EFFECTS OF NUTRIENT AMENDMENTS ON EXPANSIVE SOFT ROCK AND THEIR IMPACT ON SANDY LAND STRUCTURE AND CROP (*TRITICUM AESTIVUM* L.) ROOTS

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Abstract. Sandy soil has excellent water drainage but poor retention of water and nutrients, leading to ecological fragility and land degradation. Desertification management has long been a focus of control efforts. This study examines the potential of natural soft rock to improve sandy soil structure and reduce project costs by analyzing its microstructure and mineral composition. The feasibility of enhancing sandy soil structure was assessed by mixing it with expansive soft rock. The study examined the mechanism for improving the soil structure of sandy land using soft rock. Additionally, it investigated the effects of four types of nutrient amendments—organic fertilizer, oil residue, microbial agents, and straw—on plant root structure. The results indicated that expansive soft rock plays a significant role in reducing the porosity of sandy soil. The montmorillonite present in expansive soft rock can absorb polar water molecules into its crystal layers, causing the crystals to expand and form pores of varying sizes. This mechanism effectively addresses issues related to water and nutrient loss in sandy soil. Following the addition of expansive soft rock and tillage activities, soil particles became progressively finer, resulting in a more balanced particle distribution. Structural improvements to sandy soil using soft rock created better soil conditions for plant growth, increased vegetation carbon density per unit area, enhanced regional ecology, and curbed soil degradation in sandy land. Four nutrient amendments significantly promote plant root development. The effects of these amendments on root development vary in magnitude, with organic fertilizer having the most substantial impact, followed by oil residue, microbial agents, and straw. Additionally, the combination of soft rock and nutrient modifiers exhibits a greater synergistic effect on both soil structure and plant root development.
Keywords: *soft rock, sandy soil, soil structure, root characteristics, clay minerals*

Introduction

Soft rock is a sedimentary material composed mainly of sand and clay, typically characterized by high clay mineral content. It generally forms in humid environments through processes such as flooding or marine deposition. Soft rock exhibits a variety of colors, with common hues including gray, brown, and red, and possesses a hard texture. It is widely used in building materials, decorative stone, and other applications. Due to its composition and structure, soft rock holds significant value in geology. Furthermore, soft rock enhances soil structure by improving ventilation and drainage, promoting root growth, reducing erosion, and protecting farmland. Additionally, soft rock may provide essential nutrients for plant growth, enriching the soil with beneficial minerals. Deserts in China are predominantly found in regions such as Inner Mongolia, Gansu, Xinjiang, as well as in Qinghai and Ningxia in the west (Wang et al., 2024a; An and Li, 2024). Sandy soils are characterized by good water drainage; however, excessive drainage can lead to rapid nutrient loss, adversely affecting plant growth. Consequently, sandy soils typically exhibit poor water retention, making it challenging to maintain an adequate water supply for plants (She et al., 2024). Additionally, these soils often lack organic matter and nutrients, resulting in low fertility and heightened susceptibility to wind and water erosion. This vulnerability is particularly pronounced in areas with sparse vegetation cover or where land reclamation practices are improper, which can exacerbate soil erosion. The large soil particles in sandy soils contribute to a loose soil structure, potentially resulting in insufficient root support and unstable plant growth (Wang et al., 2024b; Meng and Rao, 2024). Over the years, China has implemented various strategies to combat desertification, including the application of organic fertilizers and the covering of plant residues to enhance soil organic matter content, fertility, and water retention (Zhang and Han, 2019). Additionally, planting species suitable for sandy conditions or covering unplanted areas can help mitigate the risks of soil and wind erosion (Yao et al., 2024). The use of soil chemical amendments, water-retaining agents, curing agents, and other soil enhancers can further improve soil structure and water retention (Sun et al., 2019). These measures can effectively reduce the impacts of sand and soil erosion. To investigate the effects of soil consolidation in sandy areas more comprehensively, as well as the diverse applications of various soil structural improvements, it is essential to go beyond relying solely on indirect benefit responses and basic physical and chemical analyses (Wang and Li, 2022; Zhao et al., 2024). It is essential to conduct a fundamental study on the micro-forms of soil structural improvement, as well as the types and strengths of the cementation forces between soil particles (Musei et al., 2024; Liang et al., 2024; Liu et al., 2021). This research will establish a solid foundation for the controllable adjustment of the performance and efficacy of sand soil structures (Choobbasti and Saman, 2017; Ye et al., 2019; El-Akhdar et al.2024). To enhance sandy soil effectively, it is essential to address its structural deficiencies and to improve its nutritional content, as sandy soil is inherently low in fertility. Enriching the soil with adequate nutrients fosters robust root growth and development, leading to a more extensive root system that enhances the plant's nutrient absorption capacity (Shi et al., 2013; Huang and Hartemin, 2020; Chen et al., 2024; Olmo et al., 2016). A nutrient-rich environment also supports the proliferation of rhizosphere microorganisms, which further facilitates healthy root growth and nutrient uptake (Zhang et al., 2021, 2022). Research indicates that both the type and concentration of nutrients significantly influence root morphology, including the number and density of root hairs, thereby impacting nutrient absorption efficiency (Agegnehu et al., 2016). Consequently, this study will focus on both structural and nutritional enhancements of sandy soil.

Soil microstructure is a critical factor influencing soil quality and directly impacts the ecosystem functions of soil, such as the regulation of water and gas fluxes, as well as water and nutrient storage, and root penetration and growth (Liu et al., 2019). The study of soil microstructure can yield valuable information regarding mineral composition, material migration, agricultural practices, and soil fertility. This information enhances our understanding of the soil formation process and its variations,

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thereby providing a vital foundation for developing land use, management, and improvement strategies. In this study, natural soft rock is examined as the research subject, with a focus on analyzing its mineral composition and microstructure to assess the feasibility of structural enhancement in sandy soil. Additionally, a compound soil experiment involving sand is conducted to investigate the effects of incorporating soft rock on the texture of sandy soil. Following structural improvements, the sandy soil has met the fundamental requirements for crop growth. To further enhance the cultivation and ripening processes of this sandy soil, this study selected four nutritional amendments: straw, microorganisms, oil residue, and organic fertilizer. These amendments were applied to the sandy soil enriched with soft rock to promote its maturation (Cellier et al., 2014). The study investigates the impact of these nutritional measures on the root morphology of the planted crops, as well as the effects of the combination of soft rock and nutrient amendments on soil structure improvement and crop root development in sandy land. The results of this study offer theoretical support for enhancing the soil structure of sandy land, increasing its fertility, promoting the growth and development of crop roots, and providing technical guidance for the improvement of similar sandy soils.

Materials and methods

In this study, soft rock and undisturbed sand were collected from the Jingkeliang soil field in Daji Han Village, Xiaoji Han Town, Yuyang District, Yulin City, Shaanxi Province, China. The collected soil samples were transported to the experimental base (34.70°N, 109.19°E) in Fuping County, Weinan City, Shaanxi Province for field tests. The climate in this region is classified as a warm temperate semi-humid continental monsoon climate, with an average annual temperature ranging from 13 to 14°C and an average annual precipitation of approximately 500 to 600 mm, which is suitable for wheat cultivation. Three ratios of soft rock to sand were established at 1:1, 1:2, and 1:5, with three replicates for each treatment. Soil and crop samples were collected in June 2023, focusing on the 0-30 cm soil layer for experimental analysis. A 100 cm^3 ring knife was employed to collect undisturbed soil samples. After returning to the laboratory, the polished surfaces of the samples were coated with a gold film approximately 10 to 20 nm thick using an ion sputtering instrument, and subsequently examined under a scanning electron microscope. Micromorphological characteristics of the composite soil, including particle size, morphological distribution, pore characteristics, and the connectivity between soil particles, were directly observed using an FEI Q45 scanning electron microscope (Thermo Fisher Scientific). The composition of soft rock, sand, and composite soil particles was analyzed with a Mastersizer 3000 laser particle size analyzer (Malvern Panalytical), with three repetitions for each soil sample.

A ratio of 1:2 for soft rock to sandy soil was selected for the nutritional amendment experiment. This ratio facilitates the formation of a more effective agglomeration structure, which promotes crop growth and development, a finding supported by the author’s team (Cao et al., 2023). Four nutritional amendments were tested: organic fertilizer, oil residue, microbial bacteria, and straw. Each amendment test was conducted with three replicates. The organic fertilizer consisted of 50% organic matter, nitrogen (N) at 2%, phosphorus (P_2O_5) at 1.5%, and potassium (K_2O) at 1%. The oil residue contained 60% organic matter, nitrogen (N) at 5%, phosphorus (P_2O_5) at 2%,

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and potassium (K_2O) at 1%. The microbial agent contained between 10^8 and 10^{10} active bacteria per gram, along with 30% organic matter. The straw had a composition of 75% organic matter. The application rates for the four nutrient amendments were as follows: organic fertilizer at 100 kg/mu, oil residue at 30 kg/mu, microbial agent at 1 kg/mu, and straw at 100 kg/mu.

The experimental crop used in this study was *Triticum aestivum* L. (wheat), which was sown in early October 2022 at a planting density of 12 kg/mu and with a row spacing of 20 cm. At the time of sowing, the basic fertilizer application included 10 kg/mu of nitrogen (N), 6 kg/mu of phosphorus (P_2O_5), and 5 kg/mu of potassium (K_2O). Following the maturation of the wheat in June 2023, the above-ground biomass was harvested, and soil samples were collected from the 0-30 cm depth using a root drill with a diameter of 10 cm and a height of 15 cm. The soil containing roots was subsequently washed with water, and the roots were cleaned and analyzed using the WinRHIZO root scanner (Regent Instruments). The layout of the test field and the sample collection process are illustrated in *Figure 1*. Data processing was conducted using Excel, and one-way analysis of variance (ANOVA) was employed to evaluate statistical significance among the treatments.

***Figure 1.** Test field and the sample collection process*

Results and discussion

Study on the influence of soft rock on the soil structure of sandy soil

Clay mineral morphology of soft rock

Soft rock is a complex mineral composed of well-crystallized quartz particles intermixed with clay minerals exhibiting varying degrees of weathering. The sedimentary environment of soft rock arises from the clastic rock deposition of alternating fluvial and continental facies under both oxidation and reduction conditions, with the primary intergranular connection mode being cementation. The intergranular cementing material consists of chemical sediments that precipitate directly from the intergranular solution, predominantly including clay minerals, carbonates, and siliceous minerals, which are primarily self-formed during the diagenetic stage. The composition, morphological characteristics, and content of the intergranular cementing material significantly influence the properties of both rock and soil. As illustrated in *Figures 2* and *3*, clay minerals in soft rocks are tightly cemented together, resulting in intricate pore structures characterized by high hydrophilicity, large specific surface area, and substantial interlayer space. Additionally, montmorillonite and green montmorillonite exhibit strong ion exchange properties due to their weak interlayer bonding and propensity for expansion. The presence of honeycomb and thin-film clay mineral

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coatings on particle surfaces leads to the formation of discontinuous coated particles that extend outward. The occurrence of clay minerals demonstrates a high degree of idiomorphism, with no distinct vertical or parallel relationship between the crystal elongation direction and the particles. When multiple chlorites aggregate, some will make contact with one another while others will interact with the surface, resulting in the formation of rose-shaped chlorite aggregates, while some remain as dispersed sheets, exhibiting strong cementation potential.

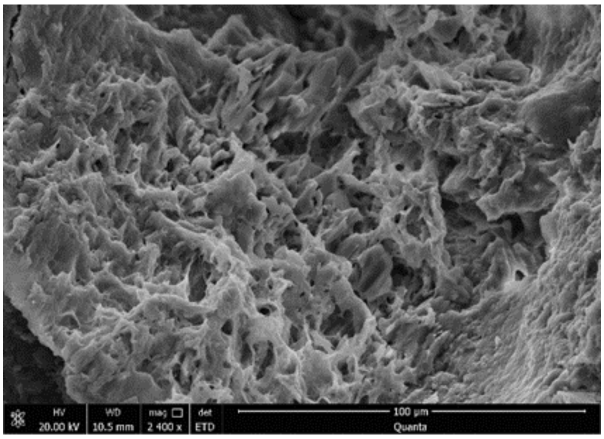

Figure 2. *Honeycomb and thin film clay mineral layers in soft rock*

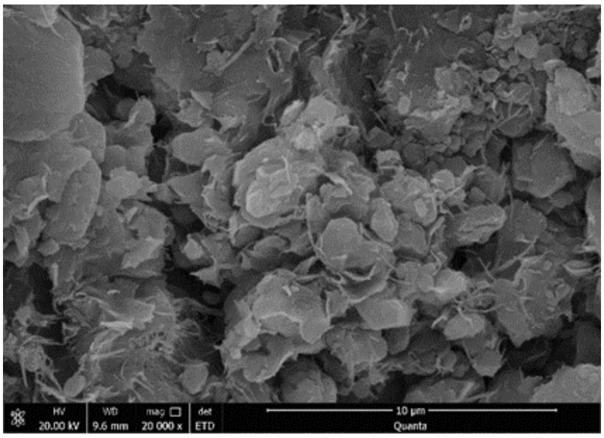

Figure 3. *Honeycomb and thin film clay mineral layers in soft rock*

Elemental analysis of soft rock

Through energy spectrum analysis of soft rock, as illustrated in *Figures 4* and *5*, it is evident that soft rock contains a significant concentration of elements such as oxygen (O), aluminum (Al), silicon (Si), and gallium (Ga), alongside trace amounts of magnesium (Mg), potassium (K), and iron (Fe). The results presented in *Table 1* indicate that soft rock comprises compounds including magnesium oxide (MgO), aluminum oxide (Al_2O_3), silicon dioxide (SiO_2), potassium oxide (K_2O), calcium oxide (CaO), and iron oxide (FeO). Notably, the SiO_2 content is as high as 40.83%, while Al_2O_3 and CaO content are 13.93% and 35.37%, respectively. Both aluminum and calcium ions can bind to soil particles, thereby enhancing the adhesion between them.

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The formation of an aggregate structure contributes to the improvement of the soil structure in coarse sand, and an appropriate amount of calcium can stimulate the activity of soil microorganisms, thus promoting soil health. Inorganic colloids in soil interact with organic matter to form combined humus, primarily through the bridging bonds of calcium, iron, and aluminum. Calcium ions can establish ionic bridges on the surfaces of organic colloids and minerals, thereby reinforcing the aggregate structure of the soil. Based on the elemental composition of soft rock, it possesses the potential to enhance the soil structure of coarse sandy land.

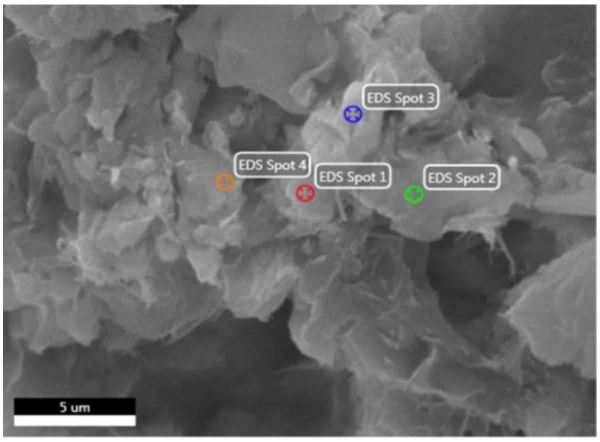

Figure 4. *Points of soft rock energy spectrum analysis*

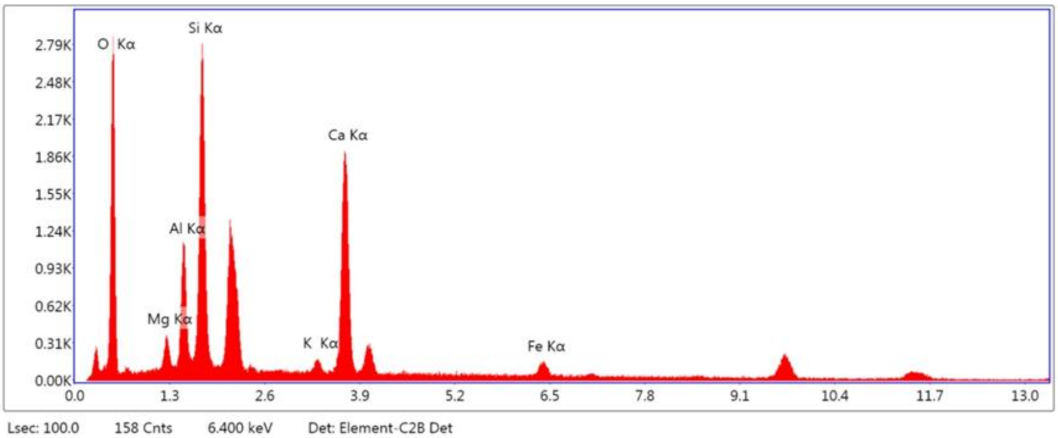

Figure 5. *Energy spectrum of soft rock*

Table 1. *Mineral composition of soft rock*

Element	Weight %	Atomic %	Net Int.	Error %	Kratio	Z	R	A	F
MgO	3.24	4.97	18.86	10.85	0.0092	0.9944	0.9916	0.4994	1.0090
Al2O3	13.93	8.45	85.33	6.51	0.0424	0.9581	0.9991	0.6314	1.0125
Si O2	40.83	42.05	238.87	4.90	0.1225	0.9795	1.0062	0.6921	1.0085
K2O	1.08	0.71	9.06	15.17	0.0077	0.9094	1.0364	0.9266	1.0816
CaO	35.37	39.03	207.59	2.67	0.2124	0.9262	1.0415	0.9511	1.0161
FeO	5.55	4.78	17.00	11.72	0.0347	0.8269	1.0641	0.9798	1.0585

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Microstructure of mixed soft rock and sand

The analysis of the surface topography of soft rock and sand composite soil, as illustrated in *Figure 6,* reveals that the pores within the micro-aggregate of aeolian sand soil are poorly distributed. The pore structure of the soft rock and sand composite soil predominantly consists of narrow, accumulative pores, exhibiting a wide range of apertures, including fine, medium, and large pores. Following the mixture of soft rock and sand, the soil particles exhibit tight contact with one another, resulting in smaller pores and an abundance of cementing material between the particles. Additionally, there are numerous attachments on the surfaces of the soil particles, which are primarily in surface contact, further enhancing the bonding between particles due to the presence of cementing materials. This configuration allows the soil to maintain good agglomeration while retaining certain pore spaces. Over the years of crop planting, irrigation, and fertilization, factors such as plant root exudates, biological activities, and their byproducts, along with an increase in humus, have contributed to a rise in soil organic matter content, thereby significantly enhancing soil agglomeration and improving soil structure.

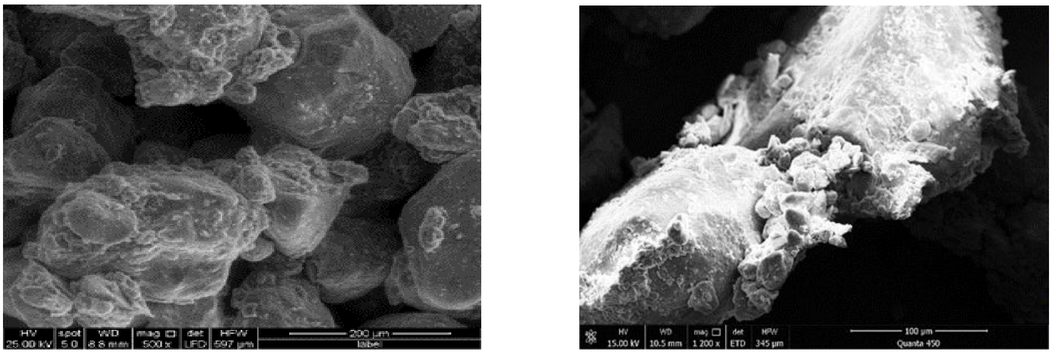

Figure 6. *Electron microscope images of soft rock and sand composite soil (left 200 times), (right 100 times)*

Soil texture after mixing soft rock and sand

The loose structure and easy weathering of soft rock impart it with fundamental characteristics of the parent material. However, soft rock is deficient in organic matter and nutrients essential for plant growth, resulting in a slow accumulation of nutrients and a protracted soil formation process. Given its excellent cementation properties, the soil texture and aggregates were analyzed following the mixture (*Table 2*) of soft rock and sand (*Figs. 5* and *6*). The results indicated that the clay content in the soft rock and sand treatment at a ratio of 1:5 differed significantly from that in the whole sand treatment, with an increase of 1.23 percentage points in clay content observed in the former. Furthermore, the clay content in the soft rock and sand treatments at ratios of 1:1, 1:2, and 1:5 exhibited a significant upward trend compared to the total sand treatment. The quantity of soft rock added had a pronounced effect on the texture of the sand soil; as the amount of soft rock increased, the fine particulate matter within the soil aggregates also rose, significantly enhancing the agglomeration structure of the sand and soil. The complementarity of soft rock and sand in terms of texture structure (particle size composition characteristics) has emerged as a crucial factor contributing to the notable sand-fixation effect of soft rock, thereby establishing its potential as a parent

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material for improving the texture of sand. This characteristic of soft rock creates favorable basic growth conditions for the development of crop roots in sandy soil. It also offers a viable strategy for subsequent nutrient application, which can positively influence the roots of crops planted in sandy soil following the improvement of soft rock.

Table 2. *Soil texture after mixing soft rock and sand*

Compounding ratio	Clay (%)	Silt (%)	Sand (%)
1:1	4.27	39.05	56.68
1:2	3.32	31.47	65.21
1:5	2.75	25.92	71.33
0:1	1.52	15.43	83.05

Study on the influence of nutrient amendments on the root system of improved sandy plants

Study on the influence of nutrient amendments on plant root length

As illustrated in *Figures 7* and *8*, the root length of wheat in the improved sandy soil derived from soft rock varies between 0 and 30 cm, with measurements ranging from 9521.68 to 19656.87 cm under different treatments. The root length density ranges from 4.04 to 8.34 cm/cm^3 Four types of nutrient amendments significantly enhanced the root length of wheat, with their efficacy ranked in the following order: organic fertilizer > oil residue > microbial agent > straw. The root lengths of plants subjected to these four nutrient amendments increased by 48.34% to 106.44% compared to the control group. Longer roots enable deeper penetration into the soil, facilitating access to water at greater depths. The expansion of the root system allows plants to explore a larger soil area, thereby enhancing nutrient absorption. Additionally, longer roots contribute to plant stability in the presence of strong winds or soft soils and can foster symbiotic relationships with soil microorganisms and fungi, further promoting plant growth.

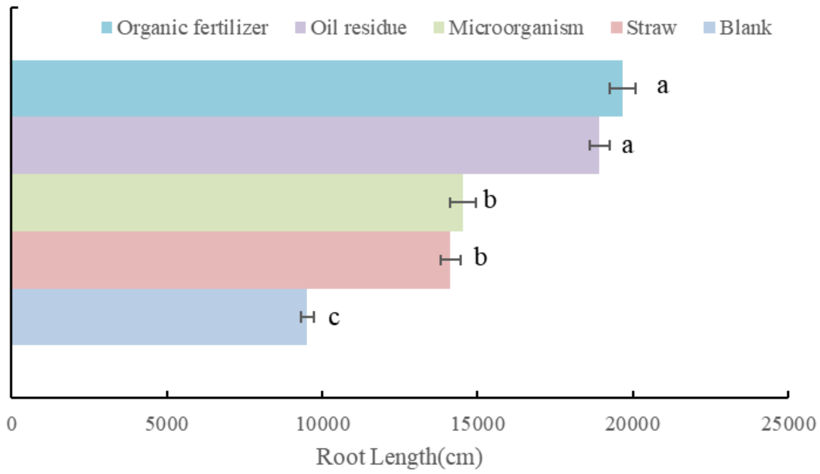

Figure 7. *Root length under different treatments. The error bars in this chart represent the standard deviation of the data between 3 replicates in the same treatment group, and this note applies to all the charts below*

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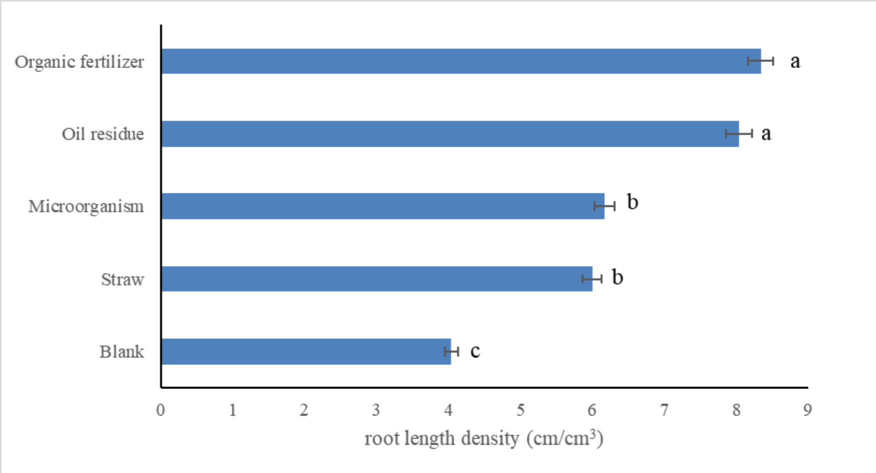

Figure 8. *Root length density under different treatments*

Study on the effect of nutrient amendments on plant root surface area

As illustrated in the *Figure 9,* the root surface area of wheat in the improved sandy soil derived from soft rock varies between 0 and 30 cm, with values ranging from 1170.39 cm^2 to 2105.48 cm^2 under different treatments. The application of organic fertilizer, microbial agents, and oil residue significantly enhanced the surface area of wheat roots. The effectiveness of nutrient amendments on the growth of plant root surface area follows the order: organic fertilizer > microbial agents > oil residue, while the impact of straw on wheat root surface area was not significant. The root surface area of plants subjected to the three types of nutrient amendments increased significantly by 10.63% to 79.9% compared to the control treatment. A larger root surface area enables plants to access more water and facilitates greater contact with soil nutrients, such as minerals and organic matter, thereby promoting nutrient absorption and enhancing the plant's growth rate. Furthermore, an extensive root surface area contributes to the development of a diverse rhizosphere microbial community, which assists plants in decomposing organic matter and converting nutrients, ultimately improving the nutrient utilization efficiency of the plants.

Study on the effect of nutrient amendments on plant root diameter

As illustrated in the *Figure 10,* under various treatments, the average root diameter of wheat in the improved sandy soil of soft rock ranges from 0 to 30 cm, with measurements between 1.52 mm and 4.80 mm. All four nutrient amendments significantly influenced the average diameter of wheat roots. The impact of these amendments on root diameter was ranked as follows: organic fertilizer > oil residue > microbial agent > straw. Compared to the blank treatment, the average diameter of the plants increased by 10.66% to 216.50%. A larger root diameter is indicative of a more robust root system, which enhances the plant's ability to withstand environmental pressures. This improved root structure contributes to better physical support for the plants, aiding their resilience against natural phenomena such as drought and wind. Additionally, strong plant roots can store greater amounts of water and nutrients, thereby providing an extra source of energy for plants during adverse conditions.

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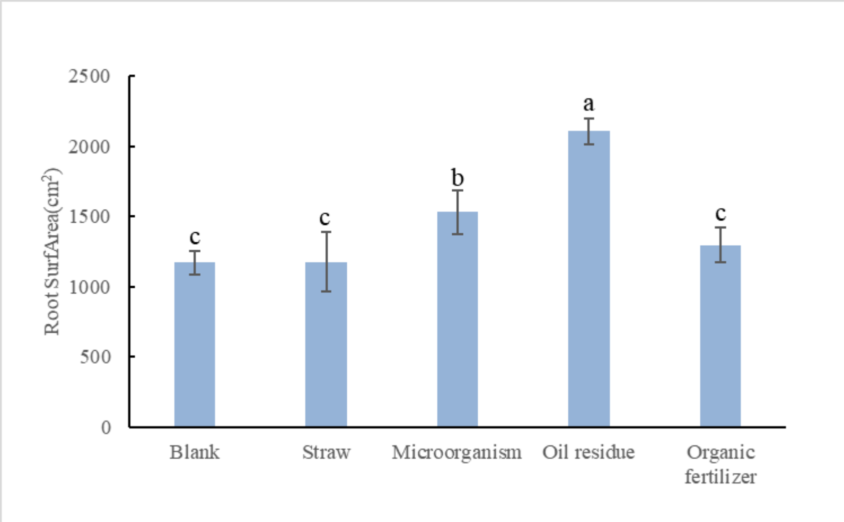

Figure 9. *Root surface area under different treatments*

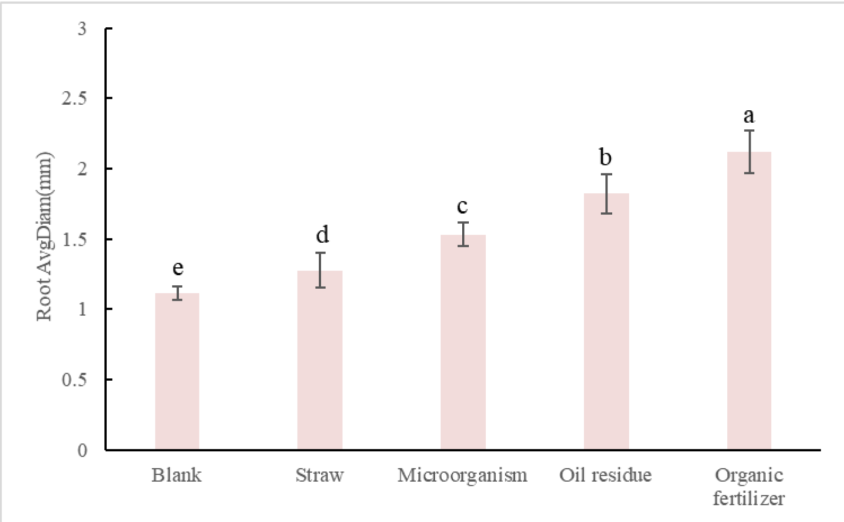

Figure10. *Root average diameter under different treatments*

Study on the effect of nutrient amendments on plant root volume

As illustrated in the *Figure 11,* the root volume of wheat in improved sandy soil derived from soft rock varies from 0 to 30 cm, with measurements ranging from 6.83 cm^3 to 54.63 cm^3 under different treatments. All four nutrient amendments significantly influenced wheat root volume, with the efficacy of these amendments ranked as follows: organic fertilizer > oil residue > straw > microbial bacteria. The root volume of plants treated with these four nutrient amendments exhibited a significant increase of 15.11% to 699.93% compared to the control group. Larger root volumes enhance the anchorage of plants in the soil, improving their resistance to erosion, while also facilitating the storage of sugars and other nutrients, which provide energy support during the growing season or under adverse conditions. Furthermore, increased root volume offers a more expansive growth and development space for rhizosphere microorganisms, thereby contributing to enhanced soil health and overall plant growth.

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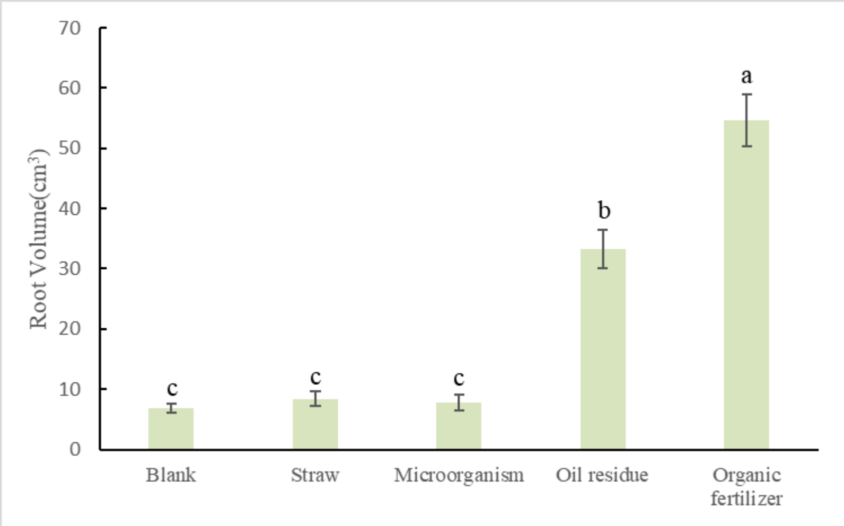

Figure 11. *Root volume under different treatments*

Study on the effects of nutrient amendments on the number of root tips, root forks and root crossings of plants

As illustrated in *Figure 12,* the number of root tips of wheat in sandy soil after soft rock improvement varied between 45562~94860 across different treatments, while the number of root forks ranged from 102694~165305, and the number of root crossings fluctuated between 17969~41655. The four nutritional amendments significantly influenced the number of root tips, root forks, and root crossings numbers of wheat. Notably, the growth trend for these parameters in response to the nutritional amendments was consistent, with the effectiveness ranking as follows: organic fertilizer > oil residue > microbial bacteria > straw. Compared to the control treatment, the number of root tips increased by 10.04% to 108.20%, the number of branch roots rose by 11.22% to 60.97%, and the number of cross roots enhanced by 57.25% to 131.82%. Root tips are critical components of the root system responsible for water and nutrient absorption. An increase in root tips can enhance the absorption efficiency of plants, thereby improving their adaptability to varying soil conditions and increasing their competitive survival. Additionally, a greater number of root branches expand the distribution range of roots within the soil, facilitating a more comprehensive utilization of nutrient resources. Concurrently, root forks establish a broader network in the soil, which enhances plant stability and resistance to lodging. root crossings can improve interactions between plants and promote the sharing of water and nutrients, which is particularly beneficial for wheat suited for dense planting. Furthermore, through root overlapping, plants can gain a competitive edge, inhibiting the growth of neighboring plant roots and thereby supporting overall vegetation growth.

As illustrated in *Figure 13,* wheat root lengths exhibited significant variation across different root diameter regions under the four treatments. Specifically, when $0 < l \leq 0.5$, plant root lengths comprised 85.96% to 93.81% of the total root lengths. In the case of $0 < l \leq 1.0$, root lengths accounted for 94.58% to 98.34% of the total root length. Across the various treatments, the root lengths in different root diameter regions demonstrated the following trend: organic fertilizer > oil residue > microbial agent > straw.

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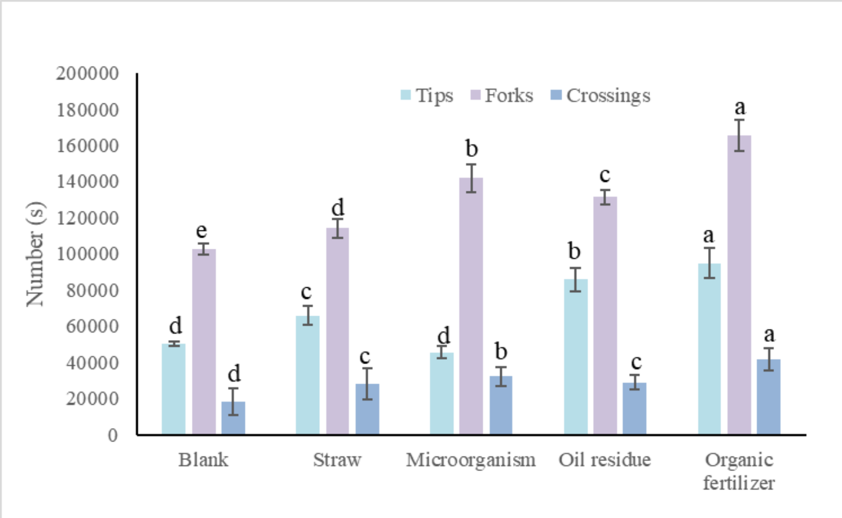

Figure 12. *Root volume under different treatments3.2.6 Study on the influence of nutrient amendments on root indexes in different root diameter ranges. Lowercase letters indicate differences between the same indicator under different treatments*

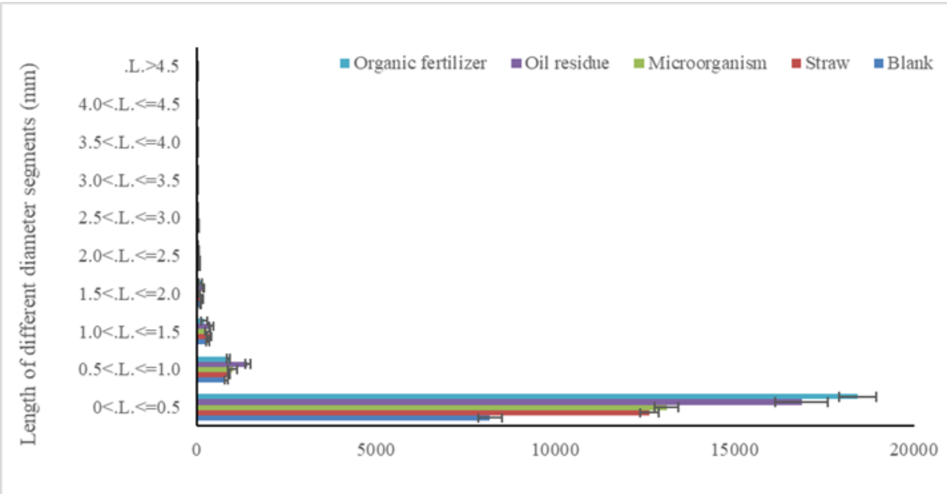

Figure 13. *Root length in different root diameter regions*

Figure 14 illustrates that, across the four treatments, the surface area of plant roots in different root diameter regions was significantly different. When 0 < l < = 0.5, the root surface area constituted 44.49% to 70.30% of the total root surface area. For the range of 0 < l < = 1.0, the root surface area represented 67.44% to 86.92% of the total root. In the interval of 0 < l < = 1.5, the root surface area accounted for 81.90% to 93.77% of the total root. The root surface area across different root diameter regions displayed the following trend: oil residue > organic fertilizer > microbial agent > straw.

As shown in *Figure 15,* significant differences in root volume were observed across different root diameter regions under the four treatments. When $0 < l \leq 0.5$, the root volume constituted 11.25% to 30.30% of the total root volume. For the range of $0 < l \leq 1.0$, the root volume represented 30.46% to 55.86% of the total. In the case of $0 < l \leq 1.5$, the root volume accounted for 51.03% to 74.49% of the total. The root

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volume across different root diameter regions exhibited the following trend: organic fertilizer > oil residue > microbial agent > straw.

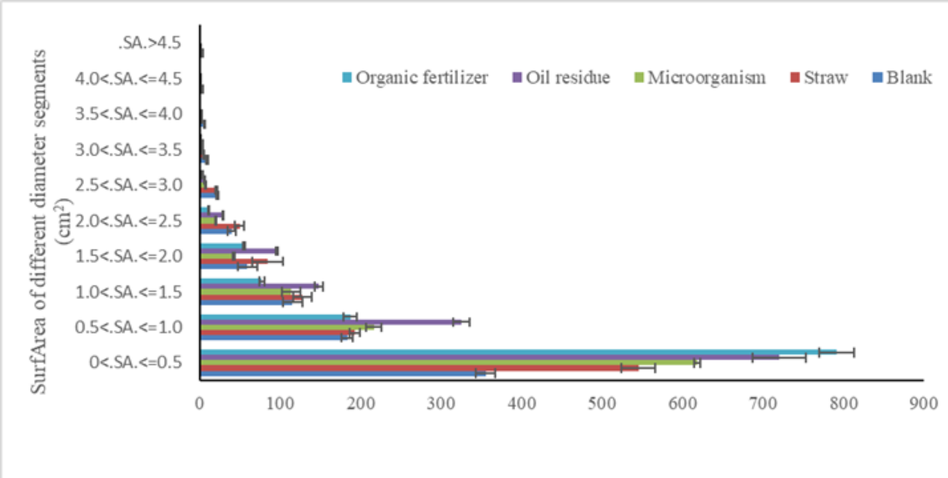

***Figure 14.** Root surface area in different root diameter regions*

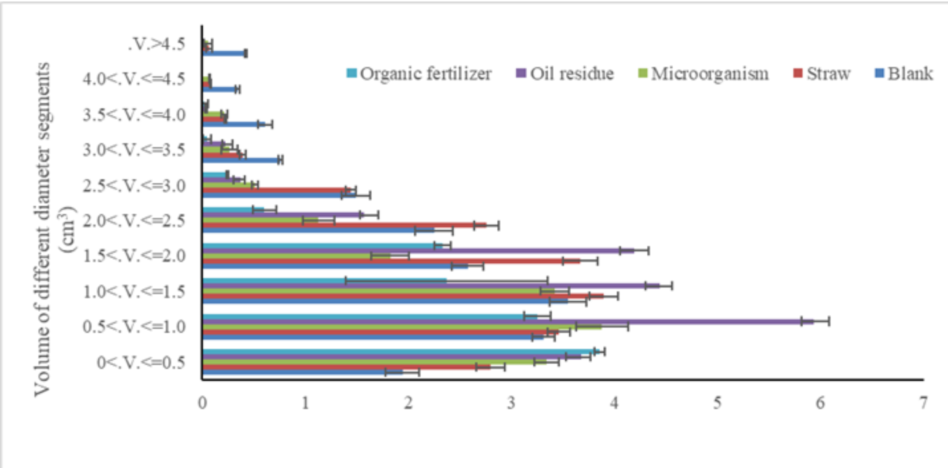

***Figure 15.** Root volume in different root diameter regions*

Figure 16 illustrates that significant differences in the number of plant root tips were observed across the four treatments in different root diameter regions. Specifically, for the interval 0 < l < = 0.5, the number of root tips constituted 99.05% to 99.38% of the total root tips. In the interval 0 < l < = 1.0, this figure increased to 99.65% to 99.88% of the total roots. For the interval 0 < l < = 1.5, the volume of plant roots represented 99.86% to 99.97% of the total roots. Additionally, the number of root tips in different root diameter regions demonstrated a trend in effectiveness: organic fertilizer > oil residue > microbial agent > straw.

- Based on the analysis of root length, root surface area, root volume, and the number of root tips across different root diameter ranges, it is evident that the root system primarily falls within the range of 0 < l < = 1.5, with the range of 0 < l < = 0.5 representing the largest proportion. As the root diameter increases, there is a significant decrease in root distribution. This finding effectively illustrates the characteristics of

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plant roots. The wheat root system comprises a taproot along with numerous lateral roots, forming an extensive whisker root system. The lateral roots are well-developed, contributing to the formation of a robust root network. Additionally, the numerous root hairs significantly enhance the surface area of the root system, thereby improving the absorption of water and nutrients (Yao et al., 2024; Ye et al., 2019).

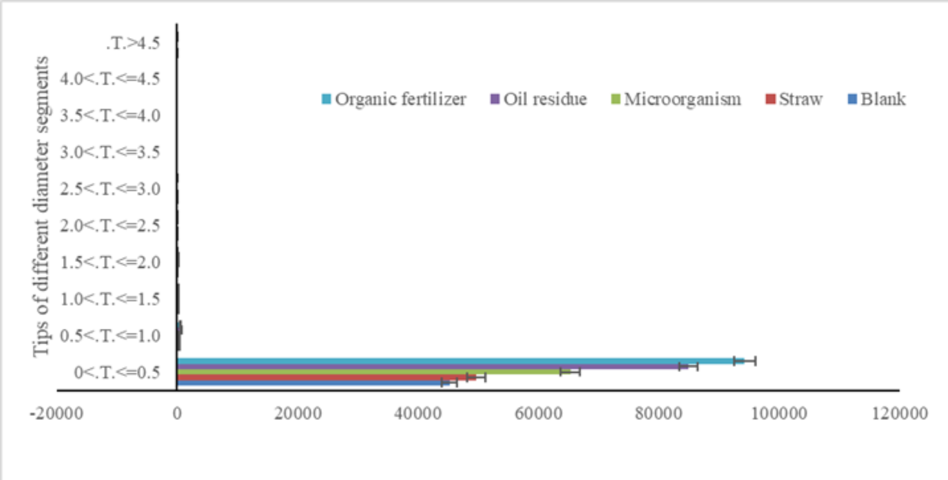

Figure 16. *Root tips in different root diameter regions*

The four different treatments also showed that adding soft rock to the sandy soil followed by nutrient supplementation helped plant root development. The general trend of the effects of the four nutrient amendments on root growth and development was organic fertilizer, oil residue, microbial agent and straw. Organic fertilizer can rapidly increase soil organic matter, improve soil structure, continue to supply nutrients needed by plants, and promote healthy root growth. Organic fertilizer not only provides nutrients for plant roots, but also provides a relatively rich carbon source for rhizosphere microorganisms, which can further promote the reproduction of rhizosphere microorganisms and improve the growth environment of roots (Zhang and Han, 2019). Oil residue is rich in organic matter and rich mineral elements such as calcium, magnesium, phosphorus, potassium and so on. The application of oil residue can improve soil fertility and promote root development. The application of microbial inoculants can directly improve rhizosphere microbial population, increase microbial abundance, accelerate the rapid conversion of nutrients in soil into easily absorbed forms of plants, and enhance the nutrient acquisition ability of roots (Zhang, 2022; Zhang, 2021). Straw helps to improve the water retention of soil and reduce the evaporation of water in soil, which has a good effect on improving the water retention capacity of coarse sand soil and promoting the development of plant roots. The mechanism of influence of different nutrient amendments on plant root development is different, but the combined application of four nutrient amendments can significantly improve the development of plant root system in the improved sandy soil.

Conclusion

(1) Clay minerals in soft rocks are primarily composed of multi-angular, disordered dust particles. In the cementing material of soft rock, the predominant authigenic clay is

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montmorillonite, along with green montmorillonite and a minor presence of illite. Soft rock plays a significant role in reducing the porosity of sandy land. Its cementation primarily occurs by obstructing the large pores of sand grains; however, it does not diminish the intergranular volume and instead creates pore channels of varying sizes. Due to its expansibility, polar water molecules can be absorbed into the intergranular layer, leading to crystal expansion. A key characteristic of montmorillonite is its ability to absorb water and expand, which can effectively address issues related to water and fertilizer leakage within sandy soil structures.

(2) Soft rock contains elements such as oxygen (O), aluminum (Al), silicon (Si), and gallium (Ga), along with trace amounts of magnesium (Mg), potassium (K), and iron (Fe). Aluminum and calcium ions can interact with soil particles, promoting particle bonding and forming a granular structure, which aids in enhancing the structure of coarse sandy soils. Based on the elemental composition of soft rock, it has the potential to improve the soil structure of coarse sandy land.

(3) As the content of soft rock in composite soil increases, the soil particles become progressively finer. The incorporation of soft rock effectively enhances the particle composition of sandy soil. A composite soil with a 1:1 ratio of soft rock to sand exhibits significantly higher clay and silt content compared to pure sand. Tillage activities, along with the presence of plant roots and microorganisms, contribute to the continuous refinement of soil particles in the composite soil, resulting in a more rational distribution of these particles. Soft rock serves as a natural soil modifier, improving the structure of sandy soil, facilitating essential water and nutrient retention for plant growth, and fulfilling the requirements for plant root adhesion and development.

(4) To further enhance soil quality following the soft rock improvement of sandy land, the development of plant roots can be significantly optimized through the application of four types of nutrient amendments. These amendments include organic fertilizer, oil residue, microbial agents, and straw. Although the mechanisms by which each amendment promotes root development vary, the overall addition of nutrient amendments has a markedly positive impact on sandy land post-soft rock improvement. The combination of soft rock and nutrient modifiers exhibits a greater synergistic effect on both soil structure and plant root development.

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