Microtopographic reconstruction improves soil erosion resistance and vegetation characteristics on the slopes of large dump sites in semi-arid areas

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In view of the management of slopes in large mine dumps in semi-arid regions, this study explored different methods for controlling soil erosion and improving the microenvironment of the surface of such slopes. Focusing on microtopography modifications and vegetation measures on the slopes of a large mine dump in a semi-arid region, the soil erosion resistance of the slope was continuously monitored using installed observation plots. In addition, the characteristics of plant communities that thrived on the dump were investigated. The results indicate that the soil erosion resistance, soil organic matter content, and biodiversity increased to different degrees in the large mine dump that experienced microtopography modifications and implemented vegetation measures compared with those of slopes managed only by soil cover and planting. Compared with that in the control plot, under the same vegetation restoration measures, the macroaggregate content in the four plots that implemented microtopography modifications increased by 20%, 24%, 21%, and 30%; the soil erodibility (K-factor) decreased by 7.8%, 8.5%, 10%, and 10.7%; and the soil organic matter increased by 2%, 4.5%, 3.4%, and 4.7%. Microtopography modification consisting of U-shaped blocking boards and fixed rods embedded in the slope, combined with vegetation measures, resulted in a protective effect, which in turn induced the highest diversity, evenness, and richness index values of 2.35, 0.87, and 1.94, respectively. The study results revealed that a combination of microtopography modifications and vegetation measures can be used to achieve effective vegetation restoration, prevent soil erosion, and create different microhabitats, indicating that our approach is an effective way to control critical issues affecting large mine dumps in semi-arid regions.

KEYWORDS

semi-arid region, mine dump, microtopography modification, soil erosion, species diversity

1 Introduction

Mine dumps are a necessary by-product of surface mining (Monjezi et al., 2009; Franco-Sepúlveda et al., 2019; Shi et al., 2021), and the operation and management of such dumps have a profound impact on soil erosion, surface vegetation, and landscapes (Chen et al., 2019; Blake et al., 2018; Esmali Ouri and Kateb 2020). Owing to an increasing emphasis on ecological conservation in China, the number of studies on soil erosion control and vegetation restoration techniques associated with mine dumps has increased. Previous studies have shown that the biodiversity of mine dumps depends on vegetation restoration efforts (Feng et al., 2019; Tang et al., 2022). Suitable vegetation restoration techniques improve the nutrient contents and activity in the surface soil of mine dumps (Yuan et al., 2018; Raghunathan et al., 2021). Furthermore, soil aggregates are the basic structural units of soil. They are closely related to soil erosion, and their size and stability significantly affect soil erodibility. Thus, they are an important factor for evaluating the soil erosion resistance environment (Nie et al., 2018; De Laurentiis et al., 2019). Composition and stability of soil aggregates are the main indicators of soil structure and quality (Hao Wang et al., 2018; Lehmann et al., 2020). The formation of surface soil aggregates and improvement of erosion resistance of mine dumps also require appropriate vegetation restoration (Guo et al., 2020; Ke et al., 2021; Ma et al., 2022).

Large mine dump slopes represent soil erosion and vegetation restoration sites between platforms (flat sections (steps) and step slopes), whereby soil erosion and vegetation restoration have contrasting effects of intensification and suppression of soil erosion, respectively. Slopes are key areas of vegetation restoration and soil erosion control in large mine dumps, but vegetation restoration on the slopes of mine dumps is difficult to achieve using soil and vegetation cover alone. Furthermore, these slopes are important for the ecological conservation of mining areas, and it is important to overcome chronic soil and water conservation issues in large mine dumps.

To overcome these shortcomings in soil and water conservation in mine dumps, experts and scholars have carried out theoretical and practical analyses covering various topics, such as vegetation, engineering, and soil improvement measures to manage mining wastelands (Fischer et al., 2013; Chen et al., 2018; Luo et al., 2018). Previous studies have indicated that vegetation restoration and soil improvement measures can significantly control soil erosion in mining areas (Ouyang et al., 2018; Neuenkamp et al., 2019), but relying solely on the natural restoration of soil and vegetation through natural succession to shrubs and grasses requires 15–30 years, which can extend to more than 100 years in forest communities (Groninger et al., 2017; Mander et al., 2017; Chen et al., 2020). Poorly considered measures can increase the slope erosion more than that observed on bare land (Vinci et al., 2017; Guo et al., 2019). As

a result, it is important to adopt appropriate measures and methods during the ecological restoration of large mine dumps. Some studies have shown that microtopography modifications affect rainfall infiltration, control soil erosion (Prosdocimi et al., 2017; Eltner et al., 2018; Zhang et al., 2018; Caviedes-Voullième et al., 2021), improve surface habitat, and promote water and soil conservation as well as vegetation restoration (Perreault et al., 2017; Yixia Wang et al., 2018; Wang et al., 2020; Mata-González et al., 2022). Following microtopography modifications, vegetation measures can significantly increase the content of nitrogen, phosphorus, potassium, and other organic matter in the damaged soil of mining areas, which further improves the physical and chemical properties of this soil, as well its erosion resistance (Orgiazzi and Panagos 2018; Zhao et al., 2018). To date, studies on the slope management of large mine dumps tended to focus on a single vegetation restoration model, and the selection of suitable vegetation species plays an important role in these studies. Only a few studies have analyzed the effects of microtopography modifications in conjunction with appropriate vegetation restoration on the regulation of soil erosion on the slopes of mine dumps in semi-arid areas.

Based on the shortcomings in slope management of large-scale mine dumps in semi-arid areas, in the present study, we analyzed the efficacy of microtopography modifications used in combination with appropriate vegetation measures and proposed viable soil and water conservation measures to control the chronic issues faced by large surface mine dumps in semi-arid areas. The results of the present study can be used to guide the ecological restoration of soil dumps and promote the sustainable exploitation of large surface mine dumps.

2 Materials and methods

2.1 Study area overview

Our study area was the southern mine dump of the East No. 2 Shengli Surface Coal Mine in the northeast city of Xilinhot in the Inner Mongolia Autonomous Region of China (44°3′29.68″–44°3′39.36″ N and 116°14′23.75″–116°14′36.03″ E; Figure 1). The soil and water conservation area is designated as the Xilinhot Plateau Soil Conservation Ecological Maintenance Area. The original terrain of the mine dump site was relatively flat, with an altitude range of 990–1,021 m. The relative height range of the mine dump was 100–120 m, with steps every 20 m. The dumping period was 10 years. The angle of slope repose was 33°. The steps had a longitudinal slope of 8°–10° and a transverse slope of 3°–5°. The test area was a slope containing bare patches. The average thickness of the surface layer of the slope was 20 cm. In terms of physical and chemical properties of the upper soil layer (0–20 cm), the bulk density
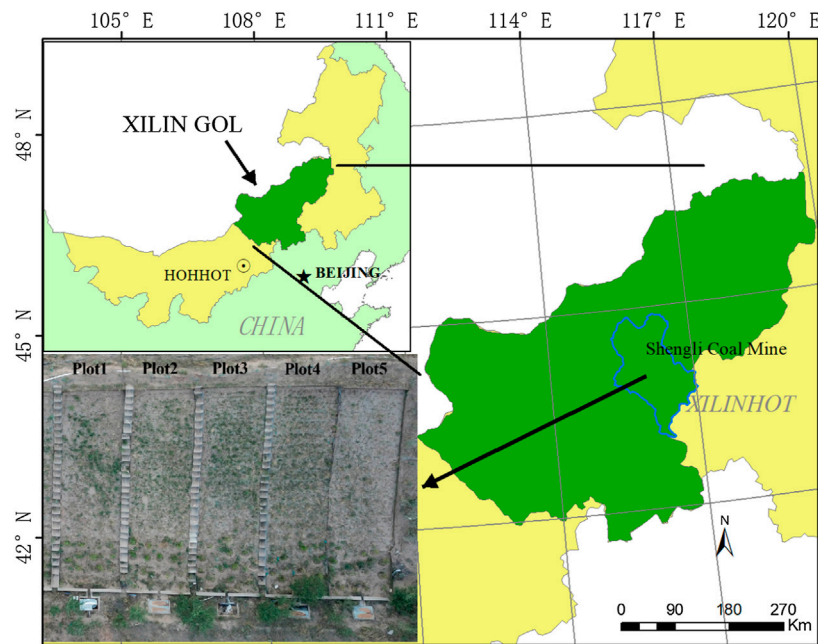
FIGURE 1
Location of the experimental site.

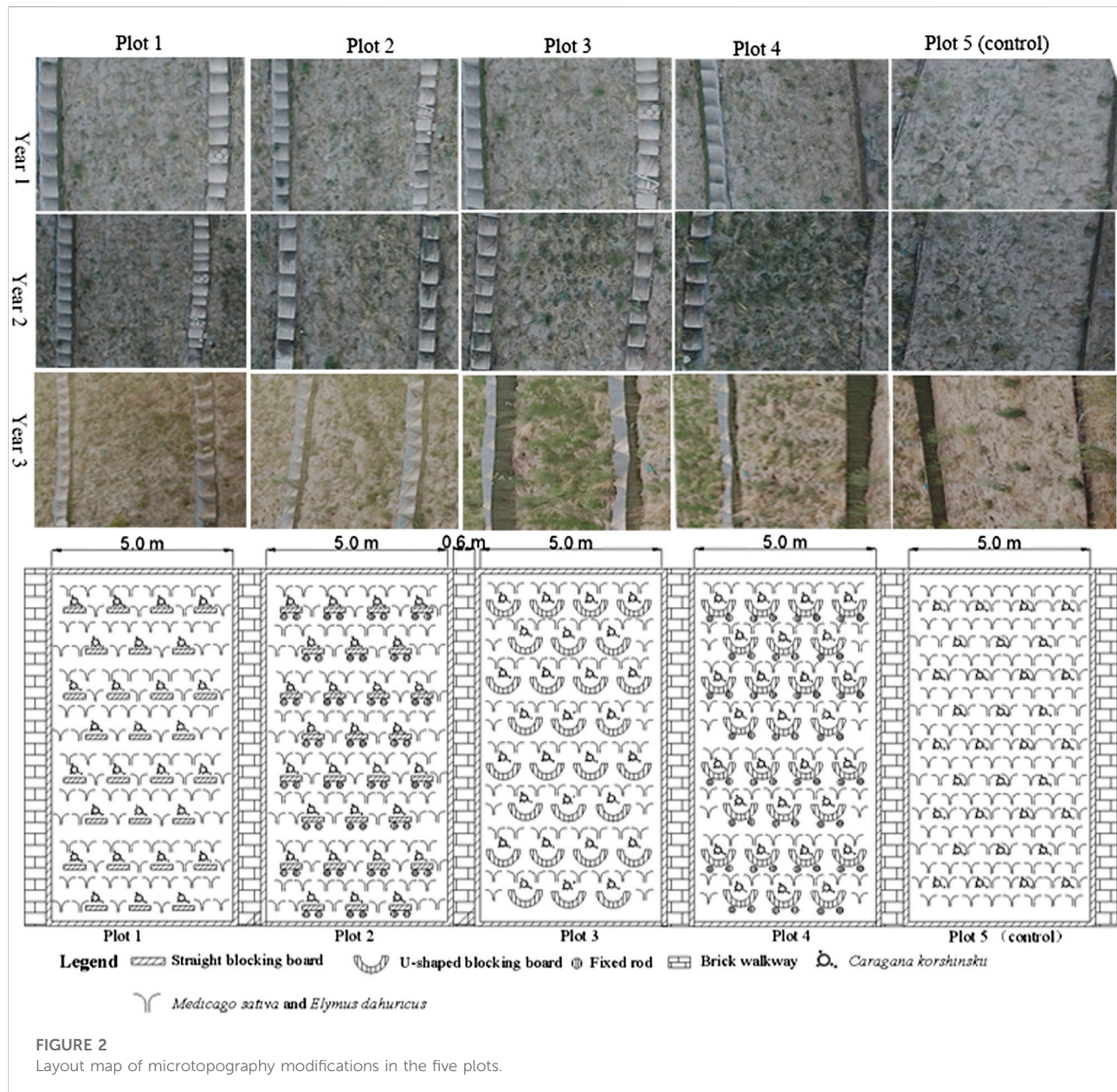TABLE 1 Slope microtopography modifications in the five plots analyzed in the present study.

Runoff plot no.	Size (m × m)	Slope (°)	Microtopography modifications	Ground preparation
1	20 × 5	33	Straight blocking board	Cover with soil, hole sowing *Caragana korshinskii*, and spreading *Medicago sativa* and *Elymus dahuricus*
2	20 × 5	33	Straight blocking board + fixed rods	Cover with soil, hole sowing *Caragana korshinskii*, and spreading *Medicago sativa* and *Elymus dahuricus*
3	20 × 5	33	U-shaped blocking board	Cover with soil, hole sowing *Caragana korshinskii*, and spreading *Medicago sativa* and *Elymus dahuricus*
4	20 × 5	33	U-shaped blocking board + fixed rods	Cover with soil, hole sowing *Caragana korshinskii*, and spreading *Medicago sativa* and *Elymus dahuricus*
5 (control)	20 × 5	33	None	Cover with soil, and hole sowing *Caragana korshinskii*, and spreading *Medicago sativa* and *Elymus dahuricus*

The straight blocking board was wooden plywood, and the fixed rods were sand willow sticks (10 mm in diameter).

was 1.53 g cm^{-3}, soil particle size was mainly medium sand >0.25 mm, and soil quality was poor. Total nitrogen content in the 0–20-cm soil layer of the slope was 0.12 g kg^{-1}; available potassium content was 0.08 g kg^{-1}, available phosphorus content was 0.92 mg kg^{-1}, organic matter content was 2.0 g kg^{-1}, and pH was 8.47.

The study area was located in the hinterland of the Inner Mongolia Plateau, which is known to have a mid-temperate semi-arid climate. The mean annual precipitation was 289.2 mm, 69% of which occurred from June to August. The maximum 24 h rainfall was 85.3 mm in the past

10 years and 111.5 mm in the past 20 years. The mean annual evaporation was 1805.1 mm, which was six times higher than the mean annual precipitation. The annual dominant wind direction was southwest, mean annual wind speed was 3.5 m s^{-1}, and number of strong wind days (≥17 m/s) was 58. The zonal soil in the study area was sandy loam, and the non-zonal soil was chestnut soil. The vegetation type was typical grassland vegetation, with *Stipa krylovii* and *Leymus chinensis* as the main constructive species in the region. The vegetation coverage was 35–50%.

FIGURE 2
Layout map of microtopography modifications in the five plots.

2.2 Experiment installation

On the third step of the southern mine dump of the East No. 2 Shengli Surface Coal Mine, we chose the middle section, which had a uniform slope, to select five runoff plots. Plots 1, 2, 3, and 4 were microtopography modification plots, and Plot five was a control plot (see Table 1; Figure 2 for details). Each plot was laid out in sequence along the longitudinal direction of the slope, and 0.6 m wide brick walkways were created between the plots to allow observations and sampling. The size of each plot was 20 × 5 m.

The microtopography modification method of Plot one involved embedding straight blocking boards (plywood boards) on the slope surface, with blocking boards laid in a zigzag shape along the longitudinal direction of the plot. The straight blocking boards were 60 cm long, 60 cm wide, and 0.5 cm thick. The horizontal spacing of the straight blocking boards was 60 cm, and the vertical spacing was 120 cm. The blocking boards were inserted in pre-cut grooves perpendicular to the slope at a depth of 30 cm. After they were buried, we ensured that the edges of the blocking boards were levelled with the slope. The main function of the blocking boards was to reduce the downhill movement of surface soil so that plant seeds would be evenly distributed in the slope surface layer before the vegetation had an effect on soil and water conservation as

well as to avoid bare patches during the process of vegetation restoration. Once the blocking boards were in place, the open space of the plot was planted with *Caragana korshinskii* from top to bottom, with the inter-plant spacing of 120 cm and row spacing of 120 cm. The planting holes had a depth of 5 cm and radius of 5 cm, with a semi-circular cross section. The rest of the open space of the plots was scattered with a mix of *Medicago sativa* and *Elymus dahuricus* in a mixing ratio of 1:1.

The microtopography modification method of Plot two was to embed straight blocking boards and insert fixed rods in the slope. The layout positions and method of the blocking boards and the specifications were the same as those in Plot 1. The fixed rods were sand willow sticks, with a diameter of 10 mm and length of 35 cm. They were wedged into the slope along the back of the blocking boards so that their tops were flush with the edge of the boards. Once the blocking boards and rods were installed, the plot was levelled.

The microtopography modification method applied in Plot three consisted of U-shaped blocking boards (also plywood boards) arranged in a zigzag shape across the entire plot. The U-shaped blocking boards were 60 cm in length, 60 cm in width, and 0.5 cm in thickness. The layout and method of installing the U-shaped blocking boards were the same as those in Plot 1. After the blocking boards were installed, the plot was levelled.

The microtopography modification method of Plot 4 consisted of embedding U-shaped blocking boards and fixed rods in the slope. The layout positions and method of the blocking boards and the specifications were the same as those in Plot 1. The blocking board specifications were the same as those in Plot 3. The material, length, and installation method of the fixed rods were the same as those in Plot 2. Once the blocking boards and the rods were installed, the plot was levelled.

Plot 5 was the control plot. No microtopography modifications were applied to the plot, and only shrubs and grasses were planted after the topsoil was restored, which is the most common restoration method used in mine dumps. The thickness of the soil cover and the method of planting shrubs and grasses were the same as those in Plot 1. The implementation of the methods in all five plots was completed on 16 May 2019. Notably, the vegetation selection and planting methods for all the plots were the same.

2.3 Data processing

2.3.1 Soil sample collection and analysis

In this study, only the surface layer (0–20 cm) of the mine dump, which was covered with surface soil, was sampled. Below 20 cm, the lithology consisted of a mixture of clay, shale, and coal gangue; therefore, no sampling was carried out below this depth. Soil sampling were taken at the end of the plant growth season (mid to late September) in the period between 2019 and 2021. In each plot, nine soil samples of the 0–20-cm soil were randomly collected

(i.e., three samples from the upper, middle, and lower parts of the slope, respectively) using a soil drill. In each plot, the samples collected from the upper, middle, and lower parts were mixed respectively and analyzed in a laboratory. The undisturbed soil was segregated into portions with diameters of 5 cm based on their structure. Plants, fine roots, stones, and other debris were removed, and the samples were placed in a ventilated place to dry naturally. After being air-dried, the soil samples from each plot were mixed, sieved, and stored in Ziplock bags for indoor analysis.

The dry sieving method was used to sort the soil according to the particle size, so that the contents of soil aggregates could be measured at all levels. One air-dried soil sample (240 g) was dry sieved, and the weight of soil aggregates in the particle sizes of 0.5, 0.1–0.25, 0.05–0.1, and <0.05-mm was measured to calculate the weight proportions for each soil aggregate particle grade. Another air-dried soil sample (50 g) were wet sieved and analyzed using an aggregate analysis meter. The water-stable aggregate content of the 0.25–0.5, 0.1–0.25, 0.05–0.1, and <0.05-mm grades were measured. After drying in an oven at a constant temperature of 4°C, the samples were weighed to calculate the percentage of water-stable aggregates in the soil for each grade.

The air-dried soil samples were sieved through a 2 mm sieve, and the samples were ground before being sieved again. The content of soil organic matter was determined using the potassium dichromate-volumetric method (external heating method).

2.3.2 Calculation methods for soil erosion resistance index

The specific formulas for calculating the mean weight diameter (MWD; mm) of soil aggregates (calculated using wet sieve aggregate size) and soil erodibility K-factor (in the case of limited soil physical and chemical properties, only the geometric mean soil particle size was considered) (van Bavel 1950; Shirazi et al., 1988) were as follows:

$$\text{MWD} = \sum_{i}^{n} x_i w_i \Big/ \sum_{i}^{n} w_i \tag{1}$$

$$\text{GMD} = \exp\left[\left(\sum_{i}^{n} w_i \ln x_i\right)\Big/\sum_{i}^{n} w_i\right] \tag{2}$$

$$K = 7.954 \times \left\{0.0017 + 0.0494 \times \exp\left[-0.5 \times \left(\frac{\log \text{GMD} + 1.675}{0.6986}\right)^2\right]\right\} \tag{3}$$

where x_i is the diameter of the aggregate at each particle grade level (mm), w_i is the percentage of aggregate mass, and GMD is the geometric mean diameter of the soil aggregate.

2.3.3 Plant community survey

In mid-August 2021, three quadrats (1 × 1 m) were randomly selected from the upper, middle, and lower parts of the five plots, and the individual plant height and density were measured; additionally, the cover of each plant species in each quadrat was
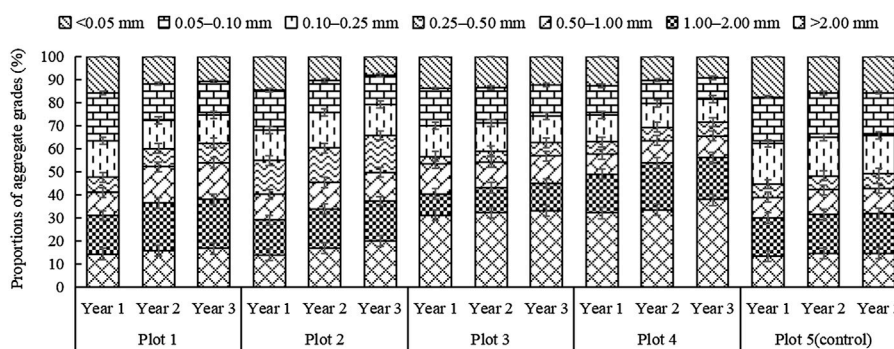
FIGURE 3
Changes in the soil aggregate grain sizes in the plots corresponding to different microtopography modifications.

measured, and the plant species present in the quadrats were recorded (Zhang 2007).

Species diversity was analyzed using three indices: Shannon–Wiener index of diversity, Pielou's evenness index, and Margalef's richness index. The calculation formulas for the indexes are given below (Clobert et al., 2018):

$$\text{Shannon} - \text{Wiener index of diversity}\,(H'):\ H' = -\sum P_i \ln P_i \tag{4}$$

$$\text{Pielou evenness index}\,(J):\ J = \frac{H'}{\ln S} \tag{5}$$

$$\text{Margalef's richness index}\,(R):\ R = \frac{S-1}{\ln N} \tag{6}$$

where P_i is the relative importance value, that is, $P_i = N/N_i$; N_i is the importance value of species i; N is the sum of importance values of species in the surveyed quadrat; and S is the number of species in the surveyed quadrat.

The calculation method of importance value (I) was calculated using the following equation:

$$I = R_C + R_F + R_D \tag{7}$$

where R_C is the relative cover, R_F is the relative frequency, and R_D is the relative density.

We analyzed the data using SPSS Statistics V22.0 (IBM. Corp., Armonk, NY, United States) and plotted the data using Microsoft Excel 2016 (Microsoft Corp., Redmond, WA, United States).

3 Results and analysis

3.1 Effects of microtopography modification on soil aggregate structure

As shown in Figure 3, in Plots 3 and 4, after 3 years of vegetation restoration, the content of aggregates larger than 2.0 mm constituted 30–40% of the soil, whereas that of aggregates larger than 2.0 mm in the other plots constituted only 15–20% of the soil. The microtopography modification method, consisting of U-shaped blocking boards and fixed rods (Plot 4), resulted in different degrees of increase in macroaggregates after vegetation restoration.

As shown in Figure 3, the trends for the content aggregates larger than 0.25 mm in plot 1 to plot 4 were basically similar, increasing year by year in each plot; however, there was no obvious trend for aggregates of grade 0–0.25 mm. Following microtopography reconstruction on the slope surface of the mine dump site and the implementation of similar vegetation measures, the order of the plots, from large to small, in terms of the content of aggregates larger than 0.25 mm was: Plot 4 > Plot 3 > Plot 2 > Plot 1 > Plot 5 (control) in the first year; Plot 4 > Plot 2 > Plot 1 > Plot 3 > Plot 5 (control) in the second year; and Plot 4 > Plot 2 > Plot 3 > Plot 1 > Plot 5 (control) in the third year. The analysis revealed that during the same vegetation restoration periods, the plots with microtopography modifications had higher contents of aggregates larger than 0.25 mm than those of the control plot (Plot 5).

3.2 Effects of microtopography modifications on the MWD of soil aggregates

As shown in Figure 4A, the MWDs of the plots with microtopography modifications as well as that of the control plot increased more slowly with increasing vegetation restoration. During the same vegetation restoration periods, the soil MWDs of the plots managed by microtopography modifications were greater than that of Plot 5. This indicated that even though we adopted the same vegetation restoration measures, microtopography modifications were more effective in gradually increasing the amounts of soil aggregates. Under the same vegetation
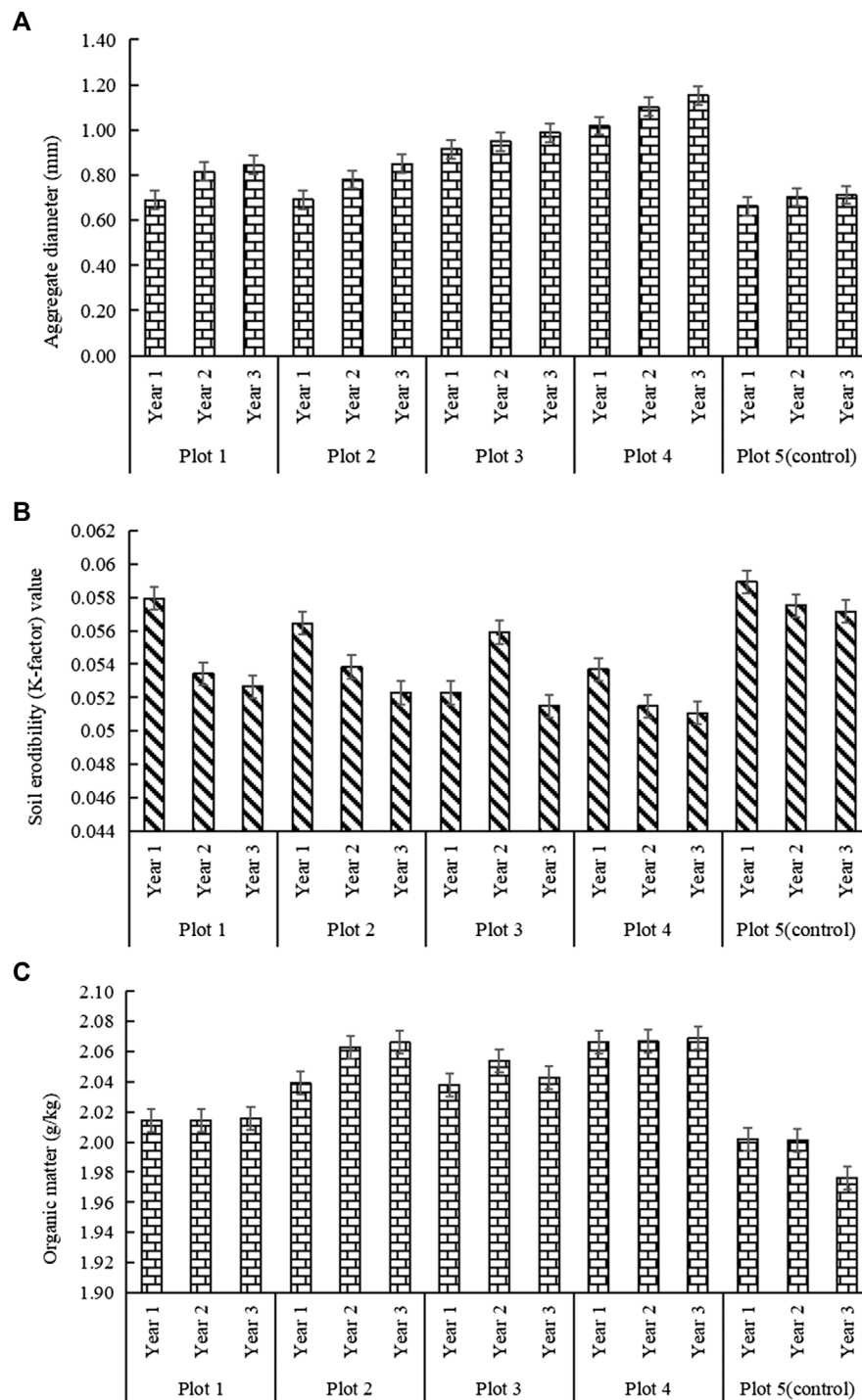
FIGURE 4
(A) Changes in mean weight diameter (MWD) of the soil aggregates in the four plots corresponding to different microtopography modifications.
(B) Changes in soil erodibility in the plots corresponding to different microtopography modifications. **(C)** Changes in organic matter in the plots corresponding to different microtopography modifications.

restoration measures, the order of the plots, from large to small, in terms of soil MWD was: Plot 4 > Plot 3 > Plot 2 = Plot 1 > Plot 5 (control) in the first year; Plot 4 > Plot 3 > Plot 1 > Plot 2 > Plot 5 (control) in the second year; and Plot 4 > Plot 3 > Plot 2 > Plot 1 > Plot 5 (control) in the third year. Even though the vegetation restoration measures were the same, in

any given year, the U-shaped blocking boards and fixed rod modification method (Plot 4) resulted in the greatest MWD, followed by the plot that only used U-shaped blocking boards (Plot 3).

3.3 Comparison of soil erodibility of plots under different microtopography modifications

Soil erodibility (K-factor) values are used as comprehensive indicators of soil resistance to water erosion. The higher the K-factor value, the weaker the soil erosion resistance and vice versa. As shown in Figure 4B, except for the K-factor value of Plot 3, which increased and then decreased with time (after vegetation restoration), the K-factor values of the other plots gradually decreased with time (after vegetation restoration). Following vegetation restoration at the same time point, the order of K-factor values of the plots, from small to large, with respect to various microtopography modifications was: Plot 3 < Plot 4 < Plot 2 < Plot 1 < Plot 5 (control) in the first year; Plot 4 < Plot 1 < Plot 2 < Plot 3 < Plot 5 (control) in the second year; and Plot 4 < Plot 3 < Plot 2 < Plot 1 < Plot 5 (control) in the third year. After the vegetation restoration measures were implemented, the K-factor value of Plot 4 decreased at the quickest rate, decreasing by 10% in the second year and 11% in the third year compared to that of the control plot. This indicated that with respect to the same vegetation restoration measures, the K-factor value of the plot with microtopography modifications consisting of U-shaped blocking boards and fixed rods decreased gradually with time, indicating an overall increase in soil erosion resistance.

3.4 Effects of microtopography modifications on soil organic matter content

Previous studies have reported that an increase in the soil organic matter content can promote soil cementation, strengthen the adsorption between particles, and increase the amount of macroaggregates, thereby improving the soil structure, aeration and water permeability, and erosion resistance (Šimanský et al., 2019; Chung et al., 2021; Liu et al., 2021). As shown in Figure 4C, with respect to the same vegetation restoration measures, the organic matter content in the surface soil of the plots that underwent microtopography modifications was higher than that in the control plot in the second and third years. With the exception of Plots 3 and 1, the surface soil organic matter content in the modified plots had the same change trend. After vegetation restoration, the organic matter content in the soil showed a slow increasing trend, consistent with the changes in soil erosion resistance. Under the same vegetation restoration measures, the order of organic matter content of the four plots,

from large to small, under various microtopography modifications was: Plot 4 > Plot 2 > Plot 3 > Plot 1 > Plot 5 (control) in the first year; Plot 4 > Plot 2 > Plot 3 > Plot 1 > Plot 5 (control) in the second year; and Plot 4 > Plot 2 > Plot 3 > Plot 1 > Plot 5 (control) in the third year. After vegetation restoration, the surface organic matter content in the soil of Plot 4 increased slowly, up 3.2% in the first year, 3.2% in the second year, and 4.7% in the third year, compared with that in the control plot. After 3 years of vegetation recovery, the implementation of microtopography modifications increased the organic matter content in the slope surface soil from 2.0 to 2.06 g/kg. This may be related to the fact that microtopography modifications created a stable environment for plant growth. Vegetation restoration increased the soil organic matter content, and the organic matter content increased the soil resistance to erosion (Fonseca et al., 2017; Herrick et al., 2018; Guo et al., 2020).

3.5 Effects of microtopography modifications on plant community diversity

Previous studies have demonstrated that appropriate microtopography modifications can enhance the effects of vegetation restoration (García-Ávalos et al., 2018; Qiu et al., 2019; Wentzell et al., 2021). Furthermore, studies have shown that microtopography modifications are closely linked to vegetation restoration status and the corresponding soil and water conservation and biodiversity (Melnik et al., 2018; Tukiainen et al., 2019). In mid-August 2021, we conducted a plant community survey in the four plots wherein we implemented microtopography modifications, as well as in the control plot. In the five plots, 15 plant species were identified, and they belonged to five families and 14 genera. The plant species and their importance values (P_i) are shown in Table 2, and the results of the species diversity index analysis are shown in Table 3.

Species diversity is a comprehensive quantitative indicator of species richness and distribution uniformity in a habitat; thus, it is a good reflection of community composition (Tonkin et al., 2017; Hubbard et al., 2018). As shown in Table 3, compared to those in the control plot (Plot 5), the number of species, diversity (H′), evenness (J), and richness (R) indexes were all higher in the four plots where we implemented microtopography modifications. Among the four modified plots, Plot 4 had the highest diversity value (2.35), while Plots 2, 3, and 1 had the second, third, and fourth highest diversity values of 2.25, 2.20, and 2.10, respectively. In general, the evenness index indicates the evenness of plant distribution in a community. In the present study, Plot 4 had the highest evenness index, with a value of 0.87, followed by Plots 2, 3, and 1, with evenness index values of 0.83, 0.82, and 0.79, respectively. Generally, the species richness index indicates the total number of species in a community. In the

TABLE 2 Importance values of plants (Pi) in the plots.

No.	Plant species	Family, genus	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5 (control)
1	*Caragana korshinskii*	Fabaceae, *Caragana*	50	30	29	10	100
2	*Lespedeza davurica*	Fabaceae, *Lespedeza*	219	256	255	270	169
3	*Elymus dahuricus*	Poaceae, *Elymus*	263	308	315	324	203
4	*Chloris virgata*	Poaceae, *Chloris*	130	152	145	100	100
5	*Medicago sativa*	Fabaceae, *Medicago*	263	308	308	324	203
6	*Corispermum mongolicum*	Amaranthaceae, *Corispermum*	68	80	90	84	53
7	*Allium polyrhizum*	Amaryllidaceae, *Allium*	50	23	23	24	15
8	*Eragrostis Pilosa*	Poaceae, *Eragrostis*	130	152	200	20	150
9	*Chenopodium aristatum*	Chenopodiaceae *Chenopodium*	46	46	80	30	48
10	*Salsola collina*	Chenopodiaceae *Salsola*	70	46	60	30	70
11	*Panicum miliaceum*	Poaceae, *Panicum*	76	76	76	50	30
12	*Setaria viridis*	Poaceae, *Setaria*	76	76	90	50	150
13	*Chenopodium acuminatum*	Amaranthaceae, *Chenopodium*	15	15	50	10	60
14	*Amaranthus retroflexus*	Amaranthaceae, *Amaranthus*	23	23	45	15	-
15	*Bassia dasyphylla*	Amaranthaceae, *Bassia*	-	20	20	15	-

[a]Indicates that the plant did not appear in the surveyed quadrat.

TABLE 3 Comparison of the community diversity, evenness, and richness of the different plots.

Plot	No. of species	Diversity index (H)	Evenness index (J)	Richness index (R)
1	14	2.10 ± 0.76	0.79 ± 0.13	1.78 ± 0.43
2	15	2.25 ± 0.79	0.83 ± 0.15	1.89 ± 0.48
3	15	2.20 ± 0.75	0.82 ± 0.15	1.86 ± 0.46
4	15	2.35 ± 0.81	0.87 ± 0.24	1.94 ± 0.54
5 (control)	13	1.97 ± 0.55	0.77 ± 0.13	1.66 ± 0.40

present study, Plot 4 had the highest richness index value among the plots having microtopography modifications, with a value of 1.94, followed by Plots 2, 3, and 1, with richness index values of 1.89, 1.86, and 1.78, respectively. The Shannon–Wiener index of diversity objectively reflects the changes in species of a plant community, while taking into account any insufficiencies in species richness and evenness. Thus, it can indicate the diversity of a community more effectively than other indices. The plant community in Plot 4, which underwent microtopography modifications, had a higher species diversity than that of the other plots.

In Plot 4, we applied the microtopography modifications of U-shaped blocking boards and fixed rods. This combination prevented slope soil from slipping and additionally increased surface infiltration. The blocking boards embedded in the slope prevented the surface soil from separating from the slope, and the fixed rods reinforced the blocking boards. Thus, these modifications could provide a safe and stable environment for plant growth. They protected the slope before the vegetation measures took full effect and played an important role in

improving the soil organic matter content as well as its erosion resistance. Therefore, Plot 4 had the highest plant community diversity, evenness, and richness index values.

In Plot 2, we applied straight blocking boards and fixed rods, which refined the space within the plot and ensured the initial evenness of plant species distribution. Although it prevented the surface soil from separating from the slope, the surveys revealed that it suffered more longitudinal erosion than Plot 4 did, which may have accounted for its diversity index value being lower than that of Plot 4. Plots 1 and 3 used single microtopography modification methods, and the surveys revealed that they contained bare patches ranging from 0.01 to 0.09 m² in area. Owing to fewer species and more bare patches, the biodiversity of Plots one and three was lower than that of Plot 4. Plot 5 (control) only had soil cover and planted vegetation, with no protection methods for the surface soil on the slope. Therefore, the slope surface soil suffered severe slippage, indicating that the vegetation measures were not effective and did not stop slope erosion; thus, the bare patches on the slope increased over the duration of the study period. This plot had bare patches ranging

from 0.5 to 1.0 m² in area, which increased in size each year; additionally, compared to the other plots, this plot had fewer species and the least diverse plant community. By collating the surveys from the 3 years, we concluded that the plant species in the plots were the same in 2019, consisting primarily of artificially planted species, with minimal gradation and a single-layer structure. By 2021, the number of species in Plots one to four increased, and gradation appeared, indicating that microtopography modifications can allow vegetation restoration to take effect.

4 Discussion

4.1 Effects of microtopography modifications on soil erodibility

In the plots with microtopography modifications, the amount of macroaggregates increased every year. In 2021, compared with those in the control plot, aggregates larger than 0.25 mm increased by 20, 24, 21, and 30% in plots 1, 2, 3 and 4, respectively. Plot 4 exhibited the fastest increase in the amount of aggregates larger than 0.25 mm, followed by Plot 2. Some studies have reported that the water-stable aggregate content, particularly the content of aggregates larger than 0.25 mm, is one of the best indicators of soil erodibility (Hao Wang et al., 2018; Lehmann et al., 2020). The plots with microtopography modifications have different manifestations in terms of the three indicators of MWD, erosion resistance, and mine dump surface soil organic matter content. By 2021, compared with those in the control plot, the MWD in plots 1, 2, 3, and 4 increased by 15, 16, 27, and 38%; the soil erodibility (K-factor) values decreased by 7.8, 8.5, 10, and 10.7%, and the soil organic matter content increased by 2, 4.5, 3.4, and 4.7%, respectively. The results revealed that if the values surpassed these increments, the soil organic matter increased, soil erodibility decreased, and the MWD of soil aggregates increased. Previous studies have also demonstrated that soil organic matter is an important indicator of soil quality (Šimanský et al., 2019; Chung et al., 2021). It is also a binding material that forms soil aggregates and is important for increasing soil erosion resistance. Thus, the number and characteristics of soil aggregates reflects soil erosion resistance. This was consistent with the findings of Chung et al. (2021) and Šimanský et al. (2019).

In the present study, we proposed different combinations of microtopography modification materials and methods known to have good soil and water conservation effects. However, our study was limited to soil erosion resistance studied for a period of 3 years. Therefore, it lacks long-term observations of erosion prevention and control. Future studies should focus on the quantitative analysis of vegetation restoration and soil erosion on the slopes of mine dumps following the implementation of microtopography modifications. Compared with the control plot, plot 4 with the microtopography modification method of embedding U-shaped blocking boards and fixed rods in the slope

was most effective at enhancing soil erosion resistance. Our study was based on the field survey of soil erosion resistance. However, we did not consider the process of the wind erosion; hence, increased observation of the amount of wind erosion is required in the future.

4.2 Effects of microtopography modifications on biodiversity

The implementation of microtopography modifications can create conditions for vegetation restoration and enhance biodiversity (Liu et al., 2020; Miller et al., 2021). In the present study, we investigated the characteristics of plant communities and showed that compared with the control plot, Plot 4 had the highest number of species (15), along with the highest Shannon–Weiner diversity (2.35), evenness (0.87), and richness indices (1.94). All four plots with microtopography modifications showed a higher plant diversity compared to that in the control (Plot 5). This indicated that single or combined microtopography modifications can create different microhabitats on the slopes of mine dumps. Before vegetation measures have an effect on soil and water conservation, modifications provide a safe and stable environment for plant growth, creating suitable conditions for species reproduction. This was consistent with the findings of Qiu et al. (2019) and Wentzell et al. (2021). In terms of vegetation restoration, we observed a close link between microtopography combinations and biodiversity. Nevertheless, as our investigation was limited to studying plant community characteristics in mid-August 2021, during a period of vigorous plant growth, it remains unclear whether microtopography modifications promote positive succession of plant communities during the other months of the year. The order of plots, from high to low, in terms of diversity, evenness, and richness were Plot 4 > Plot 2 > Plot 3 > Plot 1 > Plot 5 (control). This result was based on a survey of only a few plant community characteristics, and future studies should consider the dynamic changes in plant communities caused by single and combined microtopography modification methods.

4.3 The practicality of microtopography modification methods

The barrier plates and fixed piles used in the present study are all wooden materials. Following the application of soil and water conservation measures, such wooden materials begin to decay and are degraded into the soil. Before the plant measures come into effect, the slope surface material can be fixed to prevent the surface soil from separating from the slope and to provide a safe and stable environment for plant growth. In the project area, a large area of the slope with conventional plant measures emerged as an exposed open space. As the surface soil of the slope declined, which made the surface soil thinner, the slope

vegetation cover decreased, and the erosion ditch density increased because there are no fixed measures for maintenance of the slope surface material, and consequently, the soil and water conservation treatment effects cannot be achieved. In the present study, the resources (1.2–1.5 fold higher) invested in the test plots were greater than those in the control plot (Plot 5). Moreover, a large amount of work was invested to address the problem of soil dump slope surface material separation; however, further studies are required to determine the quantitative transformation relationship between investment benefit and ecological benefit.

5 Conclusion

Using plot-based observation facilities, we studied the effects of microtopography modifications on the soil erosion resistance and biodiversity of a large mine dump in a semi-arid region. Our findings can serve as a reference for methodological support and production practices. The major conclusions of our study are explained below.

Soil erosion resistance and the biodiversity index under single or combined microtopography modifications, along with vegetation measures, on the slopes of the investigated large mine dump in a semi-arid region, were greater than those under soil cover and vegetation only. The combination of microtopography modifications and vegetation measures may prevented the slippage and separation of surface soil from the slope, creating a safe and stable micro-environment for plant growth. Thus, our study showed that a combination of microtopography modification measures and vegetation planting is effective at improving soil erosion and vegetation restoration along the slopes of large mine dumps.

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.

References

Author contributions

Conception: XT and JW. Analysis and interpretation of data: XT. Drafting of the manuscript: XT, RY, JW, LD, BC, HL, and NG.

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.

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