Windbreak and sand-fixing effects of typical nebkhas in the Yabrai Mountain aeolian corridor

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Abstract

Nebkhas are important aeolian landforms in arid regions and have notable windbreak and sand-fixing functions. However, the effects of shrub type and developmental stage on nebkha performance in high-wind energy regions remain insufficiently understood. This study quantified the windbreak and sand-fixing effects of three typical nebkha types (i.e., nebkhas formed by Reaumuria soongorica, Caragana tibetica, and Nitraria tangutorum) at different developmental stages (i.e., initial, developing, stable, and activated stages) in the Yabrai Mountain aeolian corridor, a high-wind energy region in China. Field sampling was carried out in three subregions along the prevailing wind direction (upwind, central sand-transport, and downwind) in March and November 2025. Particle-size analysis was conducted to characterize the differentiation of surface aeolian sediments, and field measurements combined with numerical simulations were used to analyze wind-speed profiles, windbreak efficiency, and airflow structure. The results showed that surface sediments on the windward slope and mound crest were dominated by clay and silt, whereas higher sand fractions occurred on the leeward and lateral slopes. The mean particle size followed the order: N. tangutorum (2.27 Φ) $<$ C. tibetica (2.30 Φ) $<$ R. soongorica (2.37 Φ). Windbreak and sand-fixing effects ranked as stable stage $>$ activated stage $>$ developing stage $>$ initial stage, with N. tangutorum nebkhas showing the strongest performance. When airflow passed over the nebkhas, wind speed increased above the canopy and along the lateral slopes; at the same time, a pronounced leeward deceleration zone formed with normalized horizontal distance (x/L) of 0–6 and relative height (z/H) of 0.0–0.5, where x is the horizontal distance, z is the vertical height, and L and H denote the shrub canopy major axis and shrub canopy height, respectively. Wind speed increased with z/H and x/L in the leeward direction and approached the reference wind speed over bare ground at z/H $>$ 1.2. Similar airflow patterns were observed among nebkha types. Prioritising N. tangutorum, combined with C. tibetica, and maintaining suitable developmental stages can enhance windbreak and sand-fixing performance in high-wind energy regions. These findings provide a scientific reference for constructing stable and efficient ecological protection systems in extreme wind environments, and support sand-control planning and vegetation configuration in arid and semi-arid areas.

Full Text

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Abstract: Nebkhas are important aeolian landforms in arid regions and have notable windbreak and sand-fixing functions. However, the effects of shrub type and developmental stage on nebkha performance in high-wind energy regions remain insufficiently understood. This study quantified the windbreak and sand-fixing effects of three typical nebkha types (i.e., nebkhas formed by *Reaumuria soongorica*, *Caragana tibetica*, and *Nitraria tangutorum*) at different developmental stages (i.e., initial, developing, stable, and activated stages) in the Yabrai Mountain aeolian corridor, a high-wind energy region in China. Field sampling was carried out in three subregions along the prevailing wind direction (upwind, central sand-transport, and downwind) in March and November 2025. Particle-size analysis was conducted to characterize the differentiation of surface aeolian sediments, and field measurements combined with numerical simulations were used to analyze wind-speed profiles, windbreak efficiency, and airflow structure. The results showed that surface sediments on the windward slope and mound crest were dominated by clay and silt, whereas higher sand fractions occurred on the leeward and lateral slopes. The mean particle size followed the order: *N. tangutorum* (2.27 Φ)<*C. tibetica* (2.30 Φ)<*R. soongorica* (2.37 Φ). Windbreak and sand-fixing effects ranked as stable stage>activated stage>developing stage>initial stage, with *N. tangutorum* nebkhas showing the strongest performance. When airflow passed over the nebkhas, wind speed increased above the canopy and along the lateral slopes; at the same time, a pronounced leeward deceleration zone formed within normalized horizontal distance (x/L) of 0–6 and relative height (z/H) of 0.0–0.5, where x is the horizontal distance, z is the vertical height, and L and H denote the shrub canopy major axis and shrub canopy height, respectively. Wind speed increased with z/H and x/L in the leeward direction and approached the reference wind speed over bare ground at z/H>1.2. Similar airflow patterns were observed among nebkha types. Prioritising *N. tangutorum*, combined with *C. tibetica*, and maintaining suitable developmental stages can enhance windbreak and sand-fixing performance in high-wind energy regions. These findings provide a scientific reference for constructing stable and efficient ecological protection systems in extreme wind environments, and support sand-control planning and vegetation configuration in arid and semi-arid areas.

Keywords: nebkha; shrub type; developmental stage; particle-size analysis; Yabrai Mountain aeolian corridor

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1 Introduction

Since the mid-20th century, under the combined influence of global climate change and intensified human activities, vegetation degradation, aeolian soil erosion, and land desertification in arid and semi-arid areas have become increasingly severe (Li et al., 2025a). The progression of desertification has led to reductions in cultivated land, losses of soil nutrients, and declines in land productivity (Ren et al., 2023), thereby constraining regional ecological security and the sustainable development of agriculture and animal husbandry, making desertification control a significant global concern (Fang et al., 2022). Nebkha, formed through the interaction between shrubs and windblown sand, is a typical biogeomorphic unit that increases underlying surface roughness, reduces near-surface wind speed, and traps transported aeolian sediments (An et al., 2025); through these processes, it effectively suppresses surface wind erosion and dune encroachment, promotes the accumulation of fine particles and nutrients (Niu et al., 2023), improves soil physicochemical properties, and plays a key role in maintaining the stability and functional sustainability of ecosystems in desert-oasis transition zones (Pan et al., 2024).

At the initial stage of nebkha development (Wang et al., 2021), particles carried by windblown sand flow first deposit on the windward side of the shrub and around the plant. As deposition increases, mound height, the lengths of the major and minor axes, and mound volume gradually increase, the slope gradient becomes steeper, and the mound shape evolves from a nearconical form to an elliptical or tadpole-like form (Shou et al., 2017; Bosq et al., 2018). Previous studies have generally divided the evolution of nebkha landforms into the initial, developing, stable, and activated stages based on geometric indices, and have pointed out that differences in mound size and morphological characteristics among these stages can alter underlying surface roughness and the degree of flow blockage (Fan et al., 2018), thereby exerting a marked influence on the distribution of near-surface wind speed and on windbreak and sand-fixing effects. Wind-tunnel experiments and numerical simulations show a similar pattern: sediment accumulation around shrubs raises the shrub–mound complex and strengthens its obstruction of near-surface airflow (Qian et al., 2021).

Airflow around a nebkha mound does not weaken evenly. Wind speed drops near the lower windward surface, a low-speed wake remains behind the mound, and faster flow is concentrated along the flanks and around the crest. The strength and extent of this sheltering pattern depend largely on shrub form. Plant height, crown width, frontal area, canopy cover, and canopy porosity determine how much airflow is blocked, diverted, or allowed to pass through the canopy, and ultimately shape the wind-speed profile and protected area around the nebkha mound. Among these variables (Furieri et al., 2013), frontal area and canopy cover are usually positively correlated with the magnitude of wind speed reduction and the sheltering distance, and are regarded as key indicators for evaluating windbreak performance, whereas canopy porosity regulates the partitioning of airflow below and above the canopy and thus affects both the position and the intensity of the near-surface deceleration zone. Under strong windblown sand conditions, different nebkha types, due to differences in plant height, crown architecture, and branching pattern, give rise to nebkha mounds that differ markedly in surface sediment particle-size composition, friction velocity, aerodynamic roughness length, and near-surface wind-field structure (Luo and Zhao, 2015). Most previous work has focused on the structural parameters of nebkha landforms or on single species and single developmental stages. A systematic comparison remains lacking for the coupled relationships among shrub type, developmental stage, and wind-field response (Li et al., 2025b). In high-wind-energy aeolian corridors, few studies have examined the protective effect of nebkha landforms by linking sediment particle-size differentiation with the surrounding wind-field structure, leaving the combined windbreak and sand-fixing role of shrub–mound systems insufficiently resolved (Zhu et al., 2021).

The Yabrai Mountain aeolian corridor is located in the arid region of western Inner Mongolia Autonomous Region, China. It lies in the piedmont transition zone between the northern Tengger Desert and the southern Badain Jaran Desert, where sediment transport and wind energy exchange connect the two desert systems. The Yabrai Mountains, together with piedmont terraces and

valley, narrow and channel the incoming airflow. As a result, near-surface wind speed increases near the mountain front, and the dominant wind direction becomes more stable (Li et al., 2023). This favors the development of stable wind-erosion and sand-transport pathways within the piedmont corridor. In terms of sediment supply, the upwind sector is connected to the southeastern Badain Jaran Desert, where large dune complexes are widely distributed, while the downwind sector grades into the mobile and semi-fixed dunes of the Tengger Desert (Ren et al., 2014). Sediment enters the corridor from several source areas, providing a continuous supply of loose material. Sand-driving winds are frequent, and near-surface wind speed remains above the entrainment threshold for long periods. Wind energy is therefore high, and wind erosion remains active. Guided by the terrain and constrained by the Yabrai Mountains, airflow and sediment transport are concentrated along the corridor axis. This produces a zone of intense sand movement with clear aeolian corridor characteristics. As a major pathway for sediment export in arid northwestern China, the Yabrai Mountain aeolian corridor subjects nearby grasslands, roads, and engineering facilities to persistent wind erosion and sand burial pressure. Its sand transport also affects downstream oasis ecosystems and increases the risk of instability in these sheltered areas (Wen and Dong, 2016). Nebkha landforms are widely distributed in this corridor, but nebkha types and developmental stages differ markedly. The close link between wind conditions and sediment supply makes the area a suitable field site for examining how nebkha landforms reshape near-surface airflow, influence sand transport, and contribute to windbreak and sand-fixing functions. These observations can support sand-control planning and vegetation configuration in arid and semi-arid areas.

This study focused on three typical nebkhas formed by *Reaumuria soongorica*, *Caragana tibetica*, and *Nitraria tangutorum* (hereinafter referred to as the three nebkha types) in the Yabrai Mountain aeolian corridor. We considered three subregions, namely the upwind, central sand-transport, and downwind segments, and conducted a systematic comparison among the initial, developing, stable, and activated stages. Through particle-size analysis and field investigation, we determined the particle-size composition of surface sediments and the windbreak and sand-fixing effects of typical nebkhas at different developmental stages. Based on measured wind speed data and numerical simulation results, we analyzed differences in friction velocity, aerodynamic roughness length, and airflow structure at different slope positions and heights around nebkhas to clarify how nebkha type and developmental stage influence windbreak and sand-fixing effects and the reorganization of the near-surface wind field. The findings will provide a theoretical basis and technical support for the scientific conservation of nebkhas and the optimization of protective vegetation configuration in high-wind energy regions.

2 Materials and methods

2.1 Study area

The study area (39°08′-41°00′N, 101°52′-105°00′E; 1200 m a.s.l.; Fig. 1) is located in Alagxa Right Banner, Alagxa League, Inner Mongolia Autonomous Region, China, and represents a typical desert–oasis transition zone. Dominant landforms include wind-eroded terraces, low-lying sand ridges, and alternating mobile and semi-fixed dunes. The region has a temperate continental climate, with cold winters, hot summers, and a large diurnal temperature range. The frost-free season is about 220 d; mean annual precipitation is less than 150 mm and falls mainly from June to September, while potential evaporation greatly exceeds precipitation. Mean annual temperature is about 8°C. Strong winds and sand-laden weather are common in this region. Wind erosion remains active, and sand transport is strong. The soils are mainly gray-brown desert soils and aeolian sandy soils, with low organic matter and visible salt accumulation. Vegetation is sparse. The dominant shrubs are *Artemisia desertorum*, *N. tangutorum*, *C. tibetica*, and *R. soongorica*. These shrubs often develop nebkhas with different mound forms and developmental stages, altering near-surface airflow and sand movement within the corridor.

Fig. 1 Overview of the study area based on the satellite imagery. The satellite imagery is derived from Google Earth (https://earth.google.com/).

2.2 Plot design

This study used long-term records of windblown-sand activity and regional wind fields to divide the corridor into three sections along the prevailing wind direction: upwind, central sand-transport, and downwind sections. The division follows the main sand-transport pathway and matches field differences in landform, wind-erosion intensity, sediment supply, and vegetation cover. The upwind section is more directly exposed to strong wind erosion and active sand movement. The central sand-transport section lies in the central part of the corridor, where transported sand is more readily deposited. The downwind section forms the terminal part of the transport pathway and is characterized by more evident sand accumulation. The sampling design therefore reflects the natural spatial heterogeneity within the aeolian corridor rather than treating the study area as a uniform surface.

Within each subregion, we selected three typical nebkha communities dominated by *R. soongorica*, *C. tibetica*, and *N. tangutorum*. Based on shrub canopy height, mound height, and mound volume measured within the study area, the developmental stages of nebkhas were classified by integrating the clustering characteristics and distribution thresholds of morphological parameters. Typical parameter ranges were defined for each stage to ensure the reliability and representativeness of the classification (Table 1).

For each developmental stage and each shrub species, ten individual nebkhas were selected as samples to measure morphological parameters and sediment particle-size characteristics. Only nebkhas with healthy shrub growth, intact mound morphology, and no visible disturbances from grazing or vehicle trampling were included. The final dataset included 120 nebkhas from each subregion and 360 nebkhas across the whole study area for morphology and particle-size analyses. Wind-speed measurements adopted a smaller subset: for each developmental stage, three representative nebkhas were selected for each shrub species, resulting in 36 wind-speed observation samples per subregion and 108 samples across the three subregions.

Table 1 Criteria for classifying developmental stages of typical nebkhas

Stage	*Reaumuria soongorica H* (cm)	*Reaumuria soongorica Hs* (cm)	*Reaumuria soongorica S* ($×$103 cm2)	*Reaumuria soongorica V* ($×$103 cm3)	*Caragana tibetica H* (cm)	*Caragana tibetica Hs* (cm)	*Caragana tibetica S* ($×$103 cm2)	*Caragana tibetica V* ($×$103 cm3)	*Nitraria tangutorum H* (cm)	*Nitraria tangutorum Hs* (cm)	*Nitraria tangutorum S* ($×$103 cm2)	*Nitraria tangutorum V* ($×$103 cm2)
Initial	<9	<6	<0.5	<5.5	<15	<10	<1.5	<15.0	<20	<15	<1.5	<20.0
Developing	9–16	6–11	0.5–1.0	5.5–8.0	15–25	10–20	1.5–3.5	15.0–50.0	20–30	15–25	1.5–4.0	20.0–60.0
Stable	16–25	11–15	1.0–1.5	8.0–20.0	25–40	20–30	3.5–5.0	50.0–100.0	30–45	25–30	4.0–4.5	60.0–120.0
Activated	$ $25	$ $15	$ $1.5	$ $20.0	$ $40	$ $30	$ $5.0	$ $100.0	$ $45	$ $30	$ $4.5	$ $120.0

Note: H is the shrub canopy height; Hs is the nebkha height; S is the basal area of the nebkha; V is the volume of the nebkha. The intervals were defined as left-closed and right-open (e.g., 0.5–1.0 includes 0.5 but excludes 1.0).

2.3 Sample collection

Field sampling was carried out in March and November 2025, during periods of frequent windblown-sand activity. Each nebkha was treated as one sampling unit. Soil samples were collected from four slope positions, including the windward slope, mound crest, leeward slope, and lateral slope, and from three depth intervals (0–10, 10–20, and 20–30 cm). These samples were used to describe vertical and lateral variation in surface sediments. For particle-size analysis, soils with the same nebkha type and depth interval from the upwind, central sand-transport, and downwind subregions were pooled into composite samples. Each composite sample represented the particle-size characteristics of a given nebkha type and depth interval.

After collection, the soil samples were air-dried, gently broken apart, and sieved through a 2 mm mesh. Before particle-size measurement, organic matter was removed with 30.00% H_2O_2 at 50°C. After the reaction was complete, carbonates were dissolved using 10.00% HCl. Sodium hexametaphosphate solution was then added to disperse the particles, followed by ultrasonic treatment. Particle size was determined with a laser particle-size analyser (Malvern Mastersizer 3000; Malvern Panalytical, Malvern, UK). Each sample was measured three times, and the mean value was used for subsequent calculations.

The plot design was structured around three factors: nebkha type, developmental stage, and location within the aeolian corridor. Samples from different slope positions and soil depths were used to characterize sediment variation inside each nebkha. Composite samples were then used for comparisons among nebkha types and corridor sections. This design allowed surface sediment differentiation to be assessed together with the windbreak and sand-fixing performance of typical nebkhas.

2.4 Wind speed measurement

Wind speed measurements were conducted in March and November 2025, during periods when windblown-sand events were frequent. Observations were made under conditions with a relatively steady wind direction, close to the prevailing direction that initiates sand transport. A unified measurement scheme was applied in the three subregions of Yabrai Mountain aeolian corridor, with simultaneous observations for the three nebkha types at four developmental stages, so that nebkha type, developmental stage, and spatial position were directly comparable. For each nebkha, the geometric centre of the shrub was taken as the origin of the coordinate system: the x-axis was aligned with the prevailing wind direction, the y-axis was set perpendicular to the wind, and the z-axis was taken as the vertical. Measurement points along the x direction were located at $x = -L$, $0L$, L, $2L$, $3L$, $4L$, $5L$, $6L$, and $7L$ (where L denotes the shrub canopy major axis); lateral positions were measured at $y = -1.0W$, $-0.5W$, $0.0W$, $0.5W$, and $1.0W$ (where W denotes the shrub canopy minor axis); and the vertical measurement heights were set at $z = 0.1H$, $0.6H$, $1.1H$, and $1.6H$ (where H denotes the shrub canopy height), forming three-dimensional measurement points covering the windward slope, mound crest, leeward slope, and lateral slope (Fig. 2). Wind speed measurements employed a YOUNG Model 05103 Wind Monitor (R. M. Young Company, Traverse City, USA) with a range of 0.1–30.0 m/s and an accuracy of \$±\$0.1 m/s, paired with

HOBO UX120-006M data loggers and HOBOware Mobile software (Onset Computer Corporation, Bourne, USA). Multiple sets of wind speed sensors and loggers were deployed to conduct multi-point synchronous observations of wind speed around the nebkhas. Sensors sampled at 1 Hz, continuously collecting wind speed sequences for no less than 30 s at each measurement point. The logger automatically calculated the average wind speed for this period. Each measurement point was measured three times. After outliers were removed, the remaining values were averaged to obtain the wind speed for that measurement point. Measurements for all nebkha types and developmental stages were made under comparable incoming wind conditions. A bare-ground control point was set upwind of each nebkha at $x = -10L$ to record open-field wind speed, enabling subsequent calculation of windbreak and sand-fixing effect indices.

Fig. 2 Layout of wind speed observation around each nebkha. (a), main view; (b), vertical wind speed measurement; (c), top view; (d), horizontal wind speed measurement. The geometric centre of the shrub was taken as the coordinate origin; x is the horizontal distance along the prevailing wind direction; y is the horizontal distance perpendicular to the prevailing wind direction; z is the vertical height; L is the shrub canopy major axis; W is the shrub canopy minor axis; and H is the shrub canopy height.

2.5 Calculation of indices

The equations used to calculate aerodynamic roughness length (z_0; cm) and friction velocity (U_*; m/s) are as follows:

$$U_z = \frac{U_*}{k} \ln \frac{z}{z_0}, \tag{1}$$

where U_z (m/s) is the mean wind speed at vertical height z (cm); and k is the von Kármán constant, taken as 0.4. To obtain z_0 and U_*, this study fitted the measured wind speed to a logarithmic wind-speed profile at four heights ($0.1H$, $0.6H$, $1.1H$, and $1.6H$). It determined the wind-speed profile equation using the least-squares regression method (Sharratt and Feng, 2009). The calculation formula is as follows:

$$U_z = a + b \ln z, \tag{2}$$

where a is the slope; and b is the intercept.

By setting $U_z = 0$, z_0 can be obtained as:

$$z_0 = \exp(-b/a). \tag{3}$$

By combining Equations 2 and 3, the equation for calculating the U_* can be written as:

$$U_* = k \times a. \tag{4}$$

The equation used to calculate the wind-break efficiency is as follows (Meng et al., 2024):

$$F = \frac{V_0 - V_{sb}}{V_0} \times 100\%, \tag{5}$$

where F is the wind-break efficiency of the nebkha (%); and V_0 and V_{sb} denote the wind speed over bare sand and the wind speed sheltered by the nebkha at the same height (m/s), respectively.

This study calculated four soil particle-size parameters of mean particle size (Mz; Φ), sorting coefficient (σ), skewness (S_k), and kurtosis (K_g) using the Folk–Ward graphical method (Folk and Ward, 1957; Armstrong, 1986; Ahmadi et al., 2011). We determined the volumetric contents of different soil particle-size fractions using a laser particle size analyser, and calculated the soil fractal dimension based on a fractal model characterized by the particle-size volume distribution. The calculation formulas are expressed as follows:

$$Mz = \frac{1}{3}\left(\Phi_{16} + \Phi_{50} + \Phi_{84}\right), \tag{6}$$

$$\sigma = \frac{1}{4}\left(\Phi_{84} - \Phi_{16}\right) + \frac{1}{6.6}\left(\Phi_{95} - \Phi_{5}\right), \tag{7}$$

$$S_k = \frac{\Phi_{16} + \Phi_{84} - 2\Phi_{50}}{2\left(\Phi_{84} - \Phi_{16}\right)} + \frac{\Phi_{5} + \Phi_{95} - 2\Phi_{50}}{2\left(\Phi_{95} - \Phi_{5}\right)}, \tag{8}$$

$$K_g = \frac{\Phi_{95} - \Phi_{5}}{2.44\left(\Phi_{75} - \Phi_{25}\right)}, \tag{9}$$

$$\left(\frac{R_i}{R_{\max}}\right)^{(3-D)} = \frac{V(r < R_i)}{V_t}, \tag{10}$$

where Φ represents the logarithmic boundary transformation for particle size grade (phi), and the numbers that follow Φ represent the percentiles of the particle size content in the cumulative curves; R_i is the measured soil particle size (μm); $R_{\max}$ is the diameter of the largest particle (μm); D is the fractal dimension; r is particle diameter; and $V(r < R_i)$ is the volumetric percentage of soil particles smaller than the measured particle size (R_i); and V_t is the total volumetric percentage of all soil particle-size fractions.

2.6 Data processing and analyses

Data processing and analyses were conducted using Excel 2021 and Origin 2025, including Pearson correlation analysis; analysis of variance and other statistical tests were performed using SPSS 27; and Surfer 23 was used to plot airflow fields and windbreak efficiency.

3 Results

3.1 Sediment characteristics and windbreak and sand-fixing effects of nebkhas at different developmental stages

3.1.1 Morphological characteristics of nebkhas

Nebkhas in the central Yabrai Mountain aeolian corridor were mainly ellipsoidal and elongated parallel to the prevailing wind, with a short, steep windward slope and a long, gentle leeward slope (Table 2). Shrub and nebkha-scale parameters generally increased with developmental stage, and most reached their maxima in the activated stage. Among the three shrub species, *R. soongorica* consistently formed the smallest nebkhas, whereas *C. tibetica* and *N. tangutorum* had much larger area, volume, and projected area, with differences becoming more evident from the stable stage onward. Overall, nebkha size ranked as *N. tangutorum* > *C. tibetica* > *R. soongorica*.

Table 2 Morphological parameters of typical nebkhas

Stage	Morphological characteristic	*R. soongorica*	*C. tibetica*	*N. tangutorum*
Initial stage	L (cm)	28.1$±7.1	67.9±19.7	74.4±$16.3
Initial stage	W (cm)	26.6$±6.7	62.1±16.5	66.0±$14.8
Initial stage	H (cm)	5.7$±1.0	13.2±1.0	13.5±$2.2
Initial stage	Ls (cm)	20.6$±4.7	52.4±16.3	58.2±$10.5
Initial stage	Ws (cm)	19.0$±3.8	47.8±14.3	53.1±$9.5
Initial stage	Hs (cm)	3.9$±0.7	8.2±2.1	8.6±$1.5
Initial stage	Lc (cm)	24.3$±4.9	60.0±17.7	67.8±$12.2
Initial stage	S ($×10^3$ cm^2)	0.2$±0.1	0.9±1.1	1.0±$0.4
Initial stage	V ($×10^3$ cm^3)	1.9$±0.7	8.5±4.9	9.9±$4.0
Initial stage	Sz ($×10^3$ cm^2)	0.4$±0.2	1.5±0.8	1.7±$0.8
Developing stage	L (cm)	47.7$±8.6	108.5±23.5	123.5±$22.2
Developing stage	W (cm)	35.1$±7.5	78.6±19.3	87.7±$15.8
Developing stage	H (cm)	10.0$±1.8	22.0±1.5	24.3±$4.4
Developing stage	Ls (cm)	33.9$±7.5	75.7±15.3	87.5±$15.8
Developing stage	Ws (cm)	23.6$±5.0	54.3±12.9	62.0±$11.2
Developing stage	Hs (cm)	7.2$±1.3	16.0±1.9	17.2±$3.1
Developing stage	Lc (cm)	37.5$±8.2	87.2±20.7	96.8±$17.4

Stage	Morphological characteristic	*R. soongorica*	*C. tibetica*	*N. tangutorum*
Developing stage	S ($\times10^3$ cm^2)	0.9±0.3	3.0±1.8	3.3±1.2
Developing stage	V ($\times10^3$ cm^3)	6.7±2.7	29.2±13.7	34.1±13.6
Developing stage	Sz ($\times10^3$ cm^2)	0.9±0.4	2.9±0.8	3.4±0.6
Stable stage	L (cm)	61.7±11.1	157.2±23.2	184.0±33.1
Stable stage	W (cm)	44.1±9.4	99.0±19.9	112.1±20.2
Stable stage	H (cm)	21.2±3.1	36.0±1.5	40.5±7.3
Stable stage	Ls (cm)	51.1±9.2	119.2±15.4	136.1±24.5
Stable stage	Ws (cm)	36.6±7.7	84.0±12.9	95.7±17.2
Stable stage	Hs (cm)	14.0±2.5	25.8±1.9	27.1±4.9
Stable stage	Lc (cm)	39.0±8.6	88.1±21.0	93.0±16.7
Stable stage	S ($\times10^3$ cm^2)	1.2±0.4	4.0±1.9	4.6±1.6
Stable stage	V ($\times10^3$ cm^3)	18.2±8.5	79.8±14.3	102.5±35.2
Stable stage	Sz ($\times10^3$ cm^2)	1.4±0.9	3.9±0.8	4.7±2.4
Activated stage	L (cm)	77.7±14.0	173.6±26.4	195.6±35.2
Activated stage	W (cm)	52.0±11.1	112.7±21.9	131.7±23.7
Activated stage	H (cm)	36.0±8.0	44.3±5.8	47.0±8.5
Activated stage	Ls (cm)	63.0±13.5	145.9±24.8	156.6±28.2
Activated stage	Ws (cm)	45.3±9.8	102.6±18.7	111.2±20.0

Stage	Morphological characteristic	*R. soongorica*	*C. tibetica*	*N. tangutorum*
Activated stage	*Hs* (cm)	17.3$±3.7	36.8±5.6	38.6±$7.0
Activated stage	*Lc* (cm)	45.0$±9.7	98.7±22.1	108.8±$19.6
Activated stage	*S* ($×10ˆ3$ cm^2)	1.9$±0.6	6.4±1.8	7.6±$2.8
Activated stage	*V* ($×10ˆ3$ cm^3)	24.1$±9.6	104.9±41.5	130.6±$52.3
Activated stage	*Sz* ($×10ˆ3$ cm^2)	1.4$±0.7	4.9±1.0	5.8±$1.7

Note: L is the shrub canopy major axis; W is the shrub canopy minor axis; Ls is the nebkha major axis; Ws is the nebkha minor axis; Lc is the horizontal scale of the nebkha; Sz is the vegetation-covered area. Mean±SE.

3.1.2 Particle-size composition of surface sediments on nebkhas

The average fine sand contents in surface sediments of *N. tangutorum*, *C. tibetica*, and *R. soongorica* nebkhas were 66.06%, 67.45%, and 55.40%, respectively (Table 3). The corresponding medium sand contents were 27.78%, 25.96%, and 41.05%, and the combined proportion of fine and medium sand exceeded 90.00% for all three nebkha types. Particle-size composition of nebkhas in the Yabrai Mountain aeolian corridor was dominated by fine and medium sand, whereas silt and clay accounted for only a small proportion. The sediments were loose and exhibited high permeability but poor water retention. Significant differences existed in particle-size composition among different nebkha types ($P < 0.05$), with the most pronounced variation observed between *N. tangutorum* and *R. soongorica* nebkhas. Clay content differed significantly between *C. tibetica* and *R. soongorica* nebkhas ($P < 0.01$). For all three nebkha types, the 10–20 cm soil layer contained significantly more sand than the 0–10 cm soil layer ($P < 0.01$). In the 20–30 cm layer, the proportions of clay and silt decreased markedly, whereas the fractions of medium and coarse sand increased. Overall, among different positions within nebkhas, the surface sediments on the windward slope of *N. tangutorum*, *C. tibetica*, and *R. soongorica* nebkhas were dominated by fine sand (64.61%, 67.92%, and 53.28%, respectively) and medium sand (28.94%, 28.05%, and 43.17%, respectively), followed by very fine sand (4.62%, 6.62%, and 2.20%, respectively), clay (0.09%, 0.10%, and 0.02%, respectively), and coarse sand (0.06%, 0.02%, and 0.61%, respectively). The clay and silt contents on the windward slope were higher than those on the lateral slope, mound crest, and leeward slope, while fine and medium sand contents showed the opposite trend. Within the 20–30 cm soil layer, soil particle-size distribution showed contrasting positional patterns within nebkhas. Across the three nebkha types, clay and silt contents in nebkhas showed the pattern: *N. tangutorum* > *C. tibetica* > *R. soongorica*. In contrast, fine and medium sand contents followed the opposite pattern.

3.1.3 Particle-size parameters

The Mz values of surface sediments in nebkhas followed the order: *N. tangutorum* (2.27 Φ) < *C. tibetica* (2.30 Φ) < *R. soongorica* (2.37 Φ), indicating that the sediments in *R. soongorica* nebkhas were finer than those in *C. tibetica* and *N. tangutorum* nebkhas (Fig. 3). The Mz of all nebkhas decreased first and then increased from the lower windward slope through the mound crest to the lower leeward slope. The K_g gradually decreased on the windward slope, increased at the mound crest, and then decreased again on the leeward slope. The σ indicates particle-size sorting. The σ values for *N. tangutorum*, *C. tibetica*, and *R. soongorica* nebkhas were 0.55, 0.54, and 0.56, respectively, indicating good sorting. The S_k of *N. tangutorum* nebkhas ranged from 0.057 to 0.084, indicating an approximately symmetric to slightly positively skewed particle-size distribution. For *C. tibetica* and *R. soongorica* nebkhas, the S_k values were 0.055–0.081 and 0.052–0.064, respectively, both indicating distributions close to symmetric. K_g showed a clear separation among the three nebkha types. For *N. tangutorum* nebkhas, the K_g values ranged from 1.594 to 1.932, with a mean of 1.763, indicating a strongly peaked particle-size curve. By comparison, K_g remained close to 1.000 for *C. tibetica* nebkhas (range of 0.965–0.997 and mean of 0.981) and *R. soongorica* (range of 0.962–0.971 and mean of 0.967), which corresponds to near-mesokurtic distributions. The surface sediments of *N. tangutorum* nebkhas were therefore more concentrated around the dominant particle-size class than those of *C. tibetica* and *R. soongorica* nebkhas. Significant differences were also found in Mz and fractal dimension among the three nebkha types ($P < 0.05$; Fig. 4). Higher fractal dimension was associated with poorer sorting, a stronger departure of S_k from symmetry, and greater concentration of particles within a narrower particle-size range.

3.1.4 Sand-fixing effect

As shown in Figure 5, the measured sand-fixing efficiency ranged from 18.92% to 76.90% for three typical nebkha types at different developmental stages. The initial-stage nebkhas had only limited protective effects, because both the shrub canopy and mound body were still small. Values increased in the developing stage and reached their highest level in the stable stage. In the activated stage, the effect declined, but it remained higher than those in the initial and developing

Table 3 Particle-size composition of surface sediments from typical nebkhas

Sample type	SP	Clay (%)	Silt (%)	Very fine sand (%)	Fine sand (%)	Medium sand (%)	Coarse sand (%)
R. soongorica(0–10 cm)	WS	0.02 ± 0.00^{DEa}	0.73 ± 0.03^{Da}	2.20 ± 0.03^{Fb}	53.28 ± 0.19^{Eb}	43.17 ± 0.23^{Bc}	0.61 ± 0.01^{Bb}
R. soongorica(0–10 cm)	LS	0.01 ± 0.00^{Eb}	0.28 ± 0.02^{Db}	1.85 ± 0.02^{Gc}	52.89 ± 0.16^{Gb}	44.35 ± 0.17^{Bb}	0.62 ± 0.02^{Bb}
R. soongorica(0–10 cm)	MC	0.01 ± 0.00^{Cb}	0.28 ± 0.01^{Eb}	2.30 ± 0.02^{Ha}	54.89 ± 0.21^{Fa}	42.00 ± 0.23^{Ad}	0.52 ± 0.02^{Ac}
R. soongorica(0–10 cm)	LS	0.01 ± 0.00^{Db}	0.23 ± 0.01^{Cb}	1.48 ± 0.01^{Ed}	49.83 ± 0.05^{Fc}	47.53 ± 0.06^{Aa}	0.93 ± 0.01^{Aa}
R. soongorica(10–20 cm)	WS	0.02 ± 0.00^{Ea}	0.71 ± 0.06^{Da}	4.56 ± 0.10^{Ca}	61.74 ± 0.36^{Da}	32.81 ± 0.46^{Cc}	0.16 ± 0.01^{Cbc}
R. soongorica(10–20 cm)	LS	0.01 ± 0.00^{DEa}	0.37 ± 0.02^{Db}	2.14 ± 0.03^{Fc}	53.67 ± 0.23^{Fc}	43.22 ± 0.26^{Ca}	0.59 ± 0.02^{Ba}

Sample type	SP	Clay (%)	Silt (%)	Very fine sand (%)	Fine sand (%)	Medium sand (%)	Coarse sand (%)
R. soongorica(10–20 cm)	MC	0.02 ± 0.00^{Ca}	0.48 ± 0.03^{Cb}	4.62 ± 0.10^{Ea}	62.49 ± 0.37^{Da}	32.27 ± 0.48^{Cc}	0.15 ± 0.01^{Cc}
R. soongorica(10–20 cm)	LS	0.01 ± 0.00^{BCDa}	0.38 ± 0.03^{Cb}	3.29 ± 0.03^{CDb}	60.30 ± 0.17^{Db}	35.83 ± 0.21^{Cb}	0.19 ± 0.01^{Cb}
R. soongorica(20–30 cm)	WS	0.01 ± 0.00^{Ea}	0.30 ± 0.01^{Dbc}	1.81 ± 0.03^{Gc}	51.02 ± 0.25^{Fc}	46.01 ± 0.26^{Aa}	0.84 ± 0.03^{Aa}
R. soongorica(20–30 cm)	LS	0.01 ± 0.00^{Da}	0.25 ± 0.01^{Dc}	1.66 ± 0.03^{Gd}	50.72 ± 0.30^{Hc}	46.54 ± 0.32^{Aa}	0.83 ± 0.03^{Aa}
R. soongorica(20–30 cm)	MC	0.01 ± 0.00^{Ca}	0.37 ± 0.03^{Da}	2.58 ± 0.07^{Gb}	55.65 ± 0.37^{Fb}	40.91 ± 0.41^{Ab}	0.47 ± 0.03^{Ab}
R. soongorica(20–30 cm)	LS	0.01 ± 0.00^{CDa}	0.33 ± 0.02^{Cab}	3.04 ± 0.02^{Da}	58.34 ± 0.14^{Ea}	37.99 ± 0.16^{Bc}	0.29 ± 0.01^{Bc}
C. tibetica(0–10 cm)	WS	0.10 ± 0.01^{Ba}	2.28 ± 0.15^{Ba}	6.62 ± 0.10^{Aa}	67.92 ± 0.14^{Ab}	23.05 ± 0.35^{Hc}	0.02 ± 0.00^{Fb}

Sample type	SP	Clay (%)	Silt (%)	Very fine sand (%)	Fine sand (%)	Medium sand (%)	Coarse sand (%)
C. tibetica(0–10 cm)	LS	0.05 ± 0.01^{BCc}	0.59 ± 0.03^{Cc}	4.66 ± 0.05^{Dd}	65.87 ± 0.22^{Cc}	28.77 ± 0.27^{Ea}	0.06 ± 0.01^{DEa}
C. tibetica(0–10 cm)	MC	0.05 ± 0.01^{ABb}	0.68 ± 0.03^{ABb}	5.92 ± 0.09^{Cb}	68.58 ± 0.22^{Ba}	24.79 ± 0.34^{EFb}	0.02 ± 0.00^{Eb}
C. tibetica(0–10 cm)	LS	0.09 ± 0.02^{Ab}	0.93 ± 0.07^{Ab}	5.64 ± 0.02^{Ac}	68.98 ± 0.03^{Aa}	24.37 ± 0.13^{Fb}	0.02 ± 0.00^{Fb}
C. tibetica(10–20 cm)	WS	0.03 ± 0.00^{DEb}	0.78 ± 0.01^{Da}	4.20 ± 0.05^{Dd}	63.76 ± 0.28^{Cd}	31.14 ± 0.32^{Ea}	0.09 ± 0.00^{Da}
C. tibetica(10–20 cm)	LS	0.04 ± 0.01^{BCa}	0.58 ± 0.03^{Cb}	6.45 ± 0.06^{Ab}	68.60 ± 0.17^{Ab}	24.34 ± 0.24^{Hc}	0.02 ± 0.00^{Ed}
C. tibetica(10–20 cm)	MC	0.03 ± 0.01^{BCa}	0.45 ± 0.01^{CDc}	7.48 ± 0.04^{Aa}	71.40 ± 0.09^{Aa}	$20.	

Fig. 3
Nebkha type and soil depth interval: *N. tangutorum* (0–10 cm), *N. tangutorum* (10–20 cm), *N. tangutorum* (20–30 cm), CK; *C. tibetica* (0–10 cm), *C. tibetica* (10–20 cm), *C. tibetica* (20–30 cm); *R. soongorica* (0–10 cm), *R. soongorica* (10–20 cm), *R. soongorica* (20–30 cm).
Panels: (a) Mz (Φ); (b) σ; (c) S_k; (d) K_g. X-axis: slope position—windward slope, lateral slope, mound crest, leeward slope.

Fig. 3 Variations in soil particle-size parameters of typical nebkhas at different soil depth intervals and slope positions. (a), mean particle size (Mz); (b), sorting coefficient (σ); (c), skewness (S_k); (d), kurtosis (K_g). CK means bare sand (control).

stages. This change indicated that sand interception strengthens with mound growth and canopy expansion, and then weakens once the shrub-mound structure begins to break down.

Across the four developmental stages, the sand-fixing efficiency increased from the initial to the stable stage and then declined slightly in the activated stage. The stage-summed values differed among the three nebkha types, with *N. tangutorum* nebkhas reaching the highest value (207.00%), followed by *C. tibetica* (198.30%) and *R. soongorica* (148.36%) nebkhas. Species-level differences appeared from the initial stage onward and were most evident in the stable and activated stages. *N. tangutorum* nebkhas had the highest efficiency (76.90%) in the stable stage, whereas *C. tibetica* nebkhas had higher efficiency (63.84%) in the activated stage. *R. soongorica* nebkhas remained the weakest in efficiency across all stages.

3.2 Wind field characteristics and windbreak efficiency

3.2.1 Effects of nebkhas on vertical wind speed

As shown in Figure 6, wind speed increased with increasing relative height (z/H) and normalized horizontal distance (x/L) for all three nebkha types, but the rate of increase differed by height layer. The increase was weak near the surface at z/H of 0.1–0.5, became strongest at z/H of 1.0–1.5, and then slowed above the shrub height. At z/H of 1.5-2.0, wind speed tended to stabilize, mostly within 8.0–10.5 m/s. Wind speed among the three nebkha types decreased in the

Fig. 4 Variations in soil fractal dimension of typical nebkhas at different soil depth intervals. Bars indicate standard deviation (SD).

Fig. 5 Windbreak and sand-fixing effects of typical nebkhas at different developmental stages

order: *R. soongorica* > *C. tibetica* > *N. tangutorum*. Among developmental stages, the order was initial > developing > activated > stable, with the lowest wind speed occurring in the stable stage. As shown in Figure 7, windbreak efficiency remained low on the windward slope (at x/L of -1–0), ranging from -25.19% to 15.10%. Negative values occurred near the windward slope, where local

Legend: $x/L = 1$ (*N. tangutorum*); $x/L = 2$ (*N. tangutorum*); $x/L = 5$ (*N. tangutorum*); $x/L = 7$ (*N. tangutorum*); CK; $x/L = 1$ (*C. tibetica*); $x/L = 2$ (*C. tibetica*); $x/L = 5$ (*C. tibetica*); $x/L = 7$ (*C. tibetica*); $x/L = 1$ (*R. soongorica*); $x/L = 2$ (*R. soongorica*); $x/L = 5$ (*R. soongorica*); $x/L = 7$ (*R. soongorica*).

(a) Initial stage

(b) Developing stage

(c) Stable stage

(d) Activated stage

Vertical axis: z/H
Horizontal axis: Wind speed (m/s)

Fig. 6 Variation in wind speed with relative height (z/H) and normalized horizontal distance (x/L) along the $y = 0$ centerline of typical nebkhas at different developmental stages. (a), initial stage; (b), developing stage; (c), stable stage; (d), activated stage.

Wind direction →

Column headings: *R. soongorica*; *C. tibetica*; *N. tangutorum*.

Row headings: Initial stage; Developing stage; Stable stage; Activated stage.

Subpanels: (a1), (a2), (a3); (b1), (b2), (b3); (c1), (c2), (c3); (d1), (d2), (d3).

Vertical axis: z/H
Horizontal axis: x/L
Color scale: Windbreak effectiveness (%), from -25 to 95.

Fig. 7 Windbreak efficiency of typical nebkhas at different developmental stages, shown as functions of x/L and z/H along the $y = 0$ centerline. (a1–a3), initial stage; (b1–b3), developing stage; (c1–c3), stable stage; (d1–d3), activated stage.

acceleration developed. The highest efficiency appeared at the leeward foot of nebkhas, reaching 50.71%–95.25%. Windbreak efficiency then decreased as z/H and downwind x/L increased, and generally fell below 30.85% when $z/H > 1.0$. The stable stage had the strongest sheltering effect. For *C. tibetica* nebkhas, windbreak efficiency remained at 65.87%–90.35% within x/L of 1–4 and z/H of 0.0–0.5. In windbreak efficiency, the overall stage order was stable>activated>developing>initial, and the species order was *N. tangutorum*>*C. tibetica*>*R. soongorica*.

3.2.2 Effects of nebkhas on horizontal wind speed

Wind speed varied distinctly with x/L, z/H, and developmental stage among the three nebkha types (Fig. 8). At z/H of 0.1–0.6, wind speed on the leeward slope was lower than that on the windward slope because of mound obstruction. Within x/L of 0–7, wind speed increased near the lower layer but decreased at z/H of 1.1–1.6. Wind speed increased markedly at the mound crest ($x/L = 0$), exceeding that at most positions from $x/L = -1$ to $x/L = 8$. The maximum value reached 13.6 m/s at $x/L = 0$ and $z/H = 1.6$ in the activated stage of *C. tibetica* nebkhas. Wind speed at z/H of 0.1–0.6 remained lower than that at

z/H of 1.1-1.6. Among the three nebkha types, wind speed on the windward slope followed *N. tangutorum*>*C. tibetica*>*R. soongorica*, whereas the leeward slope showed the reverse pattern. Figure 9 further shows that at $z/H = 0.3$, high-speed zones occurred mainly on the windward and lateral slopes. Leeward slope formed strip-shaped deceleration

Fig. 8 Variation in wind speed with x/L and z/H along the $y = 0$ centerline of typical nebkhas at different developmental stages. (a), initial stage; (b), developing stage; (c), stable stage; (d), activated stage.

Fig. 9 Wind speed distribution along x/L and normalized lateral distance (y/W) at $z/H = 0.3$ for typical nebkhas at different developmental stages. (a1-a3), initial stage; (b1-b3), developing stage; (c1-c3), stable stage; (d1-d3), activated stage.

zones, with wind speed decreasing along x/L. The stable stage produced the strongest sheltering effect, especially for *C. tibetica* and *N. tangutorum* nebkhas, whose protected distance exceeded x/L of 7. In the stable stage of *C. tibetica* nebkhas, a continuous deceleration zone developed within x/L of 0–7 and normalized lateral distance (y/W) of -0.75-0.75, where wind speed declined to 1.5-4.0 m/s.

4 Discussion

4.1 Sediment characteristics and windbreak and sand-fixing effects of typical nebkhas

The particle-size composition of aeolian deposits on the surface of nebkhas is jointly controlled by vegetation, wind regime, sediment supply, and topography. The sampling sites in this study are close to one another, with small differences in background wind conditions and terrain, and the sand supply originates from the same source within the Yabrai Mountain aeolian corridor. Under these comparable external conditions, interspecific differences among *N. tangutorum*, *C. tibetica*, and *R. soongorica* are expressed more clearly in the surface particle-size assemblages (Kidron and Zohar, 2016). The particle-size characteristics of surface sediments on nebkhas could directly indicate the extent to which shrubs modify sand transport and provide a basis for evaluating sand-fixing efficiency (Zhang et al., 2022).

In addition to shrub-type effects, particle-size sorting is consistently associated with morphological parameters of nebkhas, because these parameters regulate near-surface flow retardation, the reduction in transport flux, and the balance between deposition and re-entrainment (Zhao and Gao, 2021). Shrub canopy dimensions and vegetation cover characterize the canopy sheltering range and permeability. Nebkhas with larger canopy dimensions and greater vegetation cover, together with a prostrate canopy and dense branching, exhibit lower effective porosity in the near-surface layer. Momentum loss is enhanced on the windward side and within the canopy, thereby increasing the interception of fine sand and silt and promoting deposition around shrubs, resulting in a finer surface layer. By contrast, low and sparsely branched canopies with limited vegetation cover allow greater penetration of airflow; fine particles have a higher probability of re-entrainment after passing through the canopy, and the residual surface material becomes coarser. Mound-scale parameters, including mound height, basal area, volume, and planform dimensions, constrain roughness-element height, the capture extent on the underlying surface, and

the storage capacity of the mound. From the stable stage to the activated stage, mound height, basal area, and volume increase markedly, indicating synchronous vertical accretion and lateral expansion. The windward slope functions as an upslope deceleration zone. Higher surface roughness reduces the transport distance of coarse particles moving by saltation and creep, leading to greater proportions of medium and coarse sand (Cheng et al., 2024). At the mound crest, the canopy disturbs the passing flow and produces small eddies, so fine particles are more readily deposited and retained in this position. The leeward slope shows a different pattern. After passing the crest, coarse particles transported by creep move only a short distance before settling, which increases the coarse fraction on the lee side. The differences among nebkha types and developmental stages are therefore tied to mound size and canopy openness. Nebkhas with larger basal area, greater volume, wider vegetation cover, and higher mounds provide more space for sediment capture and storage, favoring the retention of fine particles. Where the mound is smaller or the canopy is more open, fine particles can pass through the shrub layer or be re-entrained after deposition, leaving a relatively coarser surface sediment assemblage.

Evidence from arid and semi-arid areas shows that nebkhas form through shrub interception of moving sand, followed by deposition around shrubs and subsequent re-sorting. The stage-dependent particle-size pattern in this study indicated progressive coarsening from the initial stage to the activated stage, consistent with the concurrent development of shrub and mound morphology (Zhao et al., 2020). During the developing and stable stages, wind speed in the near-surface layer was relatively low, and fine particles were readily lifted within the sand-laden airflow and preferentially deposited on the windward side, consistent with observations from *Artemisia* nebkhas (Chang et al., 2018). Although shrub growth forms differ among species, the transport-interception mechanism of shrubs acting as roughness elements remains the same. Differences in surface particle size among slope positions across stages reflected stage-related changes in shrub and mound morphology, which altered interception and redistribution among size fractions. In the stable stage, longer development produced larger shrubs and strengthened the association between surface sediments and shrub morphology, with deposits more closely linked to medium- and coarse-sand fractions ($P<0.01$). In the initial stage, smaller shrubs intercepted less sand, and relationships were mainly observed with medium sand ($P<0.05$) and aligned more strongly with canopy dimensions and vegetation cover area. In the activated stage, the increase in dead branches reduced interception by the canopy, and the link between shrub form and sediment properties became weaker.

C. tibetica and *N. tangutorum* nebkhas had higher sand-fixing efficiency than *R. soongorica* nebkhas, with peak efficiencies in the stable stage of 69.50%, 76.90%, and 51.28%, respectively. The surface sediments of *C. tibetica* and *R. soongorica* nebkhas were dominated by fine sand and contained little clay, but *R. soongorica* nebkhas had a coarser particle composition, with medium sand accounting for 41.05%. In *N. tangutorum* and *C. tibetica* nebkhas, larger mound size and low, densely branched canopies form a tighter near-surface structure, which favors the trapping of fine sand and silt around the shrub base. Litter and biological soil crusts further retained these fine fractions on the surface. In *R. soongorica* nebkhas, the shorter and more open canopy provides weaker interception, so fine particles are more easily re-entrained after deposition (Zhang et al., 2020); with limited litter and crust development, the surface remains less stable, leaving coarser sediments and lower sand-fixing efficiency. This pattern is consistent with observations from the lower Hotan River region (Sun et al., 2025).

Across slope positions, the windward slope showed increased proportions of medium and coarse sand as roughness limited the continued movement of coarse particles. At the mound crest, canopy disturbance favored the settling of fine particles; sediments of *N. tangutorum* and *C. tibetica* nebkhas were mainly fine to medium sand near the crest, with M_z values of 2.27 and 2.30 Φ, respectively. The lateral slope was located in the transition between the main flow and bypass flow, and its particle-size composition fell between that of the windward and leeward slopes. The leeward slope showed enhanced accumulation of coarse particles through short-distance creep. The slope-position trend was consistent among nebkha types: very fine sand and

fine sand are higher on the windward slope than on the leeward slope and reach maxima at the mound crest. Medium sand at the crest still accounted for 23.05%–43.17%, contrasting with reports of low coarse-particle content at the crest of *C. tibetica* nebkhas (Hesp et al., 2021). This contrast is related to the generally low mound heights and short wake lengths (0.60–0.73 m) in the study area, which allow coarse particles transported by creep and saltation to be arrested and deposited on the crest surface. Previous studies reported lower sand-fixing capacity in *R. soongorica* plantations than in plantations of other shrub species (Guo et al., 2025); in this study, the sand-fixing efficiency of *R. soongorica* nebkhas remained 51.28% in the stable stage, indicating a moderate level. Compared with *N. tangutorum* and *C. tibetica*, *R. soongorica* trapped fine sand less effectively, but it still intercepted part of the coarser fraction. This role remained relevant in areas exposed to strong wind erosion.

4.2 Windbreak effects of typical nebkhas

From the initial stage to the stable stage and later activation, nebkhas undergo continuous changes in canopy cover, mound height, and length–width ratio (Wu et al., 2015). As vegetation and mound growth proceed together, the nebkha surface changes from a simple form to a more heterogeneous shrub–mound structure. This structure differs from isolated shrubs on nearly flat ground. Around isolated shrubs, wind-field disturbance is usually limited to a small area, and changes in the vertical wind-speed profile remain weak (Latif Bhutto et al., 2022). By contrast, nebkhas act as a two-layer barrier, with the shrub canopy above and the mound body below. This structure adds resistance close to the ground and changes the wind-speed profile around the shrub–mound system.

As airflow passes through and around nebkhas, it is redirected by both canopy gaps and mound slopes. Part of the flow moves upward or sideways, while the near-ground flow slows down and forms small recirculation zones behind the mound (Zhuo et al., 2023). This arrangement separates the flow field on the windward and leeward sides of the mound and changes the pattern of downwind transport, erosion, and deposition. Canopy porosity is central to this process. In *R. soongorica* nebkhas, the space below the crown remains relatively open, allowing near-surface airflow to pass through the sub-canopy layer. Airflow is then squeezed through these gaps and accelerates locally, forming narrow high-speed zones similar to the Venturi effect. By contrast, *C. tibetica* and *N. tangutorum* nebkhas have lower, denser canopies, with fewer openings close to the ground. Airflow entering these canopies encounters stronger resistance, loses more kinetic energy, and slows within and just above the mound. In this study, windbreak efficiency in the stable stage was 30.14% higher for *C. tibetica* nebkhas and 35.52% higher for *N. tangutorum* nebkhas than for *R. soongorica* nebkhas at $x/L = 3$ and $z/H = 0.5$. This difference indicated that canopy porosity directly influences airflow around nebkhas. Previous studies also recorded strong wind-speed reduction on nebkha leeward slopes, especially where the shrub canopy and mound body formed a relatively closed shelter structure (Burylo et al., 2012). In this study, low wind speed values were mainly concentrated in the near-surface leeward zone at $z/H = 0.1$, especially between $x/L = 1$ and $x/L = 2$. Farther downwind and higher above the surface, wind speed gradually returns toward the bare-sand reference level under the same conditions, and windbreak efficiency decreases accordingly. In the horizontal plane, faster airflow occurs along both flanks of the mound. For stable-stage *C. tibetica* nebkhas, wind speed reached 10.5 m/s at $x/L = 1$ and $y/W = \pm 0.5$, exceeding the values at the other observation points. The windward face blocks the incoming flow and diverts part of it toward the lateral slope. As the streamlines converge along the flanks, local kinetic energy increases and wind speed rises. Similar flank acceleration has been reported for *N. tangutorum* nebkhas in the Ulan Buh Desert–oasis transition zone (Miri et al., 2021).

Wind-speed patterns are shaped by mound geometry and by the balance between canopy blockage and exposed sand surface. From the initial stage to the stable stage, the mound becomes higher, longer, and larger in volume. The shrub–mound body also becomes more compact, forcing airflow to bend around it rather than pass through it. Near-surface wind speed then decreases, and the sheltered zone extends farther downwind. Developing and stable nebkhas therefore produce stronger wind reduction and protect a wider area than initial-stage nebkhas. After activation, crest erosion lowers the mound and destabilizes the surface, so windbreak efficiency falls below the stable-stage level. The mound height–width ratio remains a key geometric control on wind-speed attenuation (Hesp et al., 2019).

Nebkhas at different developmental stages differ in how they modify airflow. These differences appear in the degree of wind-speed reduction, the length of the sheltered zone, and the vertical wind-speed profile. In the initial stage, the mound is small, shrub cover is limited, and canopy permeability remains high. Flow disturbance is then restricted to a short leeward zone, with weak wind-speed reduction and limited sheltering (Pan et al., 2020). By the developing stage, the mound has gained volume and the surface under the canopy is less easily disturbed. The near-ground low-speed zone extends farther to the lee, and wind reduction in the lower boundary layer becomes more evident. Similar changes have been reported for nebkhas in comparable stages (Du et al., 2010). In the stable stage, both canopy density and mound form are better developed. The shrub canopy and mound body act together, blocking the incoming flow more effectively and producing the longest sheltered distance. In this study, stable *N. tangutorum* nebkhas still showed an effective sheltering effect at $x/L = 7$. After activation, erosion at the crest and wider canopy gaps allow more airflow to pass through the shrub layer, so near-surface wind speed begins to recover. The windbreak function therefore increases from the initial stage to the stable stage and weakens after activation. Mound height–width ratio, canopy transparency, and mound volume are the main controls on wind-speed attenuation.

5 Conclusions

The three nebkha types in the Yabrai Mountain aeolian corridor—those formed by *R. soongorica*, *C. tibetica*, and *N. tangutorum*—showed distinct sediment and airflow characteristics. Fine particles were mainly retained on the windward slope and mound crest, whereas coarser particles occurred more often on the leeward and lateral slopes. This distribution indicated the joint influence of shrub architecture, mound development, and near-surface airflow adjustment on sediment sorting around nebkhas. Windbreak and sand-fixing effects changed with developmental stage. Protection was strongest in the stable stage and then declined after activation; the developing and initial stages showed weaker effects. Among the shrub species, *N. tangutorum* and *C. tibetica* intercepted sand and reduced wind speed more effectively than *R. soongorica*. The contrast among species became clearer after the shrub–mound structure had developed more fully. Airflow was accelerated over the mound crest and along the lateral slope, while a low-speed zone formed close to the surface behind the mound. This sheltered zone weakened upward and farther downwind. Although the three nebkha types shared the same basic airflow pattern, the strength and extent of wind reduction varied with nebkha type and developmental stage. This study used field observations and numerical simulations under a limited range of wind conditions. Seasonal wind changes, strong sandstorm events, and long-term changes in nebkha morphology were not fully covered. Future work should combine continuous monitoring, sediment-flux measurements, and observations during strong wind events to evaluate the persistence of nebkha windbreak and sand-fixing effects in aeolian corridors.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

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