frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 19 March 2025
DOI 10.3389/fenvs.2025.1556083

EDITED BY
Xiaoping Wang,
Northwest A&F University, China

REVIEWED BY
Hongchao Dun,
Lanzhou University, China
Chunyuan Wang,
Chinese Research Academy of Environmental Sciences, China

*CORRESPONDENCE
Zhongju Meng,
mengzhongju@126.com

†These authors have contributed equally to this work

RECEIVED 06 January 2025
ACCEPTED 25 February 2025
PUBLISHED 19 March 2025

CITATION
An H, Zhao F, Li H, Meng Z, Ding H, Ding Y, Qin L and Xin J (2025) The typical sand-fixing plants in the Ulan Buh desert-oasis area significantly changed the distribution pattern of surface sediments.
Front. Environ. Sci. 13:1556083.
doi: 10.3389/fenvs.2025.1556083

The typical sand-fixing plants in the Ulan Buh desert-oasis area significantly changed the distribution pattern of surface sediments

Hua An[1,2,3†], Feiyan Zhao[1,2,3†], Haonian Li[1,2,3], Zhongju Meng[1,2,3]*, Hailong Ding[1,2,3], Yanlong Ding[4], Lei Qin[5] and Jing Xin[6]

[1]College of Desert Control Science and Engineering, Inner Mongolia Agricultural University, Hohhot, China, [2]Key Laboratory of Aeolian Physics and Desertification Control Engineering from Inner Mongolia Autonomous Region, Inner Mongolia Agricultural University, Hohhot, China, [3]Key Laboratory of Desert Ecosystem Conservation and Restoration, State Forestry and Grassland Administration of China, Inner Mongolia Agricultural University, Hohhot, China, [4]College of Tourism, Inner Mongolia University of Finance and Economics, Hohhot, China, [5]Water Conservancy Development Center of Inner Mongolia Ancient Autonomous Region, Hohhot, China, [6]Ordos Forestry and Grassland Development Center, Ordos, China

Vegetation increases surface roughness, reduces wind speeds and decreases sand carrying capacity, thereby effectively intercepting wind-sand flows and promoting sand deposition. Exploring the distribution of sand-fixing plant sediment particles and the characteristics of plant morphology parameters in the desert-oasis transition zone can provide a certain theoretical foundation for regional ecological vegetation construction and desertification control. In this paper, the particle size of surface sediments (0–2 cm) under cover of five typical sandy vegetation in the desert-oasis transition zone at the northeastern edge of the Ulan Buh Desert was investigated, and the effects of plant morphometric parameters on the grain size distribution of sediments were analyzed. The results show: (1) Plant spatial configuration significantly influenced surface sediment characteristics, with Nitraria *tangutorum* having the largest crown width and number of branches with 283 cm and 385 branches compared to the other four species. In unit area, the degree of porosity from large to small is: *Psammochloa villosa* > *Agriophyllum squarrosum* > *Phragmites australis* > *Artemisia ordosica* > *Nitraria tangutorum*. On the whole, the interception effect of N.*tangutorum* shrub on transit airflow is more prominent. (2) The grain size distribution of the sandy material in the study area is unimodal with good particle sorting. Due to the interception of N. *tangutorum* and A. *ordosica* shrubs, the contents of medium sand and fine sand in the mechanical composition of sediments in the surface layer of vegetation-covered dunes decreased significantly, while the contents of clay, silt, and very fine sand increased significantly ($P < 0.05$); Compared to the bare dunes, the particle sorting becomes worse, and the particle size frequency curve shifts to a bimodal state with a positively skewed trend and a lower kurtosis value. Overall, the sediment grain composition in order of coarseness to fineness was: CK > P. *villosa* > A. *squarrosum* > P. *australis* > A. *ordosica* > N. *tangutorum*. (3) The mean grain size of sediments under vegetation coverage was positively correlated with sortability, kurtosis and skewness ($P < 0.01$). Mean particle size and sortability significantly correlated negatively with kurtosis and skewness ($P < 0.01$). (4) Mean grain size and sortability were significantly positively correlated with plant crown width and branch number and significantly negatively correlated with porosity ($P < 0.05$). Skewness and kurtosis were significantly negatively correlated with plant crown width and branch number and significantly positively correlated with porosity ($P < 0.05$). (5)In this paper, the mean grain size of the sediment is used as an indicator of the above-mentioned plant windbreak and sand fixation. It is concluded that the lower leaves of N. *tangutorum* and A. *ordosica* are dense, the porosity is minor, and the particle composition of the sand material is fine, forming dense vegetation shrubs on the dunes, which is more powerful in windbreak and sand fixation. Screening plants with strong vitality and outstanding sand-fixing capacity is important for controlling quicksand, improving soil quality and preventing wind erosion.

KEYWORDS

sediment, grain size parameters, phytomorphological parameters, Ulan Buh desert, distribution pattern

1 Introduction

The desert-oasis transition zone is an ecologically sensitive and fragile area that serves as a bridge between the desert and oasis ecosystems and assumes the important functions of promoting the circulation of materials, energy flow, and the transmission and sharing of information (Li et al., 2016). The desert-oasis interface at the northeastern edge of the Ulan Buh Desert suffers from severe land degradation due to the natural environment and long-term human activities (Luo et al., 2022). Many natural or artificial sand-fixing plants grow within the desert-oasis transition zone. Most of these sand-fixing plants have simple community structure, less species composition, relatively low vegetation cover, drought resistance, wind erosion and sand burial resistance, etc., and have good wind and sand blocking functions (Gao et al., 2025). Vegetation in the transition zone can resist wind and sand erosion and has an important ecological function in protecting the stability of the oasis ecosystem by reducing the flow rate of wind and sand, preventing wind erosion, fixing sand dunes, and improving the physicochemical properties of the soil (Mayaud and Webb, 2017).

In arid wind-sand areas, the grain size distribution of wind-sand sediments is both an important factor affecting the process of surface wind erosion, transport, and accumulation and a result of the sorting of near-surface winds through surface erosion and deposition (Van Hateren et al., 2020). The loss of fine particles from the surface due to wind-sand activities causes coarsening of surface particles, resulting in loss of land nutrients and reduced productivity, while the ratio of particles of different sizes influences the stability of the particles, which also has an important impact on the intensity of wind erosion on the surface (Guan et al., 2024). The study of grain size distribution and sorting characteristics of wind-sand sediment deposits is of great significance for understanding the dynamics of near-surface sand transport, analyzing wind-sand depositional environments, and inverting changes in wind-sand environments (Wang et al., 2022). Soil particle size characteristics, as an important indicator of soil physical properties, characterize the proportion and distribution of mineral particles of different size classes in the soil. The change of its parameters is controlled by factors such as transport medium, transport mode, depositional environment and climate, which can explain the transportation of particles and then judge the evolution of the depositional environment, and is more and more widely used in the study of land desertification (Wu et al., 2021).

In recent years, the Ulan Buh Desert-Oasis transition zone has been subjected to anthropogenic interference, and internal sand-fixing plants have declined to varying degrees, affecting the stability of the fixed dunes and thus seriously threatening the oasis ecosystem (Hussein et al., 2021). With the degradation of sand-fixing plants, vegetation cover decreases, soil particles gradually become coarser, and ecological vegetation stability deteriorates (Moradi et al., 2024). Methods of combating desertification mainly include mechanical, chemical, and biological measures (plant measures)are the most direct (Amiraslani and Dragovich, 2011; Khalilimoghadam and Bodaghabadi, 2020), fundamental and practical measures in the prevention and control of wind and sand disasters (Wang et al., 2023). Soil particle composition, as the material basis for the growth and development of sand-fixing plants, is important in building a stable ecosystem. The distribution of surface vegetation strongly influences the variability in the grain size distribution of wind-sand sediments (Gonzales et al., 2018). The ability of plants to slow wind speeds and reduce sediment transport is closely related to the aerodynamic response to airflow triggered by their morphology (Miri et al., 2017). In addition to vegetation cover, the protective effect of shrub vegetation against surface wind erosion is impacted by factors such as vegetation shape and plant distribution pattern (Zheng et al., 2022). Numerous studies have shown that by increasing the surface roughness (Jiang et al., 2024), the above-ground part of the vegetation can, on the one hand, reduce the surface wind speed and weaken the sand-carrying force of the wind (Mayaud et al., 2016); on the other hand, it can intercept the wind-sand flow and promote the sedimentation of sand particles, thus playing a role in preventing the wind and blocking the sand (Kang et al., 2024). In arid sandy areas, due to climate and moisture conditions, it is difficult to achieve the ideal state of vegetation cover, height, and shape needed to resist wind and sand hazards in a short period. Consequently, it is of practical significance to analyze the influence of plant morphological parameters on sediment grain size distribution and select well-adapted sand plants for specific areas to maintain ecological stability of the transition zone and recovery of desert sandy soil.

Under field conditions, most of the research is carried out on the impacts of vegetation cover and structural characteristics on wind erosion, and some scholars have found through field research that adjusting the shrub structure of the same configuration of windbreak forests can improve their effectiveness in windbreaks and sand fixation (Zhao et al., 2024). With the deepening of research in desertification control, the prevention of wind and sand fixation through plants and the protection of soil quality in sandy areas have become the focus of research (Guo et al., 2024). However, there are fewer studies on the effect of individual morphology of shrub plants on near-surface windbreaks and sand fixation, especially on the effect of morphological characteristics of sand-fixing vegetation on sediment grain-size distribution in the transition zone of Ulan Buh Desert-Oasis. In arid and sandy areas, the distribution of particle size has a significant effect on the intensity of wind erosion, material transport, and accumulation patterns on the surface and is the result of the natural screening of particles by near-surface winds through the complex process of erosion and deposition (Zhang et al., 2024). Taller plants and wider canopies promote the deposition of more sand particles, especially fine particulate matter, which is more readily immobilized by vegetation, thereby altering the sediment grain size distribution. The shading effect of vegetation branches and leaves reduces the scouring and transport of surface sand particles by wind-sand currents and promotes the deposition of sand particles near the vegetation, forming wind-shadowed dunes, which further enhances the sand-fixing capacity (Dupont et al., 2014). Therefore, the study of the effect of plant morphological indicators on sediment grain size distribution can quickly infer the dynamic changes of wind-sand transport near the ground, which is important for evaluating the wind and sand-fixing ability of different plant species (Cao et al., 2022).

In this study, we analyzed the grain size distribution of sediments and the characteristics of plant morphological parameters under cover of five desert plants in the Ulan Buh Desert-Oasis transition zone in the Inner Mongolia Autonomous Region, China, with the aim of: 1) Characterize the grain size distribution of surface sediments after types of plants have covered the surface; 2) To explore the relationship between sediment grain size parameters and plant morphological parameters; 3) To investigate the effect of plant morphological parameters on sediment grain size distribution. To analyze the role of different sand-fixing plants in the desert-oasis transition zone on the surface wind and sand activities, to provide a specific scientific basis for the screening of wind and sand-fixing plant species in the study area.

2 Materials and methods

2.1 Study area

The study area is 20 km southwest of Dengkou County, Inner Mongolia Autonomous Region, China (40.191°N, 106.839°E). The region is part of a temperate continental climate zone with strong northwesterly winds and frequent dust storms in the spring. The average annual temperature is stable at 7.5~8.1°C, the average annual precipitation is 142.7 mm, and the potential evaporation is 2258.8 mm. The mean annual wind speed is about 3.7 m/s, and the number of days with high winds is 10~32 days per year, especially during March ~ May in spring, and northwesterly and southwesterly winds dominate the wind direction. Mobile dunes of 6 ~ 15 m are widely distributed in the study area, with dune densities exceeding 0.8. The hard red clayey texture is widely distributed in the lowlands between the mounds and is covered by a sandy layer of varying thickness, ranging from 10 to 50 cm. Pioneer plants such as *Psammochloa villosa*, *Agriophyllum squarrosum*, *Artemisia ordosica*, *Phragmites australis*, *Nitraria tangutorum*, etc., are scattered on the dune slopes. In the distribution area of N.*tangutorum* shrub, the stability of sand dunes was significantly improved, and the height of these sandbags was primarily concentrated in the range of 0.5~5 m, and their surface was covered with finer-grained sandy material with a softer texture. The vegetation distribution in the study area is characterized as shown in (Table 1).

2.2 Sample collection

The selected sample site is a typical flat bare sandy land with homogeneous topography, where vegetation is the dominant factor influencing the wind speed and direction in the area. Sample plots were laid out to minimize the distance between plots while meeting the ecological minimum interval scale. Differences in the subsurface of the samples are mainly caused by differences in vegetation, the presence of which leads to changes in airflow and wind speed and direction, making vegetation the most significant control of the subsurface. Field measurements and sampling were conducted in late March 2024, which is usually the strongest wind in the study area in 1 year. Different sand-fixing plants (N. *tangutorum*, A. *ordosica*, P. *australis*, A. *squarrosum*, P. *villosa*) in the plot were selected as the research target, and the bare dunes were selected as the control (CK). Five 5 m × 5 m sample squares were set up for each plant species to be investigated, and four plants with good growth conditions and uniform morphology were selected as standard plants within each sample square, totaling 100 standard plants. Crown spread and plant height were measured, and the number of branches on the whole plant and the sparsity of the lateral projection of the plant were measured by photographic methods (Torita and Satou, 2007). A total of 20 plants of each species were measured, distributed over a 2 km^2 area. Figure 1 shows a rose diagram of sand fixing plants and wind direction in the study area (Figure 1). Photographic method: Lateral projection images of plants were taken under standard lighting conditions using a high-resolution digital camera. After denoising and contrast enhancement preprocessing, the separation of pore space from plant tissues was achieved by threshold segmentation. And the image processing software was used to calculate the pore area and the total projected area, and finally the porosity was calculated by the ratio of pore area to total projected area. To ensure the quality of the images and the accuracy of the porosity measurements, the photographs were taken under conditions where the sky was mostly covered with clouds but with a small amount of blue sky still visible, the light was soft and there was no noticeable harsh sunlight or dark shadows, there was no precipitation, there was no wind, and the cloud cover was stable. The porosity data we obtained is not in a particular direction, but is the average value in each direction calculated by selecting plants with relatively uniform growth and conformation, photographing them from multiple angles in eight directions, and combining them with advanced digital image processing algorithms.

Concentric circles were drawn around the base of a single plant as a core, with the inner circle radius being half the average crown width of the plant and the outer circle radius coinciding with the

TABLE 1 Characteristics of vegetation distribution in the study area.

Plant species	Habitat	Status of distribution	Density/(Plant·m^2)
P. villosa	Mobile sand dune	Independent distribution	0.12
P. *australis*	Mobile sand dune	Community distribution	0.41
A. squarrosum	Mobile sand dunes and semi-fixed sand dunes	Independent distribution	0.22
A. ordosica	Mobile sand dunes and semi-fixed sand dunes	Community distribution	0.23
N. tangutorum	Semi-fixed sand dunes and fixed sand dunes	Community distribution	2.54

Note: Five 5 m × 5 m quadrats were investigated for each plant.

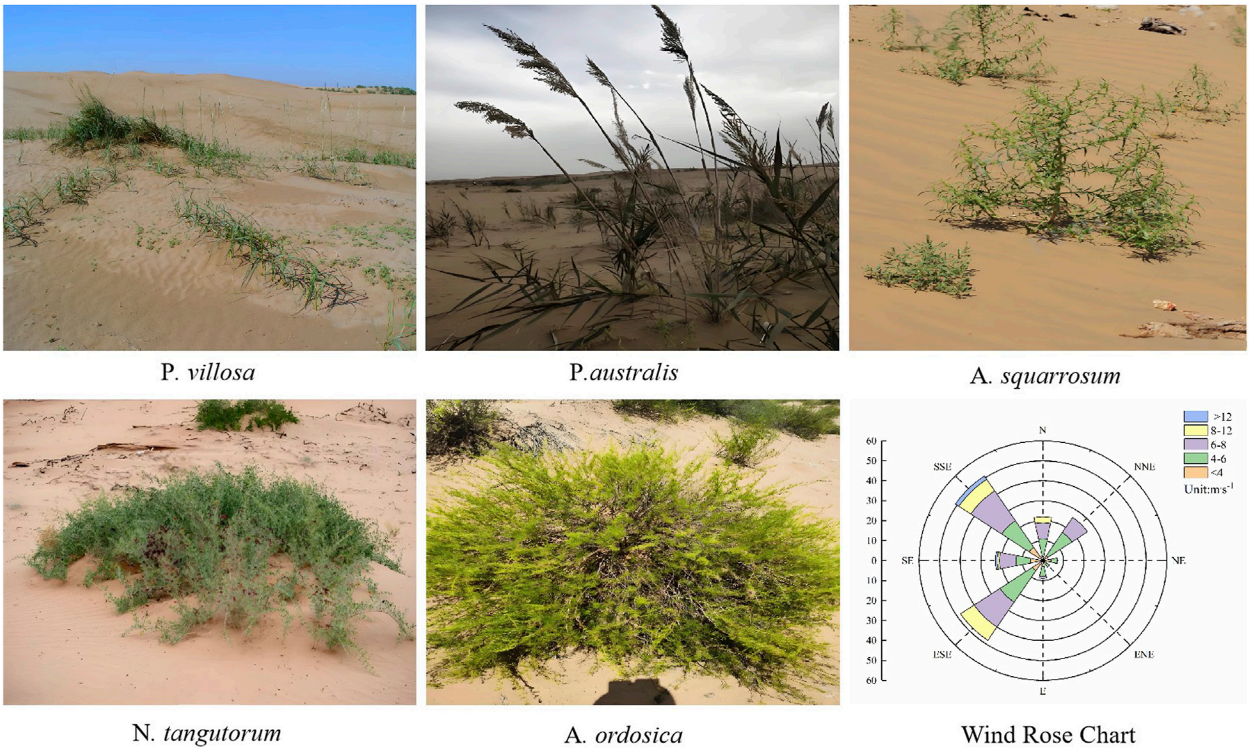

FIGURE 1
Photographs of sand-fixing plants in the study area and wind rose chart.

average crown width. Sediment samples with a surface depth of 2 cm were taken at four directional points, east, south, west, and north of the concentric circles. For the sampling of shrub sand piles, the center point of the shrub was used as the datum to ensure that the sampling area did not extend beyond the boundaries of the shrub, and sediment samples were collected at the appropriate depth in each direction as described above (Figure 2). All sediment samples beneath the same single plant were combined and thoroughly mixed to produce a mixed sediment sample of approximately 50 g. Twenty mixed samples were ultimately collected from each plant. Twenty bare dune samples were also collected as controls, for 120 mixed sediment samples. Winds in the study area are responsible for the transport of sandy material, surface erosion and accretion in multiple directions, but we are primarily concerned with wind-sand deposition processes dominated by the plant canopy itself. Concentric circle sampling covering multiple wind directions can eliminate the interference of a single wind direction on the sampling results, thus reflecting more comprehensively the integrated influence of plants on wind-sand deposition, revealing comprehensively the role of plants in regulating airflow and sediment, and providing a scientific basis for the study of spatial heterogeneity of wind-sand deposition.

2.3 Sediment sample determination

The collected samples were placed in a laboratory environment with smooth air circulation to dry naturally. After removing impurities, coarse particles larger than 2,000 μm were sieved through a 2-mm sieve. Then, ultrapure water and H_2O_2 solution

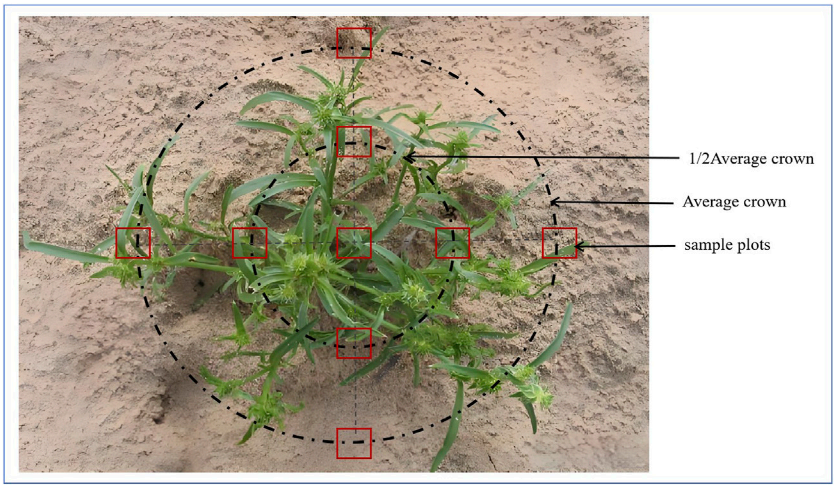

FIGURE 2
Schematic diagram of sample collection around the plant (using A.*squarrosum* as an example).

TABLE 2 Granularity parameter grading standard.

σ		SK		Kg	
≤0.35	Excellent sortability	−1.0~−0.3	Extreme negativity	≤0.67	Very wide
0.35~0.5	Very good sortability	−0.3~−0.1	Negative skewness	0.67~0.90	Wide
0.5~0.71	Better sortability	−0.1~0.1	Asymmetric	0.90~1.11	Medium
0.71~1.00	Medium sortability	0.1~0.3	Positive	1.11~1.56	Narrow
1.00~2.00	Poor sortability	0.3~1.0	Extremely positive	1.56~3.00	Very narrow
2.00~4.00	Very poor sortability			>3.00	Extremely narrow
>4.00	Extremely poor sortability				

were added and left for 24 h to remove organic matter. When no more bubbles are generated in the beaker, place an appropriate amount of the sample in the oven, heating it to dryness, which is used to volatilize all the residual H_2O_2 solution. The samples to be tested were placed in a stationary device, water and 10% HCL solution were added to dissolve the carbonates, and the supernatant was pipetted out after 24 h of stationary time. Test the pH of the sample with a pH meter by adding distilled water to the pH meter in the proper proportion until the pH is nearly neutral. The particle size composition of each sediment sample was determined independently three times using a Mastersizer 3000 high-precision laser particle sizer, and the arithmetic mean of the measurements was subsequently calculated to ensure the accuracy and reliability of the particle size data.

2.4 Particle size parameter model

Based on the Udden-Wenworth particle size classification system, the sediments were classified into six different grain sizes, namely, clay (<4 μm), silt (4–63 μm), very fine sand (63–125 μm), fine sand (125–250 μm), medium sand (250–500 μm), and coarse sand (500–1,000 μm). The Udden-Wentworth system delineates sand grains in great detail and accurately describes their grain size distribution, which helps to analyze the source of sand grains, the transport process and the depositional environment. In addition, the system is closely related to the wind transport capacity and depositional environment, which can better reveal the transport and deposition mechanism of sand grains in the Ulan Buh Desert under the action of wind. The Folk Grain Size Classification System focuses more on a combination of sand shape and sortability in the subdivision of the sand fraction, and is suitable for scenarios where sedimentary rock formation processes are being studied or where a comprehensive characterization of the sediment is required. The Krumbein phi (φ) system uses a logarithmic transformation, which is suitable for statistical analysis and can make the data more consistent with a normal distribution, facilitating hypothesis testing and modeling. Because particle size studies in the Ulan Buh Desert first require clarification of the size distribution of sand grains and their relationship to wind and sand activity, the use of the Udden-Wentworth system meets the need and avoids unnecessary complexity.

According to the Udden-Wenworth particle size classification system, combined with the Kum-dein conversion method, these particle diameters (D) are converted into Φ values according to Equation 1 by performing logarithmic conversion to facilitate more uniform analysis and comparison (Krumbein, 1934).

$$\Phi = -\log_2 D \tag{1}$$

The particle size parameters were calculated from Equations 2–5 using the Folk-Ward plotting method: mean particle size (Mz), sorting coefficient (σ), skewness (SK) and kurtosis (Kg) were calculated (Folk and Ward, 1957). Figures 4a–d were plotted and analyzed according to the grading criteria for particle size parameters (Table 2).

$$\mathrm{Mz} = \frac{\Phi_{16} + \Phi_{50} + \Phi_{84}}{3} \tag{2}$$

$$\sigma = \frac{\Phi_{84} - \Phi_{16}}{4} + \frac{\Phi_{95} - \Phi_5}{6.6} \tag{3}$$

$$\mathrm{SK} = \frac{\Phi_{16} + \Phi_{84} - 2\Phi_{50}}{2(\Phi_{84} - \Phi_{16})} + \frac{\Phi_5 + \Phi_{95} - 2\Phi_{50}}{2(\Phi_{95} - \Phi_5)} \tag{4}$$

$$\mathrm{Kg} = \frac{\Phi_{95} - \Phi_5}{2.44(\Phi_{75} - \Phi_{25})} \tag{5}$$

where: Φ_5, Φ_{16}, Φ_{25}, Φ_{50}, Φ_{75}, Φ_{84}, Φ_{95} are the corresponding quartiles of the grain size distribution.

Mean particle size (Mz) characterizes the average distribution of soil particle size and is commonly used in studies of particle deposition patterns and in tracking particle movement processes. The sorting coefficient (σ) indicates the degree of discrete distribution of soil particles; the smaller its value indicates that the more concentrated the distribution of soil particles, the better the particle sorting. Skewness (SK) reflects the symmetry of the frequency curve of soil particle size, indicating the distribution characteristics of soil particles. Kurtosis (Kg) is a parameter of the concentration degree of soil grain size distribution on both sides of the average particle size, which represents the ratio of the tail expansion degree to the middle expansion degree of the frequency curve or the ratio between the two sides of the soil particle frequency curve and the sorting degree of the middle part. It can quantitatively measure the width and steepness of the peak shape of the soil particle frequency distribution curve. In general, the larger the Kg value, the stronger the peak sharpness, indicating that the grain size distribution of the sample is more concentrated.

2.5 Calculation of mean distance between cumulative frequencies of soil particle size

The average distance (d) between the cumulative frequency distribution of soil particle size can reflect the difference in soil quality between plots, which is mutually confirmed with the cumulative frequency curve of soil particle size and can provide evidence for the judgment of soil coarsening. Calculated from Equation 6:

$$\mathrm{d} = \sqrt{\sum (\mathrm{P} + \bar{\mathrm{P}})^2 (\mathrm{K} - 1)} \tag{6}$$

where: d is the average distance between the distributions of soil particle size accumulation frequency; P is the soil particle size accumulation frequency of a certain sample site; is the average of soil particle size accumulation frequency of six sample sites; K-1 is the degree of freedom, K = 6.

2.6 Calculation of the fractal dimension

The fractal dimension (D) is widely used in characterizing the structural properties of soils, and its value is related to the number of particles of different sizes in the soil, so it can not only quantitatively indicate the structural characteristics of the soil (Dong et al., 2022), but also reflect the indicators of soil water content, soil fertility, etc., which is widely used in the research of land degradation. In this paper, the volume fractal dimension is calculated by the volume content of different diameter particles of soil measured by the Mastersizer 3000 laser particle size analyzer. The calculation method is as follows (Equation 7):

$$\left(\frac{\mathrm{R_i}}{\mathrm{R_{max}}}\right)^{3-\mathrm{D}} = \frac{\mathrm{V}(\mathrm{r} < \mathrm{R_i})}{\mathrm{V_T}} \tag{7}$$

where D is the fractal dimension; r is the diameter of soil particles (mm); r_i is the diameter of a certain diameter soil particle (mm); V $(r < R_i)$ is the volume percentage of soil particles smaller than R_i diameter particles (%); V_T is the total volume percentage of particles in each diameter grade (%); R_{max} is the maximum particle diameter (mm).

2.7 Statistical analysis

Excel 2021 was used to preliminarily sort out and analyze the data, and the mean value and standard deviation were calculated. SPSS 22 was used for one-way analysis of variance, and the significance test of grain size parameters and morphological parameters of sediments under different vegetation coverage was carried out ($P < 0.05$). LSD method was used for multiple comparisons, and Origin 2021 was used to draw relevant graphs.

3 Results and analysis

3.1 Plant modality features

From Figure 3, it can be seen that the average plant height of N. *tangutorum*, P. *villosa*, A. *squarrosum*, P. *australis,* and A.*ordosica* is 116 cm, 143 cm, 52 cm, 72 cm, and 77 cm, respectively, (Figure 3a). Of these, N. *tangutorum* had the largest crown, averaging 283 cm which was significantly higher than the other four species; P. *australis* had the smallest crown, averaging 58 cm; The crowns of P. *villosa*, A. *squarrosum* and A. *ordosica* ranged from 100–130 cm (Figure 3b). The average number of branches of N. *tangutorum* was 385, while the number of branches of P.

10.3389/fenvs.2025.1556083

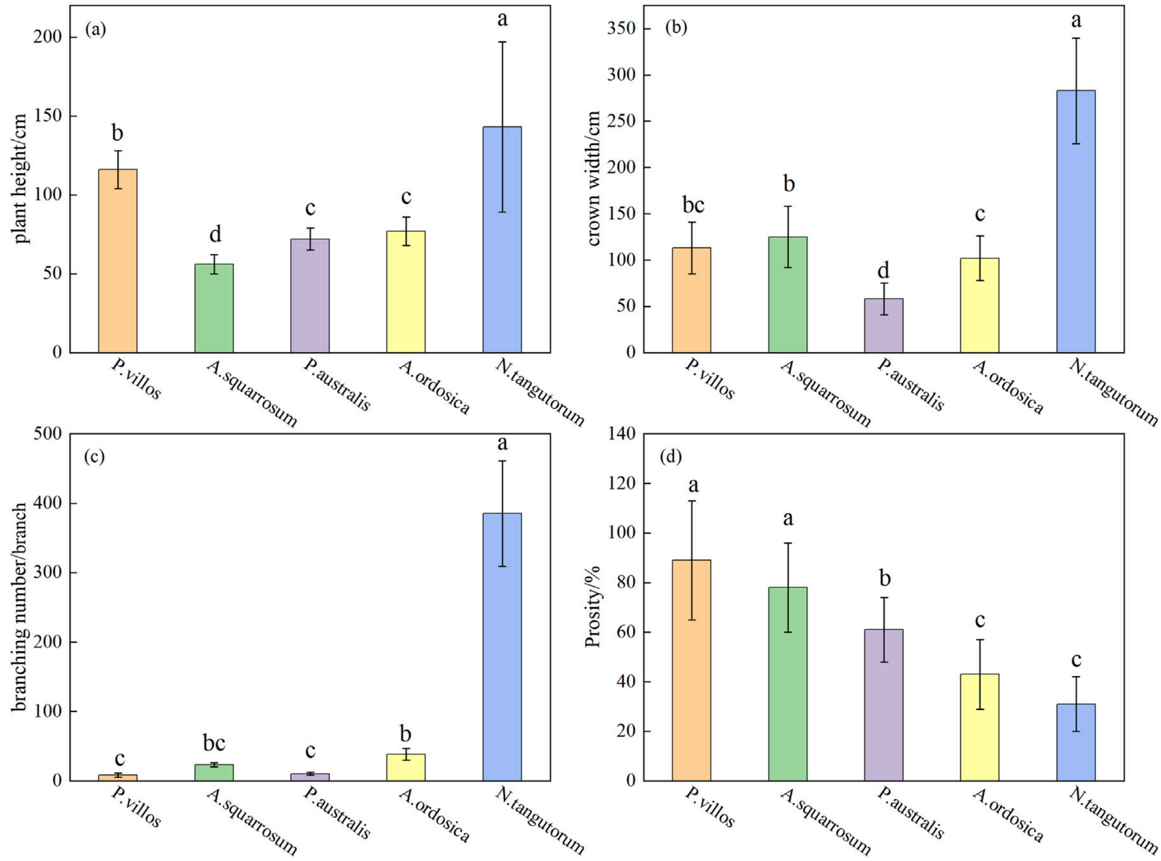

FIGURE 3
Morphological characteristics of plants.

TABLE 3 Mechanical composition of sediments covered by different plant species (%).

Sample area	Clay	Silt	Very fine sand	Fine sand	Medium sand	Coarse sand
P. villosa	0.10 ± 0.00c	1.25 ± 0.21d	15.74 ± 4.87c	52.03 ± 13.20ab	30.74 ± 5.15ab	0.14 ± 0.02a
A. squarrosum	0.10 ± 0.01c	1.53 ± 0.27d	18.13 ± 4.33bc	49.06 ± 9.37b	31.10 ± 6.44ab	0.08 ± 0.02b
P. australis	0.10 ± 0.00c	2.38 ± 0.63c	26.75 ± 5.17b	45.63 ± 6.42b	25.14 ± 3.99b	—
A. ordosica	0.81 ± 0.14b	11.04 ± 2.34b	37.71 ± 7.39a	37.06 ± 6.84c	13.38 ± 3.17c	—
N. tangutorum	2.46 ± 0.39a	36.28 ± 8.38a	23.58 ± 4.28b	27.21 ± 5.31d	10.34 ± 2.01c	0.13 ± 0.03a
CK	0.10 ± 0.01c	0.72 ± 0.14e	3.08 ± 0.55d	60.61 ± 15.85a	35.43 ± 6.08a	0.06 ± 0.01b

Note:The lowercase letters represented significant differences between different plants of the same grain size (LSD, $P < 0.05$), CK is the control (Bare sand dunes), same below.

villosa and P. *australis* was less, 8.35 and 10.35, respectively (Figure 3c). Significant differences were found among the five plants in terms of mean grain size, crown width, number of branches and porosity ($P < 0.05$).In the unit area, the order of porosity from large to small is: P. *villosa* > A. *squarrosum* > P. *australis* > A. *ordosica* > N. *tangutorum*. The porosity of P. *villosa* is the largest, indicating that the density of branches and leaves is the smallest, while the porosity of N. *tangutorum* is the smallest and the branches are the densest (Figure 3d).

3.2 Characteristics of sediment interception by plants

3.2.1 Characteristics of mechanical composition of sediment intercepted by plants

The mechanical composition of the sediment intercepted by the five plants is shown in Table 3. The fine sand and medium sand in the surface sediments of bare dunes are absolutely dominant, and their volume percentages are 60.61% and 35.43%, respectively. The

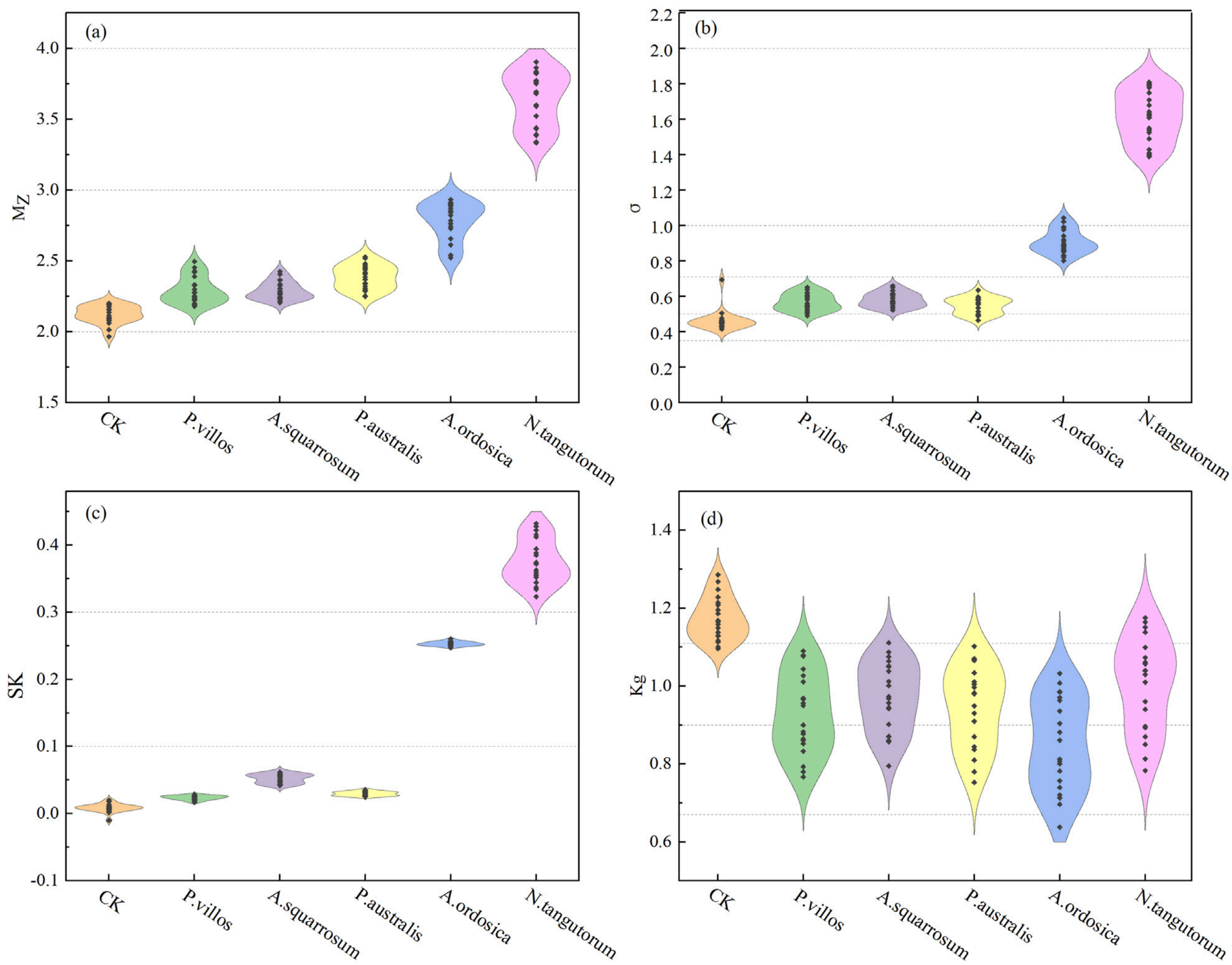

FIGURE 4
Grain size characteristics of sediments under different plant coverage.

trend of fine particle size of sediments after vegetation coverage is more obvious; the volume percentage of very fine sand, clay, and silt increases, and the volume percentage of fine sand and medium sand decreases. The variation trend of clay, silt, and very fine sand is basically the same, and the volume percentage is N. *tangutorum* > A. *ordosica* > P. *australis* > A. *squarrosum* > P. *villosa* > CK. The change trend of volume percentage content of fine sand and medium sand is basically the same, and its change trend under different plant coverage is opposite to that of fine particles such as silt and very fine sand. The change trend of volume percentage content of fine sand and medium sand is basically the same, and its change trend under different plant coverage is opposite to that of fine particles such as silt and very fine sand. The volume percentages of clay and silt in N. *tangutorum* sediment particles were the highest, at 2.46% and 36.28%, respectively. The contents of clay and silt were significantly higher than those of the other four vegetations ($P < 0.05$). The contents of fine sand and medium sand were significantly reduced ($P < 0.05$), and there was a small amount of coarse sand. Vegetation coverage significantly increased the content of fine particles in surface sediments ($P < 0.05$). The particle composition is mainly composed of fine sand, from coarse to fine: CK > P. *villosa* > A. *squarrosum* > P. *australis* > A. *ordosica* > N. *tangutorum*.

3.2.2 Grain size parameters of sediment intercepted by plants

The mean particle size of these five plantings showed: N. *tangutorum* > A. *ordosica* > P.*australis* > A. *squarrosum* > P. *villosa* > CK. According to the classification standard of the Folk-Ward graphic method, except that N.*tangutorum* is very fine sand, the rest are fine sand. The increase in the Φ value of the mean particle size of the sediment indicates a significant increase in the content of fine particles, indicating that the content of fine particles in the sediments of N.*tangutorum* and A.*ordosica* was significantly higher than that of the other three vegetations ($P < 0.05$). The mean particle size of sediments under different plant coverage was significantly different from that of CK ($P < 0.05$). N.*tangutorum* and A.*ordosica* have dense branches and leaves and relatively high plant morphology, which can form better surface coverage. The strong blocking effect on wind and sand allows the retention of fine particles in the sediment, so the Φ value of the average particle size is larger (Figure 4a).

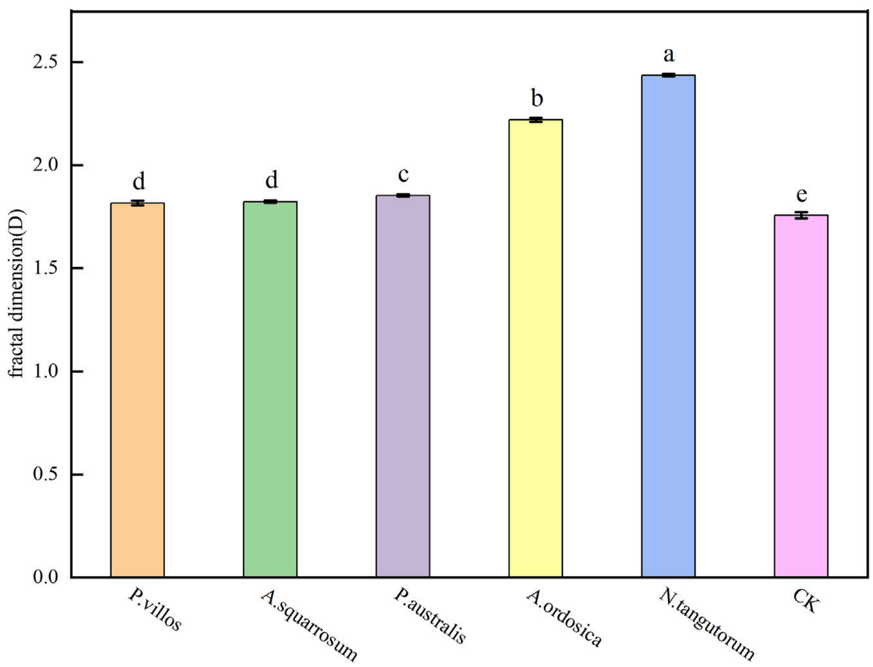

FIGURE 5
Fractal dimension of sediments covered by different plants.

According to Figure 4b, the sorting coefficient of sediments covered by vegetation is as follows: N. *tangutorum* > A. *ordosica* > A. *squarrosum* > P. *villosa* > P. *australis* > CK. The sorting levels are poor sorting, medium sorting, better sorting, better sorting, better sorting and very good sorting. With the emergence of vegetation, the sorting of particles became worse. Compared with A. *ordosica* and N. *tangutorum*, the sorting characteristics of surface sediment particles covered by P. *villosa*, P. *australis,* and A. *squarrosum* were better. The sorting coefficient of sediments under different plant coverage was significantly different from that of bare sand dunes ($P < 0.05$). By effectively reducing the wind speed, N.*tangutorum* and A.*ordosica* deposited larger particles near the vegetation, and the smaller particles were taken away by the wind, forming a deposition pattern with significant differences in particle size, and the sorting coefficient was large. However, P.*villosa*, A.*squarrosum* and P.*australis* have less influence on wind speed, uniform particle deposition and smaller sorting coefficient (Figure 4b).

The particle frequency distribution curves of bare sand dune, P. *villosa*, A. *squarrosum,* and P.*australis* are nearly symmetrical. A. *ordosica* and N. *tangutorum* have a skewness class of positive and very positive skewness, with an asymmetric pattern of surface sediment frequency curves, with the peak of the particle frequency curve biased toward the finer-grained side, where the tails are lower, and the main constituents are fine particles. A significant difference between the skewness of sediments under different plant covers ($P < 0.05$). The dense structure of A.ordosica and N.tangutorum significantly reduced the wind speed, forming a low-speed zone, resulting in coarse particle deposition, particle frequency distribution curve and positive or extremely positive bias. Bare sand dunes, *P. villosa*, *A. squarrosum* and *P. australis* had little effect on wind speed, and the particle deposition was uniform and the skewness was close to zero (Figure 4c).

The peak state of surface sediments covered by P.*villosa*, A.*squarrosum*, P.*australis* and N.*tangutorum* is medium, while the peak state of bare dunes is narrow, and A.*ordosica* is wide. It shows that the particle distribution of A.*ordosica* surface sediments is more dispersed than that of the other four vegetations. Significant differences between the kurtosis of each sediment ($p < 0.05$). Vegetation camping can change the direction and flow rate of the wind-sand flow as well as its internal structure, which promotes the settling of fine particles. The peak state values for sediments with vegetation cover were reduced compared to bare dunes, indicating a more dispersed and refined particle composition. The lack of vegetation cover on bare dunes and the direct action of wind on the surface of sand grains lead to strong jumping and creeping of sand grains under the action of wind. Due to the lack of vegetation, the wind speed is high, the fine particles are blown away, leaving the coarse particles, forming a sharp and narrow peak (Figure 4d).

The fractal dimensions of sediments with different vegetation cover in the study area are shown in Figure 5. Fractal dimension values for the five plant species and the control sediment were, in descending order: N. *tangutorum* > A. *ordosica* > P. *australis* > A. *squarrosum* > P. *villosa* > CK. Fractal dimension was negatively correlated with the content of coarse-grained components (gravel, coarse sand, etc.), which is consistent with the coarse and fine grain compositions of sediments with different vegetation covers in Table 3, where the differences between fractal dimensions of sediments under different vegetation covers were significant ($p < 0.05$). The fractal dimension is enhanced compared to the flowing dune due to the fact that after planting vegetation in the study area, when the wind speed reaches the sand initiating wind speed, the

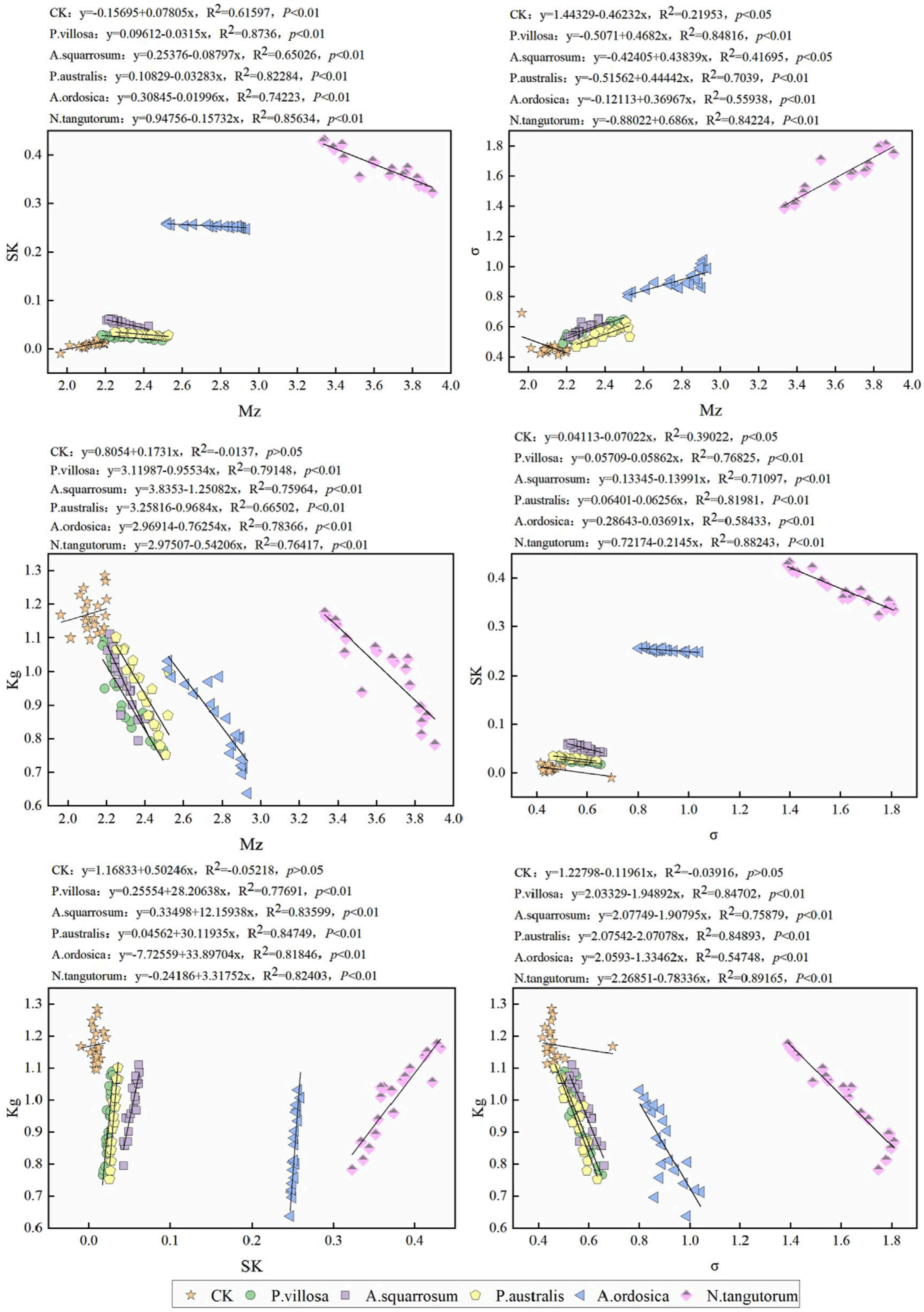

FIGURE 6
Scatter plot of sediment grain size parameters.

wind will carry the sandy material in the air, part of which will be intercepted by the plant canopy, thus accumulating underneath the plant canopy (Figure 5).

In order to visualize the distribution of the grain size parameters of the sample plots under cover of five different plants as well as the surface sediments of the bare sand dune (CK), each sampling point

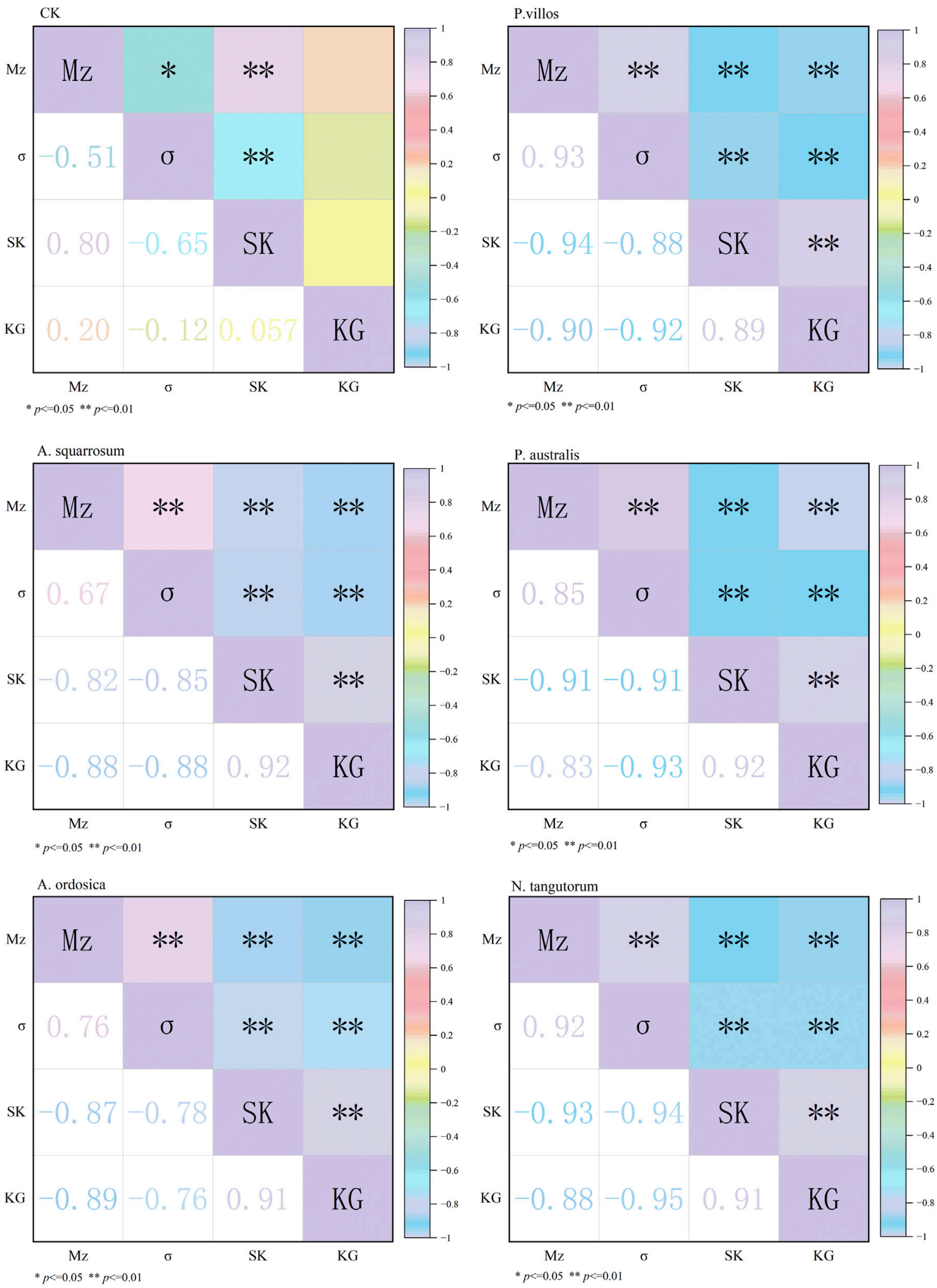

FIGURE 7
Correlation analysis of sediment grain size parameters.

of each plant was used as a data point to produce its scatterplot with its grain size parameters. As can be seen from Figure 6, A. *ordosica* and N. *tangutorum* have clear boundaries with the grain size parameters of CK, P. *australis*, A. *squarrosum*, and P. *villosa*. The scatter plots of each particle size parameter can distinguish them clearly, and the differences among the four sample sites of CK, P.

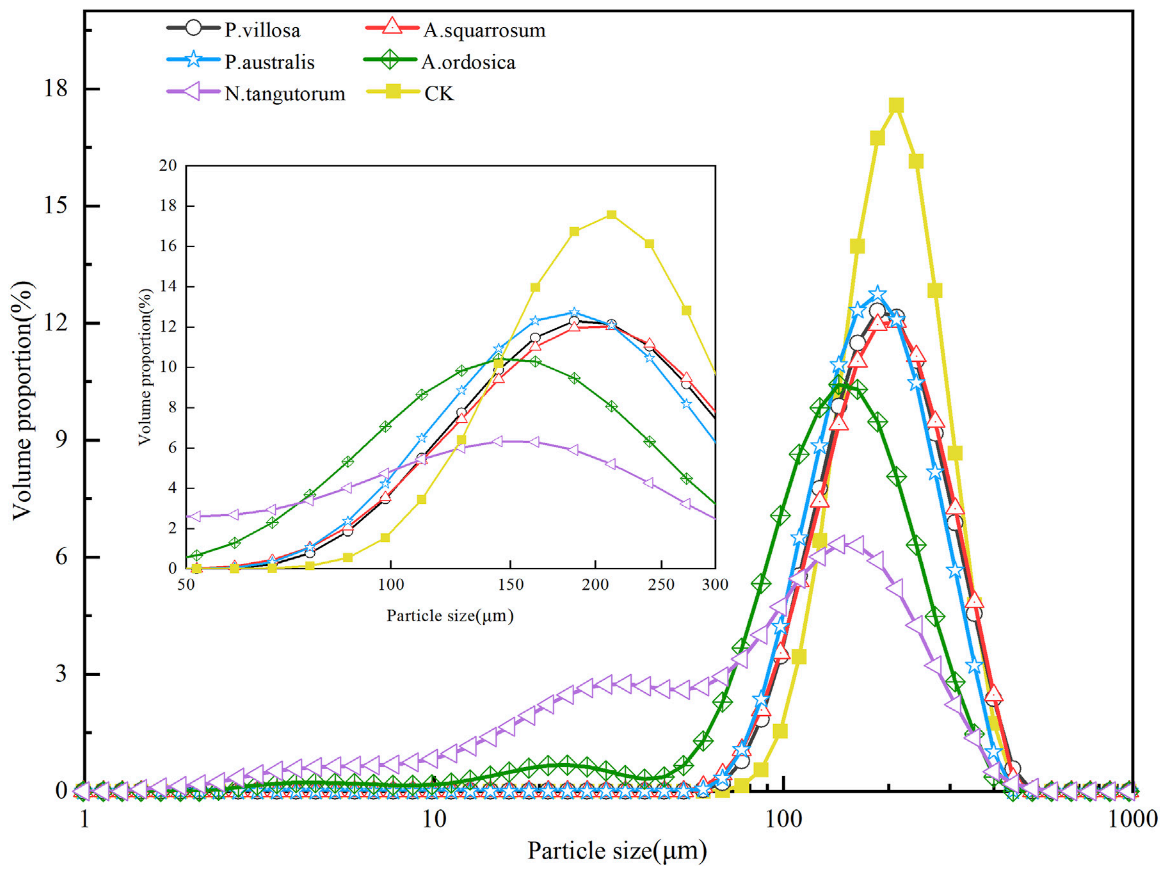

FIGURE 8
Sediment grain size frequency distribution curve.

villosa, A. *squarrosum*, and P. *australis* are not significant, and the scatter plots of particle size parameters show that the distribution of particle size parameters of the five species of plant-trapped sediment ranges from: N. *tangutorum* > A. *ordosica* > P. *villosa* > P. *australis* > A. *squarrosum* > CK. There was a highly significant correlation ($p < 0.01$) between the mean particle size, kurtosis, and sorting coefficient of N. *tangutorum*, P. *villosa*, and R^2 were all greater than 0.84, which was a good fit. There was a highly significant correlation ($p < 0.01$) between the mean particle size, sorting coefficient, and skewness of N. *tangutorum*, P. *australis*, and R^2 were all greater than 0.8, which was a good fit. There was a highly significant correlation between skewness and kurtosis for A. *squarrosum*, P. *australis*, A. *ordosica*, and N. *tangutorum*, ($p < 0.01$), and the R^2 was greater than 0.81, which was a good fit (Figure 6).

3.2.3 Correlation analysis of particle size parameters of plant-trapped sediments

Sorting coefficients of sediments from bare sand dunes showed a significant negative correlation with mean grain size and skewness ($P < 0.05$). The mean grain size of bare sand dune showed a highly significant positive correlation with skewness ($P < 0.01$). The bare sand duned kurtosis does not correlate well with Mean grain size, sorting factor, and skewness. In contrast, the mean grain size of sediments under vegetation cover showed a highly significant positive correlation with the sorting coefficient ($P < 0.01$), and the mean grain size and sorting coefficient showed highly significant negative correlation with kurtosis and skewness ($P < 0.01$), and kurtosis showed highly significant positive correlation with skewness ($P < 0.01$) (Figure 7).

3.2.4 Frequency distribution curves of sediment particles trapped by plants

Figure 8 shows the particle distribution curve of the sediments in the study area. The frequency distribution curve of CK surface sediments has a single-peak pattern, the peak grain size is located near 225 μm, the curve is higher and narrower, and the particle composition is aggregated. The distribution of P. *villosa*, A. *squarrosum*, and P. *australis* surface sediments was consistent with that of CK, all of which were unimodal, with a wider peak shape than that of CK, with smaller peak heights, diversification of particle composition, and a leftward shift of the overall peaks, i.e., the corresponding grain sizes of the peaks became finer, and the peak sizes centered on the 180–200 μm range. The sediment grain size curves of N. *tangutorum* and A. *ordosica* showed an asymmetric bimodal pattern.N. *tangutorum* has a distinct tail peak, A. *ordosica* has a lower tail peak, and the main peak grain size is concentrated near 150 μm, which is a fine sand fraction.The peak heights of the N. *tangutorum* and A. *ordosica* curves were reduced and widened, implying that N. *tangutorum* corresponded to higher levels of fine particulate matter. N. *tangutorum* sediment particles

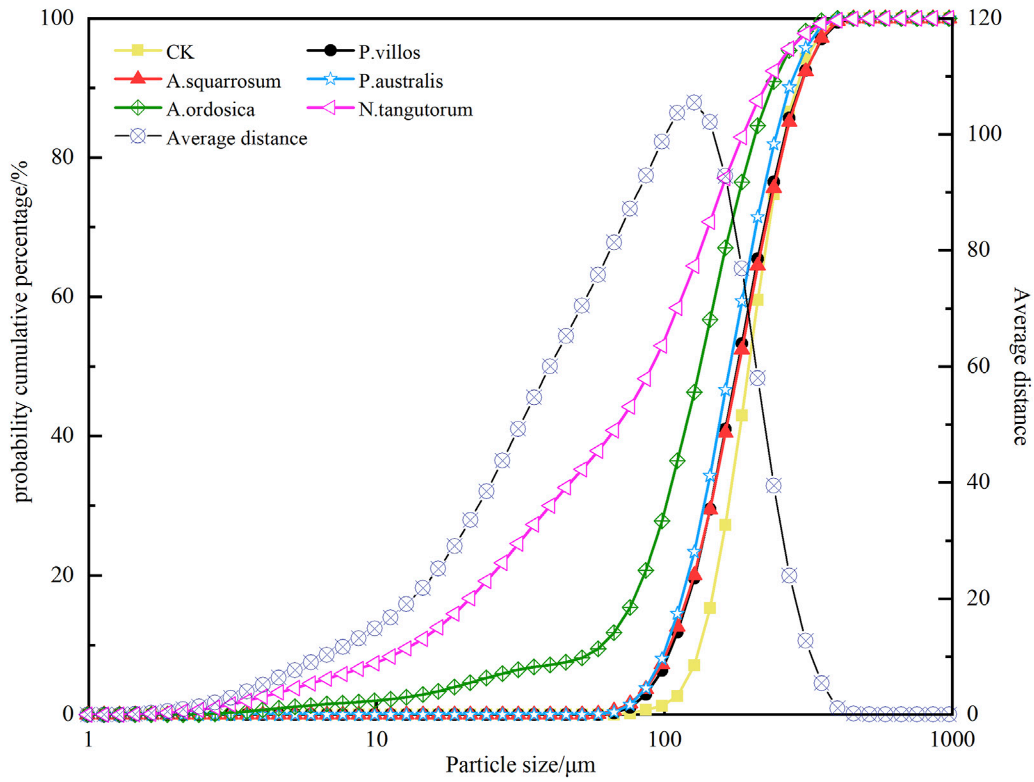

FIGURE 9
Sediment cumulative frequency distribution curve.

have the widest range of distribution and the shortest main peak, followed by A. *ordosica*. The particle distribution ranges from wide to narrow for N. *tangutorum* > A. *ordosica* > P. *australis* > A. *squarrosum* > P. *villosa* > CK. The main peaks are from high to low: CK > P. *australis* > P. *villosa* > A. *squarrosum* > A. *ordosica* > N.*tangutorum*. Due to the decrease of wind speed and particle capture, the particle sorting effect of dunes under vegetation coverage is weakened, and the peak deformation is wide and the peak height is reduced. N.tangutorum and A.ordosica further weakened the particle sorting due to their high vegetation density and complex stem and leaf structure, resulting in a wider particle distribution range, wider peak shape and lower peak height (Figure 8).

As can be seen from Figure 9, the cumulative frequency distribution curve can reflect the distribution of soil particles, and generally, the steeper the curve, the more uniform the distribution of particles. Analyzing the cumulative frequency distribution curves of the surface sediments of the five planted and bare dunes showed that the uniformity of distribution of the surface sediments under the five planted covers showed that N. *tangutorum* was the best and had a finer grain composition, followed by A. *ordosica*. The cumulative distribution curves of A. *squarrosum*, P. *villosa*, and P. *australis* subsurface sediments start off slowly and begin to steepen at about 76 μm, the bare sand dune steepens at about 100 μm and rises rapidly, and flattens out near 400 μm, suggesting that the particles tend to be concentrated in the 76–400 μm range; The sorting coefficients of the sediments under the cove of N. *tangutorum* and A. *ordosica* are larger in Figure 3, which shows that the particle sorting is poorer and finer compared to the other three covers.

Although the surface sediment particle frequency distribution curves (Figure 8) show different types in each sample, the appearance of wave crests and the shape of the curves show some consistency, and there is little difference in the sediment matrices. The mean distance between cumulative frequencies of sediment grain size reflects the grain differences between sample sites and qualitatively describes the range of wind-erosion-prone grains. The average distance between the cumulative frequencies of sediment grain sizes of the six sample sites in this study (Figure 9) was larger in the interval of grain sizes from 70 to 160 μm, and it can be assumed that the range of wind-eroded susceptible particles in the study area is from 70 to 160 μm. In general, it is believed that the wind erosion particle movement is dominated by leapfrog, and 100~150 μm size particles are the most likely to occur in the leapfrog range of particle sizes, and the range of wind erosion particles derived from this study is biased toward the finer particles (Figure 9).

3.3 Relationship between plant-trapped sediments and plant morphology

The results of Pearson's correlation analysis (Table 4) showed that the grain size parameters of sediments under different plant

TABLE 4 The correlation between grain-size parameters of surface sediments and plant morphology parameters.

Particle size parameters	Plant species	Plant height	Crown width	Branching number	Porosity
M_Z	*P. villosa*	0.71**	0.80**	0.84**	−0.76**
	A. squarrosum	0.75**	0.62*	0.72**	−0.67*
	P. australis	0.84**	0.85**	0.76**	−0.74**
	A. ordosica	0.67*	0.71**	0.57*	−0.76**
	N. tangutorum	0.85**	0.79**	0.77**	−0.90**
σ	*P. villosa*	0.80**	0.84**	0.78**	−0.81**
	A. squarrosum	0.77**	0.83**	0.74**	−0.80**
	P. australis	0.78**	0.77**	0.75**	−0.82**
	A. ordosica	0.64*	0.65*	0.72**	−0.78**
	N. tangutorum	0.82**	0.79**	0.75**	−0.86**
SK	*P. villosa*	−0.72**	−0.77**	−0.84**	0.74**
	A. squarrosum	−0.78**	−0.81**	−0.80**	0.79**
	P. australis	−0.84**	−0.83**	−0.74**	0.80**
	A. ordosica	−0.70*	−0.81**	−0.72*	0.75**
	N. tangutorum	−0.80**	−0.81**	−0.70**	0.84**
Kg	*P. villosa*	−0.83**	−0.88**	−0.87**	0.87**
	A. squarrosum	−0.87**	−0.81**	−0.84**	0.82**
	P. australis	−0.64*	−0.68**	−0.65**	0.74**
	A. ordosica	−0.71**	−0.78**	−0.60*	0.82**
	N. tangutorum	−0.83**	−0.72**	−0.77**	0.84**

Note: * indicates that there is a significant correlation at the significance level of 0.05 ($P < 0.05$). * * indicates that there is a significant correlation at the significance level of 0.01 (bilateral) ($P < 0.01$).

species: The mean particle size and sorting were positively correlated with plant height, crown width, and branch number ($P < 0.05$), and negatively correlated with porosity ($P < 0.05$). Skewness and kurtosis were significantly negatively correlated with plant height, crown width, and branch number ($P < 0.05$) and significantly positively correlated with porosity ($P < 0.01$). The correlation coefficients are all above 0.6, which has passed the test level of 0.05.

For different kinds of plants, the morphological parameters of each plant have different effects on the grain size distribution of surface sediments. In this paper, the mean particle size of sediments is used as an index to characterize the grain size distribution of sediments, and the influence of plant morphological parameters on the grain size distribution of surface sediments is analyzed. The mean particle size of P. *villosa* sediment particles had the best correlation with the number of branches, showing a very significant positive correlation ($P < 0.01$).The mean particle size of A. *squarrosum* had the best correlation with plant height, showing a very significant positive correlation ($P < 0.01$). The mean particle size of P. *australis* sediment particles had the best correlation with the crown width, showing a very significant positive correlation ($P < 0.01$), and the correlation coefficient was 0.85. For A. *ordosica* and N. *tangutorum*, the correlation between mean particle size and porosity was the best, showing a very significant negative correlation ($P < 0.01$), and the correlation coefficients were −0.76 and −0.90, respectively.

4 Discussion

4.1 The effect of plants on the distribution of underlying sand particles

The grain size distribution of wind-sand deposits is influenced by vegetation, sand sources, topography, and wind speed, and the presence of vegetation tends to increase surface roughness, alter the near-surface wind field, reduce wind speed, and deposit sand grains (Zhao et al., 2019). As the sand material gradually deposits near the plant, the wind-shadow dunes begin to form. Under the condition of a sufficient sand source, with the continuous development and succession of vegetation, the sand-blocking ability of the vegetation community will be significantly enhanced, and the sediment particles will settle in large quantities. The wind-shadow dunes gradually evolved into shrub dunes, and the dunes eventually tended to be fixed (Yang et al., 2019). Sediment frequency curves are critical for assessing sedimentation patterns. The change in the frequency curve reflects the change in the form of sedimentation. Due to the addition of foreign or coarse or fine new components, resulting in poor sediment sorting, the frequency curve becomes asymmetric so that the skewness shows a negative bias or positive changes in bias (Pan et al., 2020a). The clay, silt, and very fine sand in the wind-sand flow are blocked by plants. The analysis of sediment particle size parameters under different plant species coverage (Figure 4) shows that the sediment sorting coefficient becomes larger, the sorting becomes worse after vegetation coverage, and the curve shape develops from near symmetry to positive deviation. The peak value of the frequency curve tends to decrease as a whole, and the composition of the sediment particles becomes finer. The peak type of the bare sand dune is unimodal, and the sand pile of N. *tangutorum* and A. *ordosica* shrub is bimodal. The sand grains under P. *villosa*, A. *squarrosum,* and P. *australis* are mainly fine sand and medium sand. The sand material of the A.*ordosica* plot is mainly composed of fine sand and very fine sand. The contents of clay and silt in the sediment particles of N. *tangutorum* were significantly higher than those of the other four vegetations ($P < 0.05$). The above differences in the spatial distribution of particles of different size classes in sediments are supposed to be caused by the different botanical characteristics of plants. This may be mainly due to the fact that A. *ordosica* and N. *tangutorum* communities have higher cover, and denser branches and are clumped together, which increases the surface roughness, and when the wind and sand flow passes through, the wind speed is weakened, and the material carried by the wind and sand flow settles down and increases the content of fine-grained material on the surface (Xiaohong et al., 2019). P. *villosa*, A. *squarrosum*, and P. *australis* plants have relatively obvious main trunks, relatively few and scattered basal branches, and the plants show a sparse structure with a weak sand fixation capacity.

4.2 Differences in particle size parameters and their correlation

The sorting coefficient σ indicates the degree of discrete distribution of soil particles, and an adequate sorting process can effectively improve the degree of sorting of wind-formed sand (Xi et al., 2024). The degree of vegetation cover significantly affects the sorting process of wind-formed sands. The influence of vegetation canopy on the wind-blown sand flow field will cause the sediment to be sorted, and the final deposition around the shrub will form a difference in grain size characteristics (Huang et al., 2024). The effect of vegetation on sorting action is mainly in the following areas: Vegetation cover can effectively reduce wind speed, thus weakening the erosive effect of wind on surface wind-formed sands, weakening the transport of wind-formed sands, intercepting coarse particles in motion, and increasing the content of fine-grained components, reducing the degree of wind-formed sand sorting (Fu et al., 2021). The results of this paper show that the sorting of particles deteriorates with the presence of vegetation. The sorting characteristics of surface sediment particles covered by A. *ordosica* and N. *tangutorum* were poorer compared to the other three plants. The fractal dimension values of A. *ordosica* and N. *tangutorum* were greater than those of the other three species. The value of soil fractal dimension is positively correlated with the content of fine particles such as clay and silt. The increase of fine particle content (clay and silt) will lead to the increase of fractal dimension, which is consistent with the higher content of clay and silt in N. *tangutorum* and A. *ordosica* in Table 3. In this paper, the sediment under vegetation coverage increases with the increase of the mean particle size of sand, the sorting coefficient becomes larger, and the sorting becomes worse. The skewness value decreases with the increase of the mean particle size Φ, indicating that the fine particles increase. The kurtosis value decreases with the increase of the mean particle size, indicating that the distribution range of sand particle size becomes dispersed. The sorting coefficient is negatively correlated with skewness and kurtosis, indicating that the smaller the sorting coefficient, the greater the skewness and kurtosis values; that is, the better the sorting of sand particles, the finer and more concentrated the grain size distribution.

4.3 Mechanisms by which sand plants influence the grain size composition of surface sediments

Vegetation modifies the near-surface flow field mainly by covering the surface, decomposing wind, and blocking sand transport, and different vegetation types lead to differences in sediment composition. Some scholars have studied the relationship between the windproof effect of shrubs and plant morphology through wind tunnel tests, and the results show that the windproof effect increases with the increase of shrub height and coverage, and the windproof efficiency is an exponential function of the relationship with the coverage (Pan et al., 2020b). Wind tunnel experiments have shown that the morphology and structure of the vegetation are preferred parameters to facilitate wind erosion control (Miri et al., 2017). Pan et al.conducted field observations on the wind-proof and sand-fixing effects of simulated shrubs with different configurations, and the results showed that plant morphology had a significant effect on sand-fixing ability (Pan et al., 2021). Studies have shown that the spatial differences in particle size composition and particle size parameters of sediments under shrubs are caused by the height, crown width, and coverage of shrubs themselves. The plant height and crown width were significantly positively correlated with the sand retention area, and the volume fraction of fine components in surface sediments was positively correlated with plant height, crown width, and branch number. With the increase in vegetation coverage, the sand-fixing and sand-blocking ability of vegetation increased, and the mean particle size of the soil decreased (Liu et al., 2020). The mean particle size of sediments in this study was significantly positively correlated with plant height, crown width, and branch number ($P < 0.05$), which was the same as the existing research results. Some scholars analyzed the distribution of soil particle size under different vegetation coverage, and all believed that the mean particle size of soil became thicker with the gradual decrease of vegetation coverage. In this paper, through the analysis of the particle size characteristics of surface sediments, it is concluded that the particle composition from coarse to fine is: CK > P.*villosa* > A.*squarrosum* > P.*australis* > A.*ordosica* > N.*tangutorum*. The Φ value of mean particle size was positively correlated with plant height, crown width, and branch number and negatively correlated with porosity. This shows that the plant species with high plant community, dense branches and leaves, and high canopy density have fine sediment particles under their coverage and have strong sand fixation and sand blocking abilities; On the contrary, the plant species with sparse distribution and fewer branches and leaves, such as P.*villosa*, A.*squarrosum*, and P.*australis*, do not have strong sand-fixing ability. There are significant differences in sediment grain size parameters of different vegetation types. From the perspective of the influence of vegetation on the differential deposition of surface sediments, the height, crown type, and porosity of vegetation have great differences in the grain size characteristics of sediments, and the sand-blocking effect of compact vegetation is obvious. The vegetation with tall plants, wide crowns and dense branches and leaves can change the speed and direction of wind-blown sand flow in a larger spatial range, so that sand particles can be deposited in a wider area, and the screening effect on sand particle size is more obvious, resulting in more significant spatial differentiation of sand particles. With the increase of vegetation coverage, the grain size of sand around the dune is gradually refined, which weakens the transport capacity of wind-sand flow and promotes the deposition of fine particles due to the fixation of vegetation. The effect of short and sparse vegetation on wind-blown sand flow is relatively small, and the spatial differentiation of sand particles is relatively weak. The difference in morphological characteristics leads to the change of flow field around dunes, which affects the spatial differentiation of sand particle size characteristics.

4.4 Screening and synergistic effect of windbreak and sand-fixing plants

Our research is of great significance for guiding the screening and cultivation of windbreak and sand-fixing plants. In arid wind and sandy areas, many scholars have thoroughly explored the preferred strategies for wind and sand blocking forest trees. It was revealed that compact-structured shrubs such as N. *tangutorum* and A. *ordosica* exhibited more significant wind and sand blocking efficacy compared to sparsely structured herbs such as P. *australis*, P. *villosa*, and A. *squarrosum*. As the main sandy shrub in the study area, N. *tangutorum* has higher sand fixation and soil conservation ability than other vegetation. The shrub growth is concentrated and clustered, and the protection range is large, so it can be used as an excellent sand-fixing shrub in the study area (Li et al., 2024). A.*ordosica* also plays an indispensable role in windbreaks and sand fixation with its compact plant structure, complementing N. *tangutorum* and building a solid windbreak together. As for P. *australis*, P. *villosa*, and A. *squarrosum*, although their direct effect in preventing wind and blocking sand may be a little less effective, they form a sparse structure that contributes to the dispersion and slowing down of the wind, and at the same time, these plants can intercept and immobilize fine-grained materials to a certain extent, contributing to the improvement of soil properties. They each assume different roles, are interdependent and together constitute a multi-level protection system. It not only effectively intercepts the fine-grained material in wind-sand and reduces soil erosion but also provides the possibility of gradual improvement of soil properties through the cementing effect of the plant root system and the shading effect of the above-ground part. This diversified protection system is expected to have a strong, comprehensive effect on soil fertility enhancement, structural stabilization, and ecological restoration, laying a solid foundation for ecological management and sustainable development of the arid sandy wind area.

5 Conclusion

In this paper, the grain size distribution of surface sediments and morphological characteristics of plants under cover of five species of sand plants in the Ulan Buh Desert were determined. The effects of plant morphological parameters on sediment grain size distribution were analyzed to explore the inhibitory effect of vegetation cover on surface wind and sand activities and to compare the windproof and sand-fixing ability of sandy plants, which can provide a management basis for the screening of sand-fixing plants in desert areas.

(1) In the unit area, the porosity from large to small is: P. *villosa* > A. *squarrosum* > P. *australis* > A. *ordosica* > N. *tangutorum*, The porosity of P. *villosa* was the largest, indicating that its branch and leaf density was the smallest, while the porosity of N.*tangutorum* was the smallest and the branches were the densest.

(2) The distribution of surface sand material in P. *villosa*, A. *squarrosum*, and P. *australis* plots is the same as that of bare sand dunes, all of which are unimodal, while N. *tangutorum* and A. *ordosica* are bimodal. The particle distribution range from wide to narrow is: N. *tangutorum* > A. *ordosica* > P. *australis* > A. *squarrosum* > P. *villosa* > CK, After vegetation coverage, the content of fine sand and medium sand in surface sediments decreased, and the content of very fine sand, clay, and silt increased. Compared with bare sand dune, the sorting of sediment particles became worse, the curve tended to be positive, and the kurtosis value decreased. On the whole, the particle composition from coarse to fine is CK > P. *villosa* > A. *squarrosum* > P. *australis* > A. *ordosica* > N. *tangutorum*.

(3) Mean grain size of sediments under vegetation cover showed a highly significant positive correlation with sorting coefficient and kurtosis with skewness ($P < 0.01$). Mean particle size and sorting coefficient showed a highly significant negative correlation with peak state and skewness ($P < 0.01$). Mean particle size and sortability were significantly and positively correlated with plant height, crown width, and number of branches ($P < 0.05$) and significantly and negatively correlated with porosity ($P < 0.05$). Skewness and kurtosis were significantly and negatively correlated ($P < 0.05$) with plant height, crown width, and number of branches and highly significantly and positively correlated ($P < 0.01$) with porosity.

(4) As the main sandy shrub in the study area, N. *tangutorum* has strong sand fixation and soil conservation ability, which can effectively block the fine particles in the wind-sand flow and play a vital role in soil improvement and ecological protection.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

HA: Conceptualization, Investigation, Methodology, Visualization, Writing–original draft. FZ: Conceptualization, Methodology, Supervision, Writing–review and editing. HL: Investigation, Methodology, Writing–original draft. ZM: Conceptualization, Funding acquisition, Methodology, Writing–review and editing. HD: Methodology, Writing–review and editing. YD: Investigation, Methodology, Writing–original draft. LQ: Methodology, Writing–review and editing. JX: Conceptualization, Funding acquisition, Writing–original draft.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This study was supported by the Technology Integration and Demonstration of Integrated Management of Landscape, Forests, Fields, Lakes, Grasses and Sands (2024YFF1306305), Basic Research Funds for Universities-Innovation Team Building-Desert Ecosystem Protection and Restoration Innovation Team (BR22-13-03), Inner Mongolia Agricultural University establishes a research base for forging a strong sense of Chinese national community (ZLJD24033).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Amiraslani, F., and Dragovich, D. (2011). Combating desertification in Iran over the last 50 years: an overview of changing approaches. *J. Environ. Manag.* 92, 1–13. doi:10.1016/j.jenvman.2010.08.012

Cao, X., Jiao, J., Li, J., Qi, H., Bai, L., Wang, X., et al. (2022). Morphometric characteristics and sand intercepting capacity of dominant perennial plants in the Eastern Qaidam Basin: implication for aeolian erosion control. *CATENA* 210, 105939. doi:10.1016/j.catena.2021.105939

Dong, Z., Mao, D., Ye, M., Li, S., Ma, X., and Liu, S. (2022). Fractal features of soil grain-size distribution in a typical Tamarix cones in the Taklimakan Desert, China. *Sci. Rep.* 12, 16461. doi:10.1038/s41598-022-20755-x

Dupont, S., Bergametti, G., and Simoëns, S. (2014). Modeling aeolian erosion in presence of vegetation. *JGR Earth Surf.* 119, 168–187. doi:10.1002/2013JF002875

Folk, R. L., and Ward, W. C. (1957). Brazos River bar: a study in the significance of grain size parameters. *J. Sediment. Res.* 27 (1), 3–26. doi:10.1306/74D70646-2B21-11D7-8648000102C1865D

Fu, G., Xu, X., Qiu, X., Xu, G., Shang, W., Yang, X., et al. (2021). Wind tunnel study of the effect of planting Haloxylon ammodendron on aeolian sediment transport. *Biosyst. Eng.* 208, 234–245. doi:10.1016/j.biosystemseng.2021.05.018

Gao, F., Lv, K., Jiang, Q., Xiao, H., and Li, J. (2025). How did the regional water-heat distribution in oasis area vary with the different spatial patterns and structures of shelterbelt system—a case study in Ulan Buh desert oasis. *Agric. For. Meteorology* 362, 110345. doi:10.1016/j.agrformet.2024.110345

Gonzales, H. B., Ravi, S., Li, J., and Sankey, J. B. (2018). Ecohydrological implications of aeolian sediment trapping by sparse vegetation in drylands. *Ecohydrology* 11, e1986. doi:10.1002/eco.1986

Guo, X., Yang, G., Wu, J., Qiao, S., and Tao, L. (2024). Impacts of forest age on soil characteristics and fertility quality of *Populus simonii* shelter forest at the southern edge of the Horqin Sandy Land, China. *PeerJ* 12, e17512. doi:10.7717/peerj.17512

Guan, X., Wang, J., Liu, G., Xiao, M., Ding, Y., and Chen, J. (2024). Grain size characteristics of surface sediment in the Jilantai Salt Lake Protection System after long-term wind-sand activities. *Land Degrad Dev* 35, 321–333. doi:10.1002/ldr.4918

Huang, N., Song, Y., Li, X., Han, B., Xu, L., and Zhang, J. (2024). Spatial characteristics of aeolian sand transport affected by surface vegetation along the oshang railway. *Sustainability* 16 (10), 3940. doi:10.3390/su16103940

Hussein, E. A., Abd El-Ghani, M. M., Hamdy, R. S., and Shalabi, L. F. (2021). Do anthropogenic activities affect floristic diversity and vegetation structure more than natural soil properties in hyper-arid desert environments? *Diversity* 13, 157. doi:10.3390/d13040157

Jiang, N., Cheng, H., Liu, C., Fang, Z., and Zou, X. (2024). A wind tunnel study of the effects of vegetation structural characteristics on the airflow field. *CATENA* 242, 108064. doi:10.1016/j.catena.2024.108064

Kang, L., Zhang, M., Li, C., and Yang, Z. (2024). Effect of plant shapes on sand transport rate and aerodynamic particle entrainment rate from the perspective of plant drag. *CATENA* 237, 107818. doi:10.1016/j.catena.2024.107818

Khalilimoghadam, B., and Bodaghabadi, M. B. (2020). Factors influencing the relative recovery rate of dunes fixed under different sand-fixing measures in southwest Iran. *CATENA* 194, 104706. doi:10.1016/j.catena.2020.104706

Krumbein, W. C. (1934). Size frequency distributions of sediments. *SEPM JSR* 4. doi:10.1306/D4268EB9-2B26-11D7-8648000102C1865D

Li, X., Liu, H., Li, C., and Li, Y. (2024). A systematic review on the morphology structure, propagation characteristics, resistance physiology and exploitation and utilization of *Nitraria tangutorum* Bobrov. *PeerJ* 12, e17830. doi:10.7717/peerj.17830

Li, X., Yang, K., and Zhou, Y. (2016). Progress in the study of oasis-desert interactions. *Agric. For. Meteorology* 230–231, 1–7. doi:10.1016/j.agrformet.2016.08.022

Liu, X., Xie, Y., Zhou, D., Li, X., Ding, J., Wu, X., et al. (2020). Soil grain-size characteristics of *nitrariatangutorum* nebkhas with different degreesof vegetation coverage ina Desert-Oasis ecotone. *Pol. J. Environ. Stud.* 29, 3703–3714. doi:10.15244/pjoes/115866

Luo, F., Xiao, H., Gao, J., Ma, Y., Li, X., Li, J., et al. (2022). Microclimate and wind regime of three typical landscapes in the northeastern ulan Buh Desert. *Front. Environ. Sci.* 10, 939739. doi:10.3389/fenvs.2022.939739

Mayaud, J., and Webb, N. (2017). Vegetation in drylands: effects on wind flow and aeolian sediment transport. *Land* 6, 64. doi:10.3390/land6030064

Mayaud, J. R., Wiggs, G. F. S., and Bailey, R. M. (2016). Characterizing turbulent wind flow around dryland vegetation. *Earth Surf. Process. Landf.* 41, 1421–1436. doi:10.1002/esp.3934

Miri, A., Dragovich, D., and Dong, Z. (2017). Vegetation morphologic and aerodynamic characteristics reduce aeolian erosion. *Sci. Rep.* 7, 12831. doi:10.1038/s41598-017-13084-x

Moradi, E., Khosravi, H., Rahimabadi, P. D., Choubin, B., and Muchová, Z. (2024). Integrated approach to land degradation risk assessment in arid and semi-arid Ecosystems: applying SVM and eDPSIR/ANP methods. *Ecol. Indic.* 169, 112947. doi:10.1016/j.ecolind.2024.112947

Pan, X., Wang, Z., and Gao, Y. (2020a). Effects of compound sand barrier for habitat restoration on sediment grain-size distribution in ulan Buh Desert. *Sci. Rep.* 10, 2566. doi:10.1038/s41598-020-59538-7

Pan, X., Wang, Z., Gao, Y., and Dang, X. (2021). Effects of row spaces on windproof effectiveness of simulated shrubs with different form configurations. *Earth Space Sci.* 8, e2021EA001775. doi:10.1029/2021EA001775

Pan, X., Wang, Z., Gao, Y., Zhang, Z., Meng, Z., Dang, X., et al. (2020b). Windbreak and airflow performance of different synthetic shrub designs based on wind tunnel experiments. *PLoS ONE* 15, e0244213. doi:10.1371/journal.pone.0244213

Torita, H., and Satou, H. (2007). Relationship between shelterbelt structure and mean wind reduction. *Agric. For. Meteorology* 145, 186–194. doi:10.1016/j.agrformet.2007.04.018

Van Hateren, J. A., Van Buuren, U., Arens, S. M., Van Balen, R. T., and Prins, M. A. (2020). Identifying sediment transport mechanisms from grain size–shape distributions, applied to aeolian sediments. *Earth Surf. Dynam.* 8, 527–553. doi:10.5194/esurf-8-527-2020

Wang, M., Chen, P., Yi, P., and Ma, T. (2023). Effect of fines content on pore distribution of sand/clay composite soil. *Sustainability* 15, 9216. doi:10.3390/su15129216

Wang, S., Pan, C., Xie, D., Xu, M., Yan, Y., and Li, X. (2022). Grain size characteristics of surface sediment and its response to the dynamic sedimentary environment in Qiantang Estuary, China. *Int. J. Sediment Res.* 37, 457–468. doi:10.1016/j.ijsrc.2021.12.002

Wu, N., Ge, Y., and Abuduwaili, J. (2021). Grain size characteristics of sediments found in typical landscapes in the playa of ebinur lake, arid central asia. *Land* 10, 1132. doi:10.3390/land10111132

Xi, C., Zuo, H., Yan, M., and Yan, Y. (2024). Grain size characteristics of different types of surface sediments around Qixing Lake in Kubuqi Desert. *Front. Environ. Sci.* 12, 1409260. doi:10.3389/fenvs.2024.1409260

Xiaohong, D., Xia, P., Yong, G., Yang, L., Zhenyi, W., and Zhongju, M. (2019). Spatial heterogeneity of wind-eroded soil particles around Nitraria tangutorum nebkhas in the Ulan Buh Desert. *Écoscience* 26 (4), 347–358. doi:10.1080/11956860.2019.1646064

Yang, Y., Liu, L., Shi, P., Zhao, M., Dai, J., Lyu, Y., et al. (2019). Converging effects of shrubs on shadow dune formation and sand trapping. *JGR Earth Surf.* 124, 1835–1853. doi:10.1029/2018JF004695

Zhang, H., Liu, Y., Dang, X., Meng, Z., Li, S., and Gao, Y. (2024). Particle size characterization and sources of sediments in the Uzhumqin sand dunes. *J. Mt. Sci.* 21, 2631–2645. doi:10.1007/s11629-023-8577-5

Zhao, Y., Gao, X., Lei, J., Li, S., Cai, D., and Song, Q. (2019). Effects of wind velocity and nebkha geometry on shadow dune formation. *JGR Earth Surf.* 124, 2579–2601. doi:10.1029/2019JF005199

Zhao, Y., Huang, N., Sun, J., Zhan, K., Li, X., Han, B., et al. (2024). Numerical simulation of the plant shelterbelt configuration based on porous media model. *Atmosphere* 15, 602. doi:10.3390/atmos15050602

Zheng, Y., Yang, Q., Ren, H., Wang, D., Zhao, C., and Zhao, W. (2022). Spatial pattern variation of artificial sand-binding vegetation based on UAV imagery and its influencing factors in an oasis–desert transitional zone. *Ecol. Indic.* 141, 109068. doi:10.1016/j.ecolind.2022.109068