fractions, while the maximal contents were found in CS, except 2SN2. The total K content was ranked CS＞MI＞SM＞LM in the 2SN2, 2SN, SN2, SN, SN1/2 and CK treatments.

Straw and N fertilizer treatments obviously increased the soil total carbon (STC) contents and soil organic carbon (SOC) contents (*p* <0.05) (Fig. 6), while those measures decreased the soil inorganic carbon (SIC) contents to a certain extent. The STC contents were significantly lower than SOC contents. The maximum STC contents and SOC contents both appeared in MI aggregate fraction in each straw and N fertilizer treatment. There was no consistent law for the distribution of SIC contents during the different size soil aggregate fractions. The maximal SOC content values of different size soil aggregate sections were found in SN2 treatment, which was obviously higher than the others (*p* < 0.05). The lowest SOC contents appeared in the CK, which was obviously lower than others (*p* < 0.05). Similar to SOC, both the lowest and the highest STC contents were found in the CK and SN2 treatment, respectively.

**3.3 Soil salinity and mineral contents of aggregate sections of test treatments**

Fig.7 gives the soil salinity content of soil aggregate sections of test treatments. The salinity of LM and SM fractions were significantly decreased in straw and N fertilizer treatments compare with the CK (*p* < 0.05). No obvious differences were shown in salinity of CS and MI fractions among the different treatments. The soil salinity contents changed unobviously among LM, SM, MI and CS in each straw and N fertilizer treatment.

There are six kinds of minerals in the soil soil aggregate fractions (Fig. 8). They are quartz, muscovite, clinochlore, albite, microcline and calcite, which account for more than 98% of the total mineral content. The mineral content was ranked quartz＞muscovite＞calcite＞clinochlore＞albite＞microcline. The highest quartz contents in CS were observed in all aggregate fractions, and it was ranked CS＞MI＞SM＞LM. The lowest muscovite contents in CS were shown in all aggregate fractions, and there no significant differences among MI, SM and LM. The lowest clinochlore contents in CS were shown in the treatments 2SN2, SN, SN2, SN1/2 and CK, and the mimimum in MI was found in the treatment 2SN. The maximum albite contents in CS were found in different size aggregate fractions. The highest calcite contents in LM were shown in each treatment, and it was ranked LM＞SM＞MI＞CS. The microcline contents were lower compared with the above five kinds of minerals, and there was no consistent law among different size soil aggregate sections.

**3.4 The change of bulk soil in different treatments**

The salinity content, aggregate fractions proportions, BET surface area and pore width of the bulk soil in different treatments were shown in Table 2. After four consecutive wheat-maize cycles, the bulk soil salinity content in the treatments 2SN2, 2SN, SN2, SN, SN1/2, and CK decreased by 27.08%, 26.71%, 24.91%, 23.47%, 20.58% and 18.05%, respectively. Compared to CK treatment, straw returning and N addition experiments reduced the salinity content of the bulk soil obviously, except in the SN1/2 treatment. The salinity reduction effect was ranked 2SN2≈2SN＞SN2＞SN＞SN1/2＞CK. Compared to CK treatment, the percentages of the dry soil aggregate fractions > 0.25 mm (LM+SM) in the bulk saline soil of SN1/2, SN, SN2, 2SN and 2SN2 experimental treatments enhanced by 12.84%, 15.93%, 14.25%, 15.17% and 13.33%, respectively. The BET surface area of the bulk soil in different treatments was ranked 2SN2＞2SN＞SN2＞SN＞SN1/2＞CK, ranging from 37.81～48.29 m2/g. The bulk soil BJH adsorption average pore width (4V/A) in different straw and N fertilizer experiments was ranked SN1/2＞CK＞SN＞SN2＞2SN＞2SN2, ranging from 7.00～7.69 nm.

Table 3 shows that soil N, P, K and C of the bulk soil in different treatments. The soil total N content values were 1.08, 1.14, 1.29, 1.16 and 1.29 times larger than that in CK in treatments SN1/2, SN, SN2, 2SN and 2SN2, respectively. The highest total N content values were found in the 2SN2 and SN2 treatments, while the least in the SN1/2 plot. The soil total P content was ranked CK＞SN2＞2SN2＞SN＞2SN≈SN1/2, and most of the difference among them were indistinctly. The total K contents in the SN1/2, SN, SN2, 2SN and 2SN2 treatments were 1.15, 1.15, 1.29, 1.14 and 1.59 times larger than that in CK, respectively. The SIC contents of the bulk soil in different plots were low compared to SOC. Compared with CK plot, straw returning obviously enhanced the SOC contents of bulk saline soil (p <0.05), with the maximal advance in treatment SN2 and 2SN2, followed afterward by 2SN, SN1/2 and SN treatment. Similar change trends also appeared in STC contents in the bulk saline soil of different straw and N fertilizer treatments. Table 4 shows the soil mineral content of the bulk soil in different treatments. The mineral contents in bulk soil was ranked quartz＞muscovite＞calcite＞clinochlore＞albite＞microcline. The proportions of quartz, muscovite and calcite almost accounted for eighty percents of the total minerals. There were no obviously difference in different treatments.

**3.5** **Principal component and cluster analysis of bulk soil quality in different treatments**

The soil physicochemical properties and basic soil constitution all displayed significant differences in the different straw and N fertilizer treatments, and the interplays existed among different factors. The principal indicators of the saline soil improvement effects were distilled by a PCA (principal component analysis) of these factors. Factor loadings of principal component in test treatments were shown in Table 5. Y(1) could explicated 46.553% of the total variance, and it was the first principal component. Y(1) was the highest component, for which large factor loadings were due to soil salinity, total N, SOC content, clinochlore content, the proportion of MI aggregate fraction and the BET surface area. Y(2), the second principal component, large factor loadings belonged to muscovite content, albite content and calcite content. The cumulative contribution rate of the three principal components was up to 86.341%, which reflected most information on the saline soil physicochemical property indicators.

Moreover, a cluster analysis was used on basis of the PCA results, 10 key factor loadings were applied to estimate saline soil remediation effects of different straw and N fertilizer treatments, specifically, the soil salinity, total N content, SIC content, SOC content, muscovite content, clinochlore content, albite content, the proportion of MI aggregate fraction, the proportion of SM aggregate fraction and the BET surface area. The subordinate function value of 10 key factor loadings in different treatments was shown in Table 6. The results indicated that saline soil-remediation effects of the different straw and N fertilizer treatments were as follows: 2SN2＞2SN＞SN＞SN2＞SN1/2＞CK.

**4. DISCUSSION**

## 4.1 The effects of the different straw and N fertilizer treatments to soil structure

Soil aggregate is the the basic soil structure unit and main soil component, which is usually selected as the important indicator of a good soil structure (Ortiz et al., 2022; Sarker et al., 2018). Its formation and stability are realized by the effects of soil environment and all kinds of cementing substance in soil. The study area sits on the southern bank of the Bohai Sea. The soil salinization is mainly caused by seawater intrusion. Sodium ion, which has maximum concentration in the saline soil, is a strong dispersant and could worsen soil structure (Ju et al., 2019; Rath et al., 2015). In the paper, straw returning obviously enhanced the proportion of soil aggregation (> 0.25 mm, LM+SM), which caused by the enhancement of soil organic carbon which can twine mineral colloids to soil aggregates (Bu et al., 2020; Vadakattu et al., 2015). As is shown in this paper, the sum proportion of muscovite and clinochlore increased slowly, while the quartz contents decreased slowly. The BET surface area of the bulk soil showed 2SN2＞2SN＞SN2＞SN＞SN1/2＞CK, and the BET surface area of MI and SM were significantly larger than other aggregate fractions. These also suggested that the soil aggregates was improved after 4 years of nitrogen addition and straw returning treatment.

Compared to CK treatment, the percentages of the dry soil aggregates fractions > 0.25 mm (LM+SM) in bulk soil of the treatments SN1/2, SN2 and SN increased by 12.84%, 14.25% and 15.93%, respectively. The correlation analysis of the bulk soil characteristics (Table 7) showed that the total N contents had obvious positive correlation with SOC contents, STC contents and BET of the bulk soil. These all illustrated that moderate N fertilizer addition effectively improved soil organic carbon sequestration and saline-alkali soil coacervate formation (Chen et al., 2016; Qiu et al., 2016). Nitrogen is a significant restricted nutrient in coastal saline soil of the YRD (Li et al., 2018). Nitrogen was the most essential nutrition for the straw transformation and decomposition. The cooperative action of N fertilizer and straw addition promotes the growth and reproduction of soil microbial (Li et al., 2020; Totsche et al., 2018), and microbial metabolites and residues are important sources of soil organic carbon (Chen et al., 2019; Liang et al., 2019).

## 4.2 Salinization-inhibiting effects of the different straw and N fertilizer treatments

In order to reduce salinization of soil, many methods have been used in past years. Drip irrigation significantly decreased the inorganic ions and salinity of the cotton field soil in the YRD, China (Li et al. 2016). The grass type and coverage have obvious effect on soil salinity and alkalinity of the soda saline soil in Songnen Plain in China. Soil improvers (straw, gypsum, and animal manure) obviously affect the biochemical characteristics of salinized soil in the YRD (Wang et al., 2017; Zhang et al., 2016).

Given the shallow groundwater (2.0 m～3.0 m) and marine water intrusion, inhibiting the accumulation and upward movement of salinity in the soil's surface was an important way for coastal salinized soil remediation. Straw returning efficiently boosted salinity leaching mainly by enhancing aggregate and porosity formation, and weakened the capillary action (El Hasini et al., 2019; Kim et al., 2017). The proportions of the dry soil aggregates﹤0.25 mm (CS+MI) in the bulk soil of SN1/2, SN and 2SN2 treatments were 14.86%, 11.73% and 25.79%, respectively. The proportions of (CS+MI) increased as soil salinity increased, which could result from the highly dispersive effect that caused by Sodium ion (Huang et al., 2016). Table 7 displayed the correlation analysis of the bulk soil properties. It displayed that the salinity was obviously negatively correlated with total N, SOC content and BET (*p* < 0.05). So, increasing soil aggregate fractions and SOC using straw was one of the most important ways for coastal saline soil remediation (Zhao et al., 2016b).

## 4.3 soil nutrients-improving effects of the different straw and N fertilizer treatments

There are usually low levels of nutrients in coastal saline soils (Dong et al., 2022; Chi et al., 2020). Straw returning, nitrogen addition and crop growths have direct effects on the saline-alkali soil nutrient contents (Fu et al., 2021; Zhao et al., 2016c). The bulk soil total N contents was ranked 2SN2≈SN2＞2SN≈SN＞CK＞SN1/2. It is clear that soil total N contents enhanced with N fertilizer addition (Table 3). The bulk soil total P contents in treatment CK was larger than others, which suggested that extra phosphorus fertilization should be added. The bulk soil total K contents was ranked 2SN2＞SN2＞2SN≈SN≈SN1/2＞CK , which might be caused by straw returning quantity. Over 90% of nitrogen and carbon of this field are in organic form, which caused the total N and total C to have similar distributions as SOC in saline soil (Six et al., 2002; Kelley et al., 1995). The distribution of SOC was uneven among the different soil aggregates, and the maximal SOC content was found in the MI aggregate fraction. It might be caused by the longer ploughing times and better stability of MI (Huang et al., 2010). Thus, these are beneficial for saline soil remediation. Based on the above analysis, the nutrient contents showed considerable differences between the various straw and N fertilizer treatments.

**5. CONCLUSIONS**

After four consecutive wheat-maize cycles, different straw and N fertilizer treatments obviously reduced the salinity contents, enhanced the total nutrient contents, and improved the soil structure. So, the effects of inhibiting salinization and boosting fertilization were produced. Significant distinctions in different straw and N fertilizer treatments were shown after the saline soil reclamation. The 2SN2 treatment displayed the greatest effects in relation to decreasing salinity, increasing the soil nutrients and improving the soil structure, which resulted in the best remediation effect. Straw returning plays a major role in decreasing soil salinity and enhancing saline soil aggregate formation. N fertilizer addition supplies rich nutrients for straw decomposition, and promotes soil microbial growth and reproduction, which could result in carbon immobilization in the coastal saline soil. During the remediation process of the coastal saline soil in the Yellow River Delta, it is suggested to prioritize straw returning and moderate N fertilizer addition, and live together with moderate P fertilizer application.

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SUPPORTING INFORMATION

Supporting information is displayed at the end of this article. The methods of sample analysis and statistical analyses were shown in this part.

**CONFLICT OF INTEREST**

The authors declare no conflict of interest as to this article.

DATA AVAILABILITY STATEMENT

All data produced or analyzed during the research are contained in this paper.

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**Figure and Table captions**

Fig.1. The location map of the study field.

Fig.2. The proportions of soil aggregate fractions in different treatments.

Fig.3. The BET surface area of soil aggregate fractions in different treatments.

Fig.4. The average pore width of soil aggregate fractions in different treatments.

Fig.5. The soil nutrient content of soil aggregate fractions in different treatments.

Fig.6. The soil carbon content of soil aggregate fractions in different treatments.

Fig.7. The soil salinity content of soil aggregate fractions in different treatments.

Fig.8. The soil mineral content of soil aggregate fractions in different treatments.

Table 1 The initial soil physicochemical properties.

Table 2 The salinity content, aggregate fractions proportions, BET surface area and Pore width of the bulk soil in different treatments.

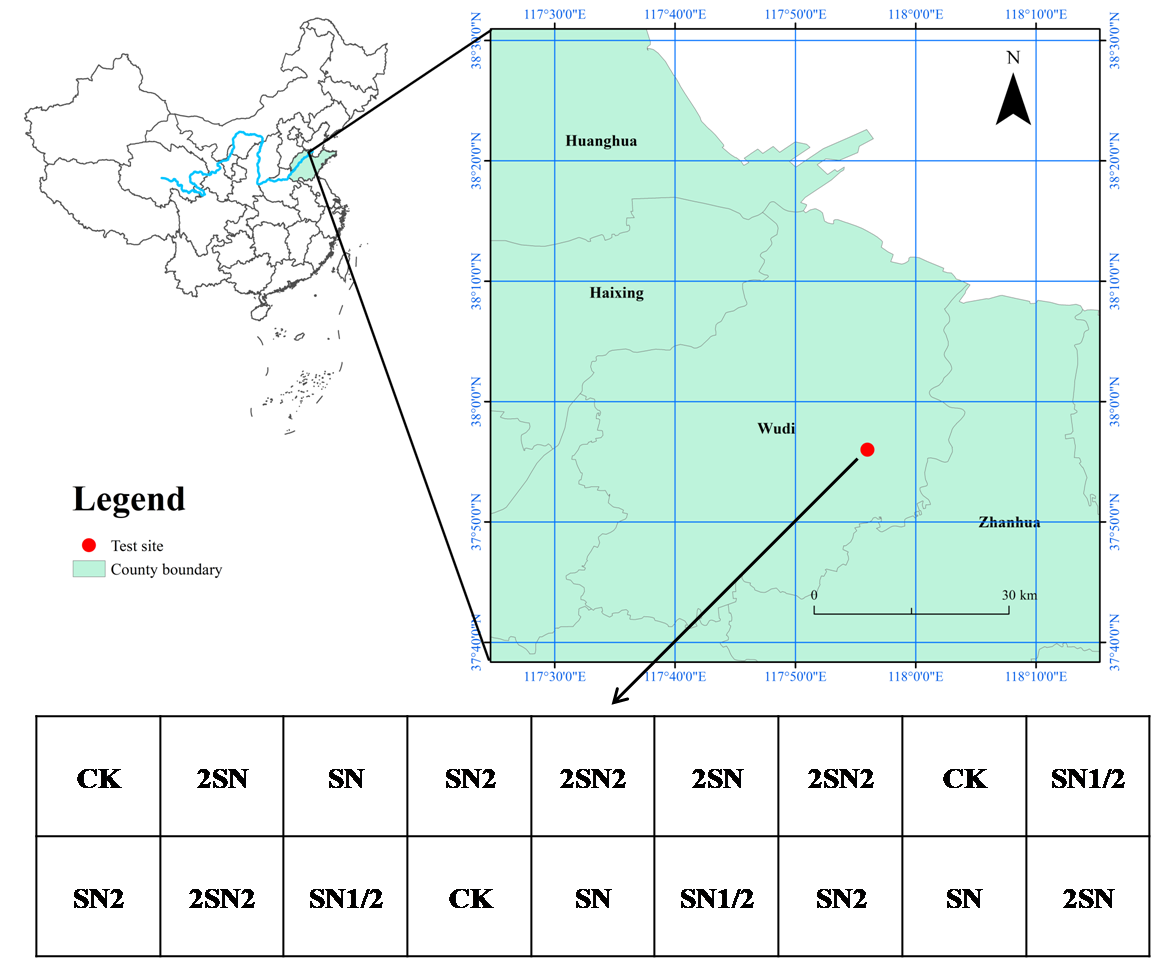
Table 3 Soil N, P, K and C of the bulk soil in different treatments.

Table 4 The soil mineral content of the bulk soil in different treatments.

Table 5 Factor loadings of principal component under different treatments.

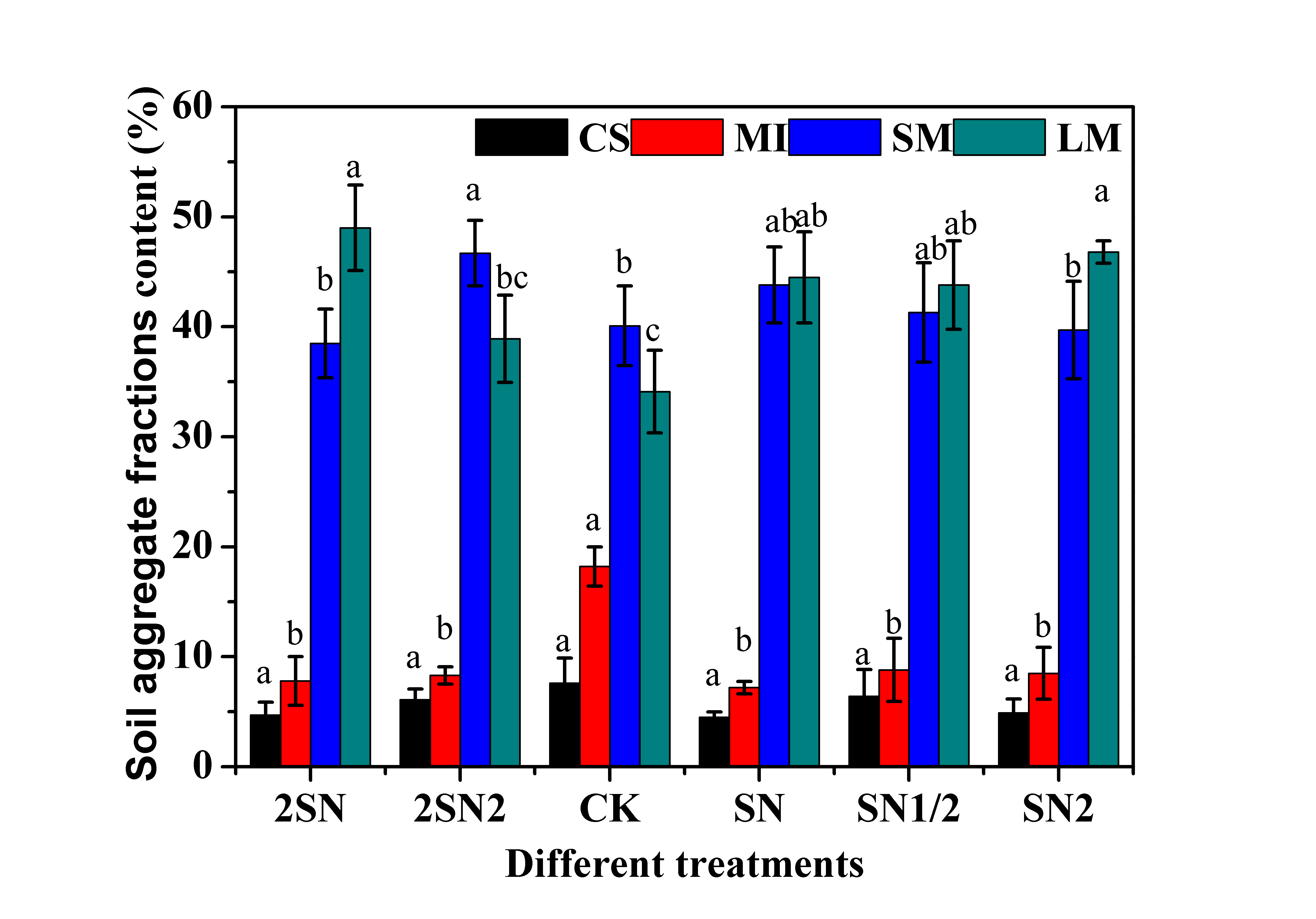
Table 6 The subordinate function value of 10 high factor loadings under different treatments.

Table 7 Correlation analysis of the bulk soil properties.

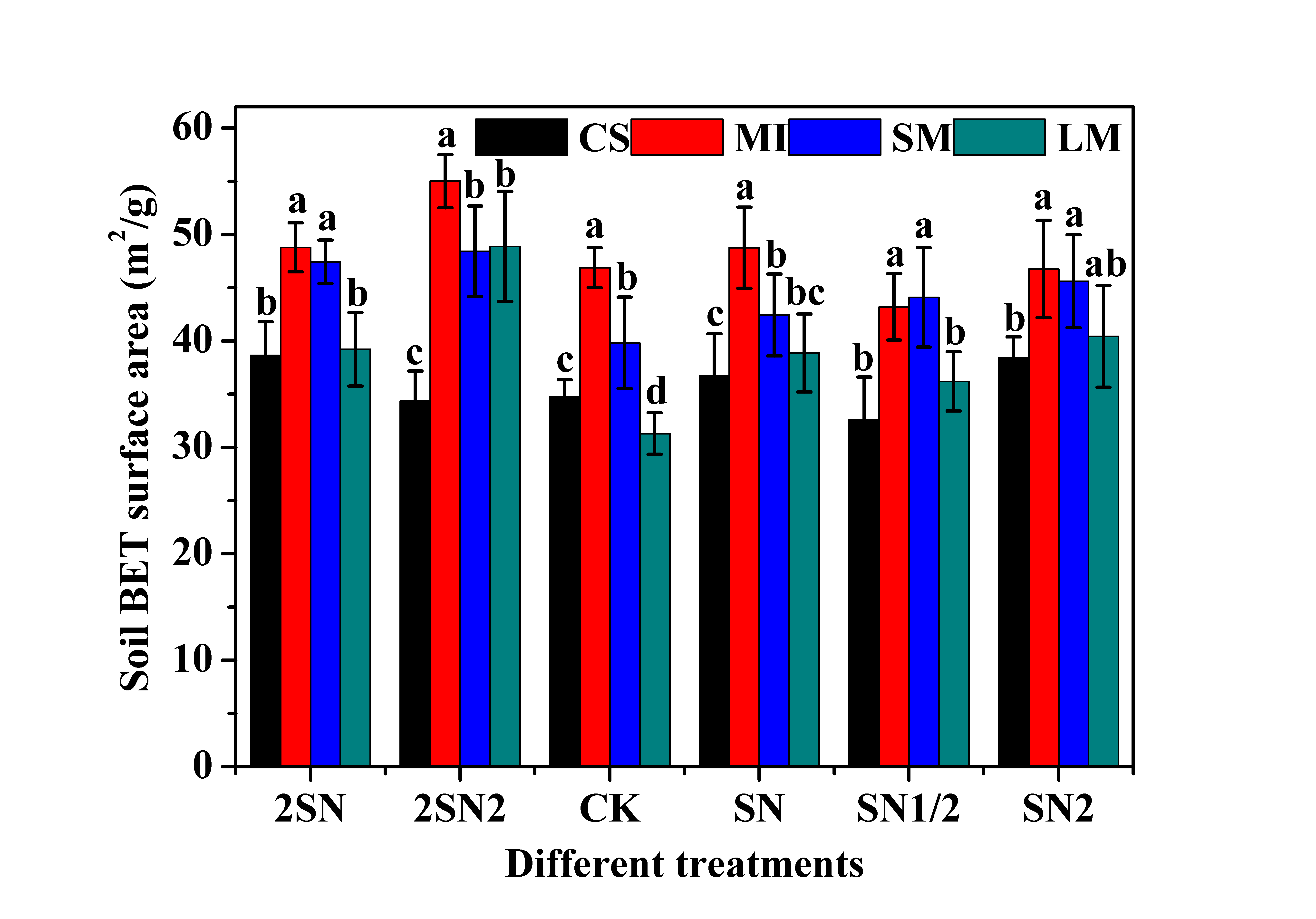


**Fig.1.** The location map of the study field

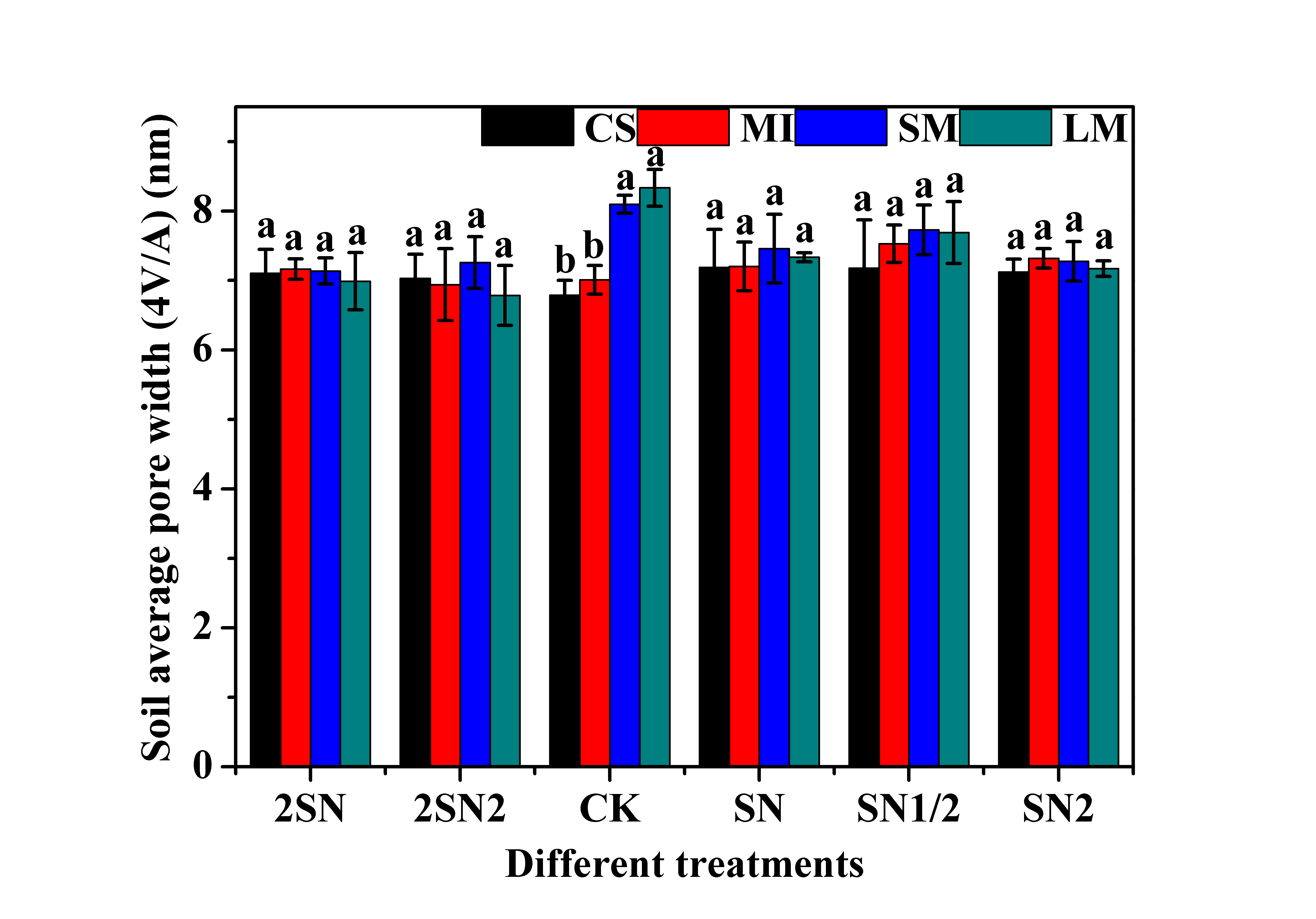
Notes: Different wheat/maize straw (S) and inorganic nitrogen (N) application rates of the different treatments in each growing season (kg ha-1). SN1/2: 5×103(S), 75(N); SN: 5×103(S), 150(N); SN2: 5×103(S), 300(N); 2SN: 1×104(S), 150(N); 2SN2: 1×104(S), 300(N); CK: 0(S), 150(N).

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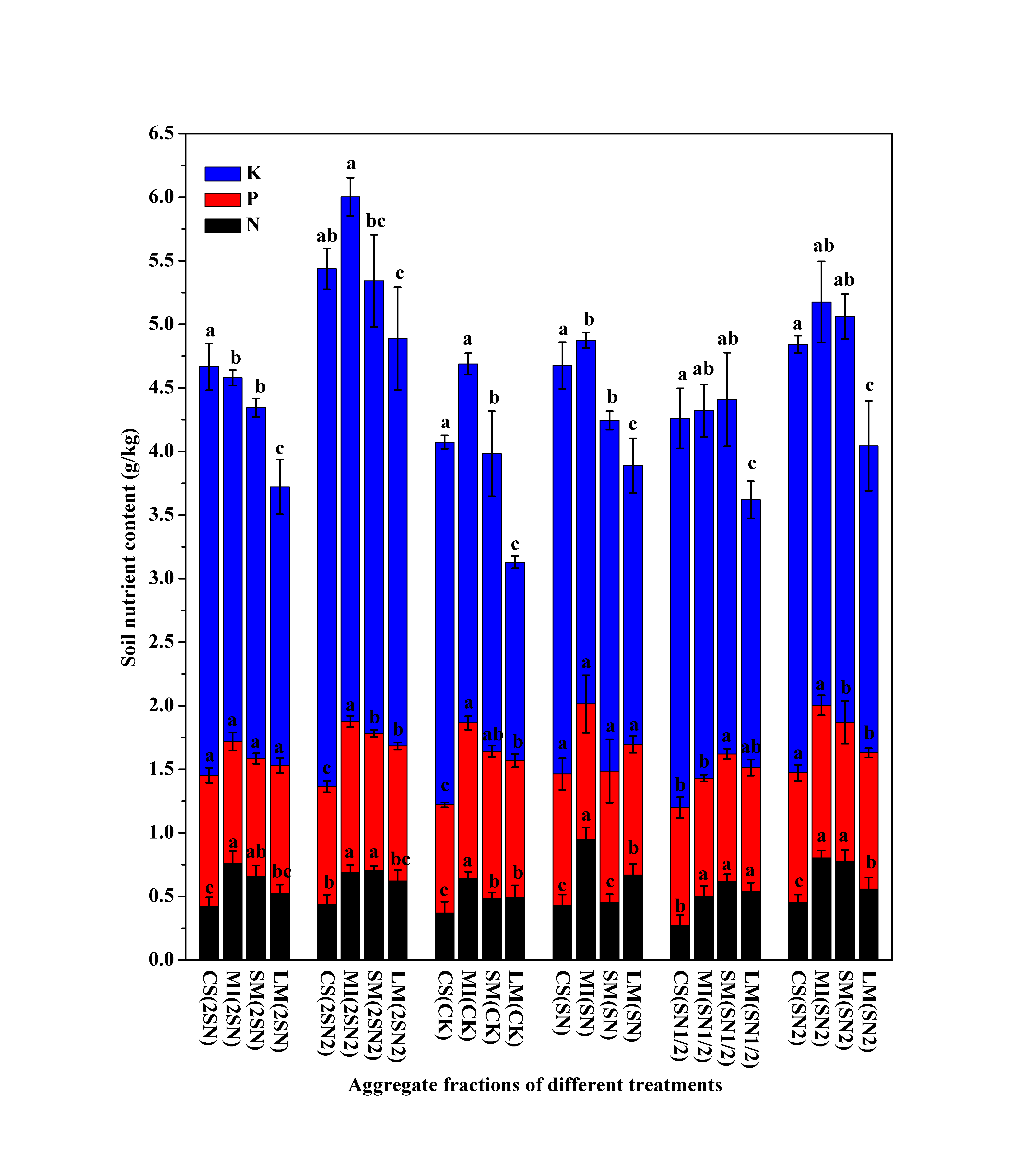
**Fig.2.** The proportions of soil aggregate fractions in different treatments

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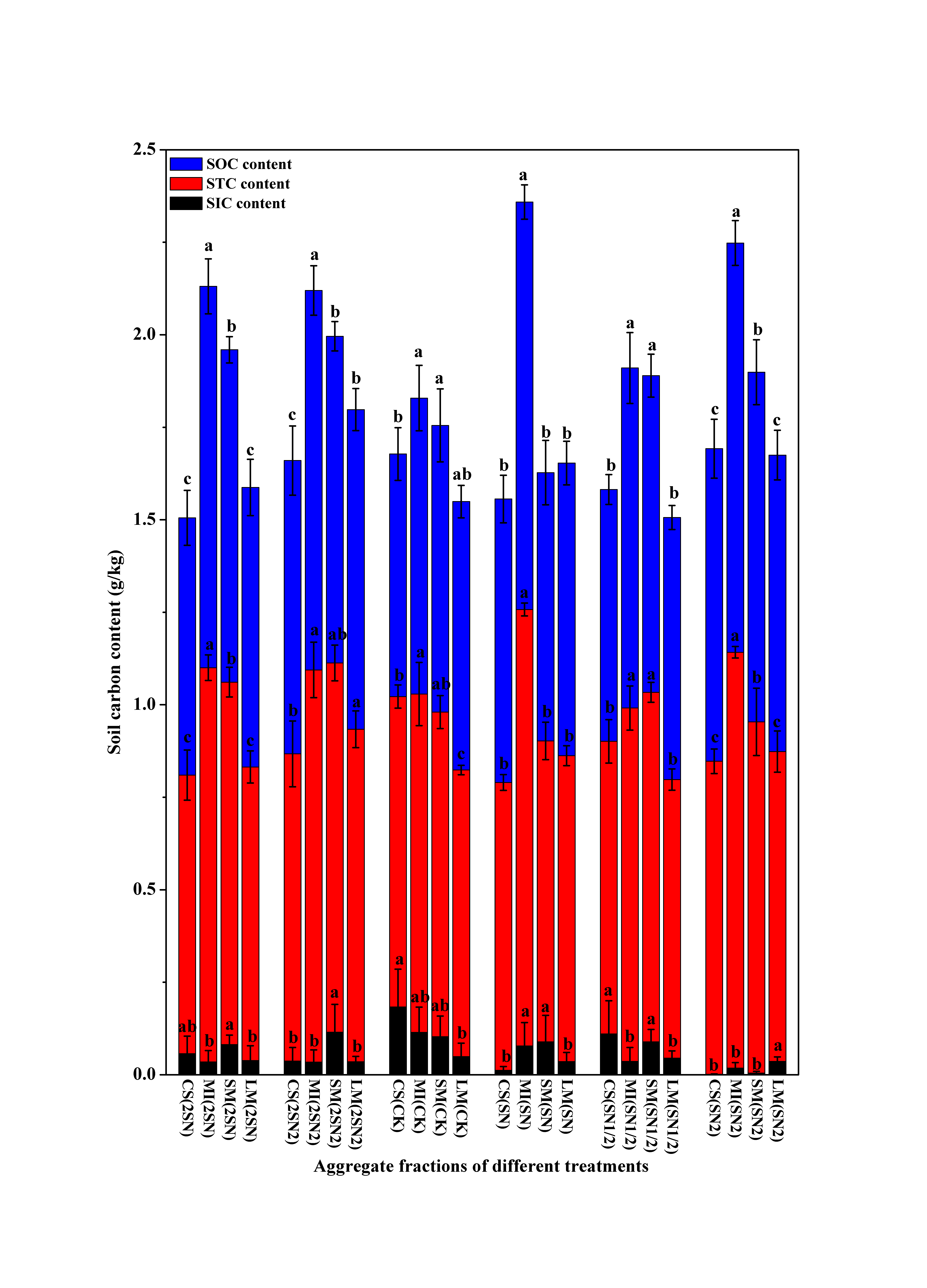
**Fig.3.** The BET surface area of soil aggregate fractions in different treatments



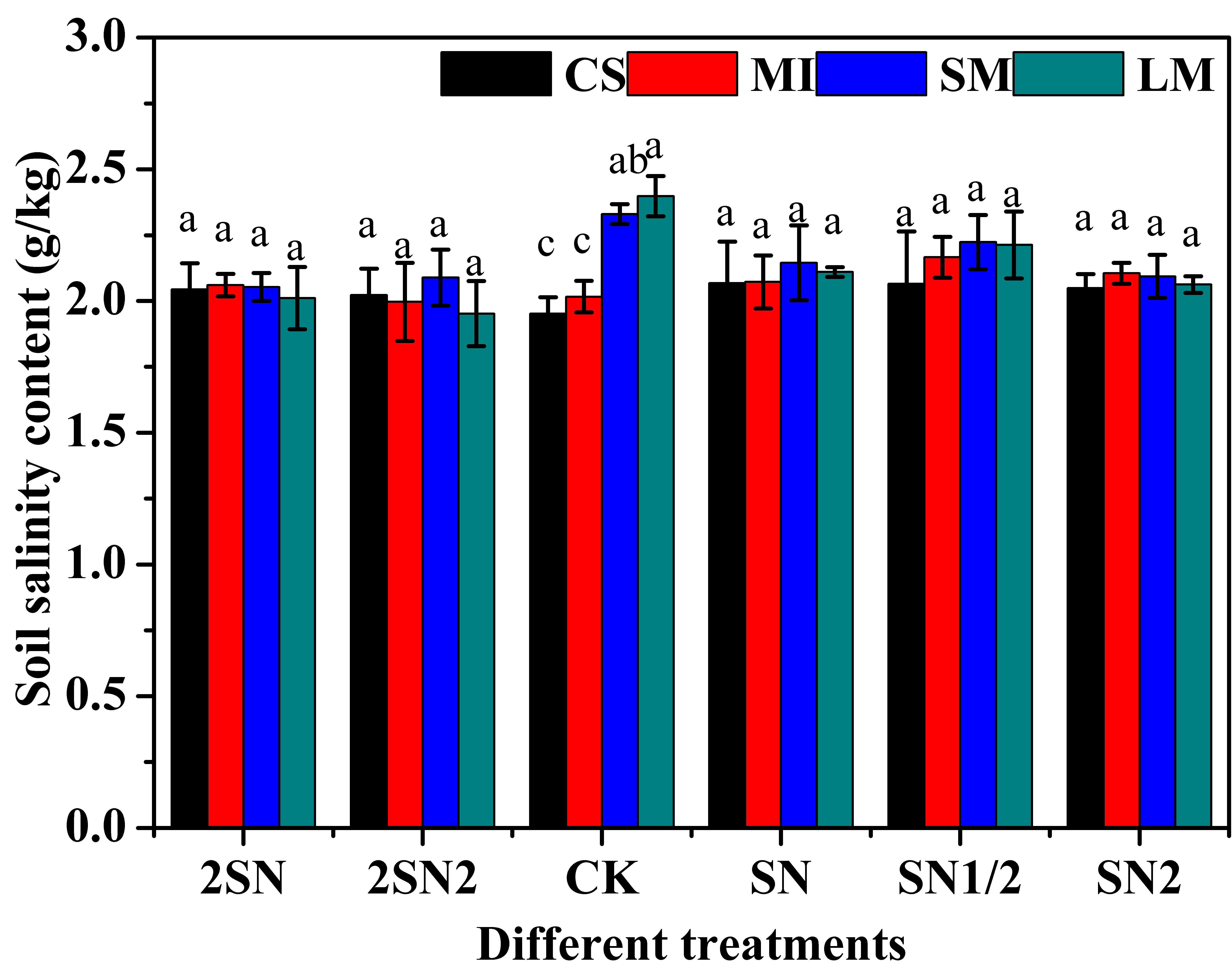
**Fig.4.** The average pore width of soil aggregate fractions in different treatments

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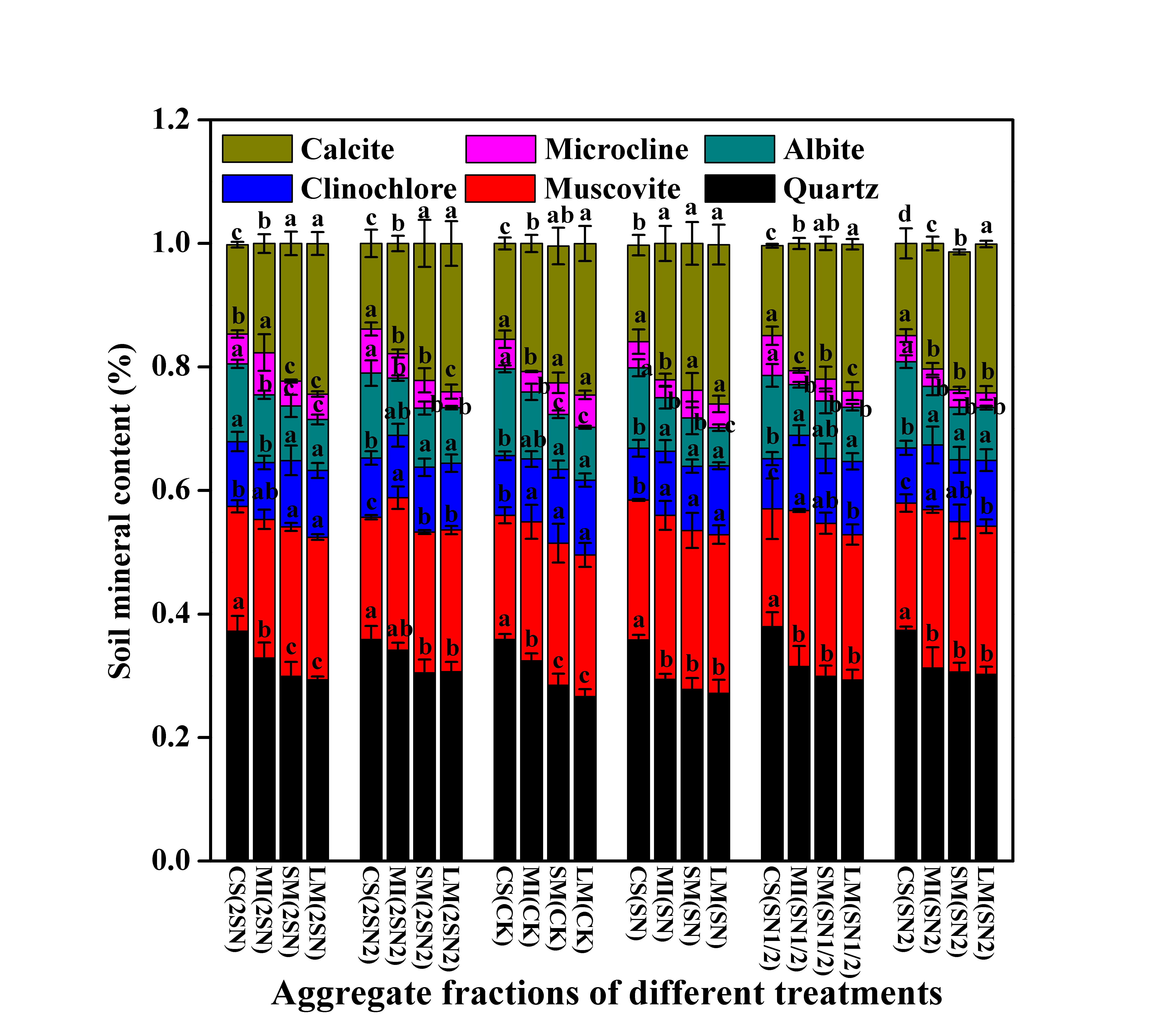
**Fig.5.** The soil nutrient content of soil aggregate fractions in different treatments

****

**Fig.6.** The soil carbon content of soil aggregate fractions in different treatments

****

**Fig.7.** The soil salinity content of soil aggregate fractions in different treatments

****

**Fig.8.** The soil mineral content of soil aggregate fractions in different treatments

**Table 1**

The initial soil physicochemical properties

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Soil pH | Soil salinity  (g/kg) | Available N content (mg/kg) | Available P content (mg/kg) | Available K content (mg/kg) |
| 8.52±0.41 | 2.77±0.14 | 23.80±0.91 | 20.40±0.98 | 537.00±24.58 |
| SOC content (g/kg) | SIC content  (g/kg) | Sand content (%) | Silt content (%) | Clay content (%) |
| 1.35±0.06 | 0.14±0.01 | 26.30±1.45 | 65.10±3.55 | 8.60±0.53 |

Notes: ±means the standard deviation (SD)

**Table 2**

The salinity content, aggregate fractions proportions, BET surface area and Pore width of the bulk soil in different treatments

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Treatments | salinity (g/kg) | CS content (%) | MI content (%) | SM content (%) | LM content (%) | BET surface area (m2/g) | Pore width (nm) |
| SN1/2 | 2.20±0.01a | 6.05±2.42b | 8.81±2.87b | 41.33±4.52ab | 43.81±4.03b | 39.86±3.66bc | 7.69±0.44a |
| SN | 2.12±0.10ab | 4.51±0.48c | 7.22±0.56c | 43.79±3.45ab | 44.48±4.14b | 41.06±3.76bc | 7.30±0.36ab |
| SN2 | 2.08±0.02ab | 4.93±1.26c | 8.53±2.35b | 39.76±4.43b | 46.78±1.02ab | 42.94±4.46b | 7.22±0.18ab |
| 2SN | 2.03±0.07b | 4.73±1.18c | 7.79±2.21bc | 38.52±3.12b | 48.96±3.89a | 43.10±2.81b | 7.10±0.27b |
| 2SN2 | 2.02±0.10b | 6.13±0.98b | 8.25±0.79bc | 46.73±2.97a | 38.89±3.98c | 48.29±4.38a | 7.00±0.42b |
| CK | 2.27±0.02a | 7.62±2.27a | 18.17±1.78a | 40.07±3.62b | 34.14±3.76d | 37.81±2.85c | 7.56±0.21a |

Notes: ±means the standard deviation (SD), different letters within groups are significantly different (p < 0.05).

**Table 3**

Soil N, P, K and C of the bulk soil in different treatments

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Treatments | N content (g/kg) | P content (g/kg) | K content (g/kg) | SIC content (g/kg) | STC content (g/kg) | SOC content (g/kg) |
| SN1/2 | 0.51±0.07ab | 0.98±0.05ab | 2.52±0.14c | 0.07±0.03a | 0.85±0.03b | 0.79±0.05b |
| SN | 0.58±0.08ab | 1.03±0.06ab | 2.53±0.11c | 0.06±0.04a | 0.84±0.04b | 0.78±0.07b |
| SN2 | 0.66±0.09a | 1.09±0.09a | 2.83±0.15b | 0.02±0.01b | 0.91±0.07a | 0.89±0.07a |
| 2SN | 0.59±0.08ab | 0.98±0.05b | 2.51±0.15c | 0.06±0.03a | 0.88±0.04ab | 0.83±0.06ab |
| 2SN2 | 0.66±0.06a | 1.07±0.03a | 3.50±0.25a | 0.07±0.04a | 0.95±0.05a | 0.88±0.05a |
| CK | 0.55±0.07b | 1.12±0.05a | 2.20±0.17d | 0.09±0.05a | 0.85±0.04b | 0.75±0.07b |

Notes: ±means the standard deviation (SD), different letters within groups are significantly different (p < 0.05).

**Table 4**

The soil mineral content of the bulk soil in different treatments

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Treatments | Quartz content (%) | Muscovite content (%) | Clinochlore content (%) | Albite content (%) | Microcline content (%) | Calcite content (%) |
| SN1/2 | 0.30±0.02a | 0.24±0.02ab | 0.11±0.02ab | 0.09±0.01ab | 0.03±0.02b | 0.22±0.01a |
| SN | 0.28±0.02b | 0.26±0.02a | 0.11±0.01ab | 0.07±0.02b | 0.04±0.02ab | 0.24±0.03a |
| SN2 | 0.31±0.01a | 0.24±0.02ab | 0.10±0.02b | 0.09±0.01ab | 0.03±0.01b | 0.23±0.01a |
| 2SN | 0.30±0.01a | 0.23±0.01b | 0.11±0.02ab | 0.09±0.01ab | 0.04±0.01ab | 0.23±0.02a |
| 2SN2 | 0.31±0.02a | 0.23±0.01b | 0.11±0.01ab | 0.10±0.01a | 0.04±0.01ab | 0.22±0.03a |
| CK | 0.29±0.01ab | 0.23±0.03b | 0.12±0.01a | 0.10±0.01a | 0.05±0.01a | 0.22±0.02a |

Notes: ±means the standard deviation (SD), different letters within groups are significantly different (p < 0.05).

**Table 5**

Factor loadings of principal component under different treatments

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Factors | Principal component | | | |  |
| Y(1) | Y(2) | Y(3) | Y(4) | Y(5) |
| salinity | -0.914 | -0.053 | -0.189 | 0.170 | 0.312 |
| N | 0.954 | 0.210 | 0.072 | 0.195 | 0.050 |
| P | -0.196 | 0.529 | 0.155 | 0.811 | 0.017 |
| K | 0.760 | 0.514 | 0.301 | -0.073 | 0.250 |
| SIC | -0.749 | 0.328 | 0.355 | -0.453 | -0.021 |
| STC | 0.735 | 0.673 | 0.048 | 0.066 | -0.027 |
| SOC | 0.922 | 0.325 | -0.156 | 0.138 | -0.010 |
| Quartz | 0.636 | 0.593 | -0.482 | -0.053 | 0.089 |
| Muscovite | 0.059 | -0.811 | 0.388 | 0.226 | 0.370 |
| Clinochlore | -0.856 | 0.271 | 0.318 | -0.240 | -0.186 |
| Albite | -0.129 | 0.927 | -0.333 | -0.068 | -0.088 |
| Microcline | -0.606 | 0.319 | 0.510 | 0.094 | -0.513 |
| Calcite | 0.296 | -0.810 | 0.328 | 0.284 | -0.263 |
| CS | -0.696 | 0.691 | -0.063 | 0.030 | 0.182 |
| MI | -0.825 | 0.429 | -0.104 | 0.327 | -0.132 |
| SM | 0.269 | 0.299 | 0.764 | -0.125 | 0.489 |
| LM | 0.628 | -0.643 | -0.334 | -0.185 | -0.212 |
| BET | 0.833 | 0.426 | 0.304 | -0.173 | -0.042 |
| Pore width | -0.769 | -0.226 | -0.365 | -0.042 | 0.472 |
| Contribution rate (%) | 46.553 | 28.178 | 11.611 | 7.121 | 6.538 |
| Cumulativecontribution rate (%) | 46.553 | 74.730 | 86.341 | 93.462 | 100.000 |

**Table 6**

The subordinate function value of 10 high factor loadings under different treatments

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Indexes | Treatments | | | | | |
| SN1/2 | SN | SN2 | 2SN | 2SN2 | CK |
| salinity \_ | 0.359 | 0.598 | 0.489 | 0.369 | 0.539 | 0.502 |
| N + | 0.315 | 0.397 | 0.795 | 0.490 | 0.883 | 0.498 |
| SIC + | 0.406 | 0.637 | 0.544 | 0.645 | 0.673 | 0.329 |
| SOC + | 0.443 | 0.678 | 0.428 | 0.598 | 0.683 | 0.155 |
| Muscovite+ | 0.784 | 0.763 | 0.741 | 0.783 | 0.615 | 0.887 |
| Clinochlore + | 0.732 | 0.820 | 0.788 | 0.904 | 0.767 | 0.755 |
| Albite + | 0.197 | 0.176 | 0.165 | 0.148 | 0.126 | 0.178 |
| MI + | 0.599 | 0.551 | 0.401 | 0.644 | 0.660 | 0.465 |
| SM + | 0.612 | 0.564 | 0.584 | 0.633 | 0.562 | 0.397 |
| BET + | 0.632 | 0.359 | 0.541 | 0.439 | 0.674 | 0.418 |
| Comprehensive value | 5.079 | 5.543 | 5.476 | 5.653 | 6.182 | 4.584 |

**Table 7**

Correlation analysis of the bulk soil properties

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | salinity | N | P | K | SIC | STC | SOC | Quartz | Muscovite | Clinochlore | Albite | Microcline | Calcite | CS | MI | SM | LM | BET | Pore width |
| salinity | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| N | -0.848\* | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| P | 0.265 | 0.095 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| K | -0.714 | 0.853 | 0.115 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| SIC | 0.517 | -0.710 | 0.007 | -0.266 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| STC | -0.714 | 0.858\* | 0.272 | 0.907\* | -0.342 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |
| SOC | -0.810 | 0.964\*\* | 0.079 | 0.809 | -0.702 | 0.898 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |
| Quartz | -0.503 | 0.691 | 0.073 | 0.669 | -0.431 | 0.838\* | 0.847\* | 1 |  |  |  |  |  |  |  |  |  |  |  |
| Muscovite | 0.069 | -0.024 | -0.191 | -0.179 | -0.283 | -0.479 | -0.242 | -0.610 | 1 |  |  |  |  |  |  |  |  |  |  |
| Clinochlore | 0.609 | -0.793 | 0.163 | -0.445 | -0.956\*\* | -0.442 | -0.783 | -0.541 | -0.271 | 1 |  |  |  |  |  |  |  |  |  |
| Albite | 0.093 | 0.031 | 0.408 | 0.261 | 0.315 | 0.511 | 0.226 | 0.625 | -0.937\*\* | 0.289 | 1 |  |  |  |  |  |  |  |  |
| Microcline | 0.296 | -0.481 | 0.434 | -0.278 | 0.707 | -0.186 | -0.517 | -0.492 | -0.265 | 0.840\* | 0.243 | 1 |  |  |  |  |  |  |  |
| Calcite | -0.323 | 0.177 | -0.210 | -0.179 | -0.493 | -0.286 | 0 | -0.489 | 0.768 | -0.387 | -0.894\* | -0.108 | 1 |  |  |  |  |  |  |
| CS | 0.674 | -0.509 | 0.520 | -0.150 | 0.708 | -0.053 | -0.406 | 0.012 | -0.552 | 0.722 | 0.733 | 0.519 | -0.825\* | 1 |  |  |  |  |  |
| MI | 0.766 | -0.647 | 0.635 | -0.495 | 0.577 | -0.298 | -0.559 | -0.249 | -0.412 | 0.736 | 0.528 | 0.682 | -0.498 | 0.863\* | 1 |  |  |  |  |
| SM | -0.275 | 0.374 | 0.130 | 0.719 | 0.214 | 0.414 | 0.204 | 0.030 | 0.223 | 0.032 | -0.047 | 0.059 | -0.076 | 0.056 | -0.279 | 1 |  |  |  |
| LM | -0.575 | 0.394 | -0.669 | 0.007 | -0.712 | 0.007 | 0.399 | 0.170 | 0.309 | -0.735 | -0.535 | -0.665 | 0.600 | -0.905\* | -0.792 | -0.359 | 1 |  |  |
| BET | -0.884\* | 0.870\* | -0.032 | 0.946\*\* | -0.297 | 0.904\* | 0.836\* | 0.642 | -0.234 | -0.452 | 0.202 | -0.208 | -0.037 | -0.318 | -0.587 | 0.585 | 0.189 | 1 |  |
| Pore width | 0.924 | -0.792 | -0.051 | -0.689 | 0.382 | -0.750 | -0.736 | -0.403 | 0.162 | 0.403 | -0.027 | -0.380 | -0.300 | 0.487 | 0.500 | -0.317 | -0.309 | -0.860\* | 1 |

\*Significant at *p* <0.05; \*\* Significant at *p* <0.01.