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Impact of Mining Area Steep Slope Conditions on the Soil and Water Conservation Benefits of Ecological Restoration

Xiaofeng Zhao [1], Haibo Li [2], Peng Li [3,*], Yajun Chen [1], Qian Dai [2], Peng Shi [3], Xin Li [1], Yonglong Qu [4] and Jianye Ma [3,*]

[1] China Nonferrous Metal Industry Xi'an Survey and Design Institute Co., Ltd., Xi'an 710000, China; 2230420414@stu.xaut.edu.cn (X.Z.); zzy_pap@163.com (Y.C.)
[2] Luanchuan County Longyu Molybdenum Industry Co., Ltd., Luoyang 471500, China; 18829036386@163.com (H.L.)
[3] State Key Laboratory of Eco-Hydraulics in Northwest Arid Region of China, Xi'an University of Technology, Xi'an 710048, China
[4] School of Architectural Engineering, Xi'an Technological University, Xi'an 710021, China; quyl2018@163.com
* Correspondence: lipeng74@163.com (P.L.); majianye126@126.com (J.M.)

Abstract: Steep slopes, characterized by their high gradient and limited soil and water resources, pose significant challenges to plant colonization. Consequently, the ecological restoration of steep slopes is one of the major challenges in the field of mine site rehabilitation. This study evaluated the impact of slope conditions on the restoration effectiveness during the early stages of ecological restoration. Two ecological restoration slopes with different slope conditions, excavated slope and filled slope, were selected, and restored by hanging net and soil spraying measures. The unrepaired slope was used as the control. The results showed that ecological restoration has a significant effect for soil and water conservation; runoff and sediment were reduced by 61.38% and 99.28%, respectively, and infiltration increased by 104.26%, compared to untreated slopes. Furthermore, ecological restoration could effectively reduce runoff erosion dynamics and soil erodibility, and alter the runoff–sediment relationship on slopes, thereby substantially influencing the yield processes of runoff and sediment of the slopes. Notably, the reduction effect of ecological restoration measures on runoff and sediment was more significant on excavated slopes than on filled slopes. The runoff and sediment yield of excavated slopes were 19.06% and 53.77% lower than that of filled slopes, respectively. From a soil and water conservation perspective, the ecological restoration measures of hanging net and soil spraying were more suitable for application to steep excavated rock slopes. However, further research is needed to evaluate its applicability to filled slopes.

Keywords: soil and water conservation; excavated slopes; filled slopes; mining area

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1. Introduction

With the acceleration of industrialization, the demand for mineral resources by human society has soared dramatically [1]. This surge has led to an increase in opencast mining activities, resulting in the creation of numerous exposed and unstable slope areas with severely degraded biodiversity. These slope areas exert significant negative impacts on the environment [2,3]. If not effectively managed, these slopes could trigger a series of hazards, including heavy metal contamination of water bodies, soil erosion, and slope instability, ultimately leading to long-term degradation of ecosystem functions [4,5]. Consequently, the effective rehabilitation of these slopes has emerged as a focal point in the global field of ecological restoration.

Slope ecological restoration refers to a technique for restoring degraded environments to their natural state or adapting them to new conditions [6]. Over years of practice, the ecological restoration technology system has gradually improved. A series of techniques has been developed, such as hanging net and soil spraying [7], green vegetation strips [8], and vegetation mats [9]. In particular, the hanging net and soil spraying technique has been widely applied in practice [10]. This technique involves protecting the slope surface with a wire mesh, then spraying improved soil and seeds onto it, creating favorable conditions for plant growth, and thus achieving the purpose of ecological restoration. Wang et al. [11] found that one year after applying the soil spraying technique to rocky cut slopes, vegetation coverage could be maintained above 88%, and soil retention above 68.6%, indicating a significant restoration effect. However, due to the steep slope, poor water retention, and weak soil and vegetation adhesion capabilities, the ecological restoration of such slopes still faces considerable challenges [12].

For the ecological restoration of high and steep rocky slopes, the primary objective is to mitigate potential geological hazards and establish a stable slope structure. On this foundation, soil conditions conducive to vegetation growth are developed, supplemented by soil and water conservation measures. A multi-species vegetation allocation approach is then employed to restore vegetation. Consequently, slope stability and ecosystem stability are two critical challenges that must be addressed during the restoration process [5]. To enhance slope stability, commonly used techniques include slope cutting, structural reinforcement, and wire mesh protection. However, vegetation restoration on rocky slopes is hindered by challenges such as poor availability of water and soil resources, as well as low soil fertility. If the selected plant species fail to adapt to the local environment and the unique conditions of high and steep slopes, secondary ecosystem degradation may occur, ultimately leading to restoration failure [13]. Key components of ecological restoration include the formulation of the spraying matrix, plant species selection, and vegetation configuration. The hanging net and soil spraying technique, which accounts for factors such as slope stability, soil matrix composition, and seed adhesion, has become widely adopted for the ecological restoration of steep slopes. However, the application of this technique is subject to certain constraints. For rocky slopes with gradients of 40–60° and surface roughness of 5–10 cm, hanging net and soil spraying is an effective restoration method. In contrast, for slopes with gradients $\geq 60°$ and surface roughness < 5 cm, this technique proves unsuitable [14].

As described by Wang et al. [15], the effect of vegetation on restoration effectiveness was stronger than other factors such as the soil matrix in the ecological restoration systems. And with increasing years of restoration, the role of vegetation in enhancing slope stability, conserving water resources, and reducing soil and water loss becomes more pronounced [16–18]. Consequently, current research on ecological restoration primarily focused on plant species selection and vegetation configuration optimization [19,20]. Furthermore, soil and water conservation capacity is a commonly used indicator to measure the effectiveness of ecological restoration. Selecting appropriate vegetation patterns based on their effectiveness in soil and water conservation has become a common strategy [21,22]. For instance, Yang et al. [22] determined that "*Agropyron cristatum* + *Artemisia desertorum*" is a preferred vegetation configuration for spoil heap slopes, based on sediment reduction benefits.

Mining areas encompass a spectrum of slope types, including earthen, rocky, filled, and excavated slopes. There are great differences in slope, soil physical structure, and stability for different slope types [23]. These variations exert a significant influence on the efficacy of ecological restoration measures, impacting the overall effectiveness of restoration within mining areas. Shen et al. [23] have demonstrated that a specific restoration measure can achieve a score of 10.00 on soil slopes, but only 5.36 on rocky slopes. Zhang et al. [24]

have indicated that soil spraying is more effective for slope restoration in plains and gently rolling hills compared to mountainous regions. The mining process involves extensive excavation and filling operations, resulting in the formation of numerous excavation and embankment slopes. These two slope types are expected to respond differently to ecological restoration efforts, due to their distinct slope conditions.

Ecological restoration is effective in preventing soil and water loss on steep slope. However, the full potential of vegetation in the early stages of ecological restoration remains underexplored. During this phase, the absence of adequate protective measures results in a heightened risk of soil and water erosion. The integration of engineering slope protection and soil matrix improvement is critical to ensuring the long-term success of ecological restoration. But, the research on soil and water conservation benefits during the initial stages of ecological restoration remains notably limited. Furthermore, most current research focuses on evaluating the suitability of vegetation for ecological restoration, leaving a critical knowledge gap in understanding how varying slope conditions influence restoration outcomes. Addressing this gap is essential for developing targeted and effective restoration strategies in mining environments.

The specific objectives are: (1) to quantify the benefits of ecological restoration on slope runoff and sediment reduction during the initial restoration stages, (2) to evaluate the effects of excavated slopes and filled slopes on the effectiveness of ecological restoration efforts. In the process of evaluating the soil and water conservation benefits of netting and soil spraying measures during the early stages of ecological restoration, both types of slopes in open-pit mining areas, namely excavated slopes and filled slopes, were selected. Through the discharge of water scouring experiment in the selected slope, we explored the effect of soil and water conservation from the ecological restoration measure of netting and soil spraying under different slope conditions. The results provide an important scientific basis for the selection of ecological restoration strategies for steep slopes in mining areas, and a deeper understanding of soil and water loss processes under complex substrate conditions.

2. Materials and Methods

2.1. Study Area

The study was conducted at the Nannihu molybdenum mine (111°29′36″ E, 33°54′36″ N), located in Luanchuan County, Henan Province, China, at an average elevation of 1377 m. The site experiences a semi-arid continental climate with monsoonal influences, characterized by an average annual temperature of 12.2 °C. The average annual precipitation is 809.6 mm, predominantly occurring during the summer months. The soil is sandy loam, composed of 54% sand, 46.6% silt, and 1.0% clay.

The Nannihu molybdenum mine, a large-scale open-pit operation in use since 2008, has generated extensive excavation and filling slopes. In May 2024, ecological restoration works has commenced on some slopes. In the process of ecological restoration, the slope was firstly levelled, then a lead wire mesh was laid to ensure the stability of the slope (Figure 1a). The aggregate soil containing water-retaining agents, adhesives, fertilizers, and plant seeds was sprayed on the slope approximately 10 cm thick. Then, a plant blanket was laid on the upper layer (Figure 1b) to prevent the slope from being washed by water.

Figure 1. Schematic diagram of lead wire mesh and plant blanket. (**a**) Lead wire mesh, (**b**) plant blanket.

2.2. Experimental Design

Two slopes, located on either side of an excavation road within the mining area, were selected for analysis: one excavated rock slope (R1, Figure 2c) and one filled slope (R2, Figure 2b), both of which had undergone ecological restoration in 2024. By the time the experiment commenced in August 2024, the average restoration period for these slopes was 45 days. Additionally, an unrestored fill slope (W, Figure 2a) was chosen as a control. Two runoff plots (length and width of 200 cm and 50 cm) were established on each slope, for a total of 6 plots across the three slopes. To simulate the early-stage conditions of ecological restoration, plots were located in sparsely vegetated areas with sparse vegetation cover (less than 10% canopy cover) on the restored slopes. Basic information for each slope is provided in Table 1.

Figure 2. Schematic diagram of runoff plot. (**a**) Unrepaired slope plot, (**b**) repaired filled slope plot, (**c**) repaired excavated slope plot, (**d**) erosion process.

Table 1. Basic information of sample site.

ID	Condition	Type	Slope Characteristic	Slope (°)	Moisture Content (%)	Coverage (%)	Plant Species
W	Filled slope	Unrepaired	Stock + soil	32	11.76	0	—
R1	Excavated slope	Repaired	Stone	40	27.00	7	*Cosmos bipinnatus*, *Medicago sativa*, *Lolium perenne*
R2	Filled slope	Repaired	Stock + soil	30	24.00	9	*Cosmos bipinnatus*, *Medicago sativa*, *Lolium perenne*

The primary soil type of the three selected slopes was classified as sandy loam. For the W and R2 slopes, the slope is mainly formed by the concentrated stacking of the excavated soil and rock mixture, resulting in slope characteristics of “soil + rock”. In contrast, the R slope is a rocky slope formed by excavation, with an underlying surface predominantly consisting of exposed rock. To mitigate the potential bias arising from varying slope gradients on the test outcomes, the gradient of the three slopes was kept relatively similar.

Specifically, the gradients of the W, R1, and R2 slopes are 32°, 40°, and 30°, respectively. Vegetation coverage across the three types of plots was measured using photogrammetry. Since the R1 and R2 slopes were in the early stages of ecological restoration, their vegetation coverages remained low, at 7% and 9%, respectively, with similar levels of coverage. The untreated slope, having undergone no ecological restoration measures, exhibited vegetation coverage approaching 0.

Both ecologically restored slopes featured similar plant species, predominantly *Cosmos bipinnatus*, *Medicago sativa*, and *Lolium perenne*. As the test was conducted on the same day, the influence of meteorological and soil moisture conditions on the results was minimal.

Based on local rainfall data and the drainage area of the mining site, the simulated erosion flow rate was set at 208 mL·s^{-1}, with an erosion duration of 9 min. During the experiment, the runoff–sediment mixture samples were collected manually, every minute for 20 s, using plastic buckets placed at the lower end of the plots. The collected samples were weighed using an electronic balance to determine their mass, and sediment mass was subsequently calculated by drying the samples at 105 °C for 24 h. Runoff volumes were then estimated by utilizing both the mass measurements of the runoff–sediment mixture and the sediment samples.

The formula for calculating cumulative runoff and cumulative sediment volume is as follows:

$$S_{total} = \sum_i \frac{m_{si}}{\Delta t} \times T \times 10^{-3} \quad (1)$$

$$Q_{total} = \sum_i \frac{m_{0i} - m_{si}}{\rho \Delta t} \times T \times 10^{-3} \quad (2)$$

where S_{total} is the total sediment mass (kg), Q_{total} is the total runoff volume (L), m_{0i} is the mass of runoff–sediment (g) taken within the Δt (s) time of the i minute, m_{si} is the mass of sediment (g) taken within the Δt (s) time of the i minute, T is the sampling interval (T = 60 s), and ρ is the water density (g·cm^3).

Flow velocity was measured using the potassium permanganate ($KMnO_4$) tracing method. A 100 cm section in the middle of the slope was selected for measurement, which was further divided into three regions: left, middle, and right. The average flow velocity of these three regions was used to represent the mean flow velocity of the plot. The interval for measuring flow velocity was consistent with that for collecting runoff and sediment samples.

The hydrodynamic characteristics were characterized by four parameters, namely shear stress, stream power [25], unit runoff energy, and total runoff energy [26]. These parameters were calculated using the following formulas

$$H = \sum_i \frac{q_i \Delta t}{A} \quad (3)$$

$$\tau = \rho g H J \quad (4)$$

$$\omega = \tau v \quad (5)$$

$$E = q_p H \quad (6)$$

$$SE = \rho_{\mathrm{m}} g q_p H J \quad (7)$$

where τ is the flow shear force (Pa), ω is the stream power (W·m^{-2}), E is the unit runoff energy (m^4·s^{-1}), SE is the total runoff energy (W), H is the average runoff depth (m), q_i is the discharge in the i minute (m^3·s^{-1}), and q_p is the maximum discharge of an event (m^3·s^{-1}). A is the area of the runoff plot (m^2), g is the acceleration of gravity (m·s^{-2}), J is the hydraulic slope (m·m^{-1}), which can be approximately replaced by the sine value of the slope, v is the average velocity (m·s^{-1}), and ρ_m is the density of muddy water.

2.3. Data Analysis

Statistical analysis was performed in Excel 2010 software, and figure generation was performed in Origin 2021. One-way analysis of variance (ANOVA) was conducted in SPSS 19.0, to evaluate the difference of runoff and sediment at different scouring periods.

3. Results

3.1. Cumulative Runoff, Sediment, and Infiltration

The cumulative runoff for the unrepaired slope (W), repaired filled slope (R1), and repaired excavated slope (R2) were 104.37 L, 36.06 L, and 44.56 L, respectively. Compared to the W slope, the runoff for the repaired slopes R1 and R2 decreased by 65.45% and 57.31%, respectively, with an average reduction of 61.38%.

The cumulative sediment yield for the W, R1, and R2 were 3.93 kg, 0.02 kg, and 0.04 kg, respectively. Compared to the W slope, the sediment yields for the R1 and R2 slopes were lower by 99.54% and 99.01%, respectively, with a mean reduction of 99.28% (Figure 3a).

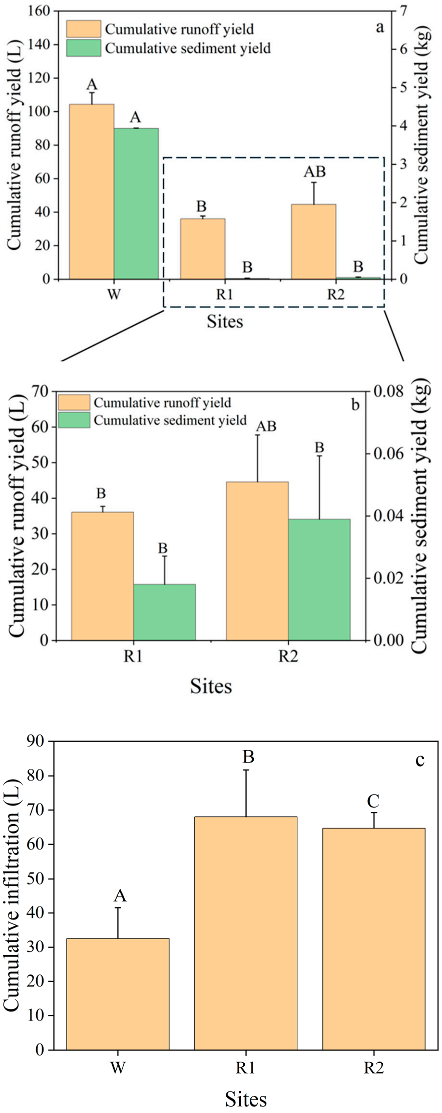

Figure 3. Cumulative runoff, sediment, and infiltration of different slopes. W: unrepaired slope, R1: repaired excavated slope, R2: repaired filled slope. (**a**) Cumulative runoff and sediment production of different slopes, (**b**) cumulative runoff and sediment production of R1 and R2 slope, (**c**) cumulative infiltration of different slopes. Different capital letters indicate significant differences between different slopes ($p < 0.05$).

The cumulative infiltration for the W, R1, and R2 were 32.51 L, 68.07 L, and 64.75 L, respectively. Compared to the W slope, the infiltration for the R1 and R2 slopes increased by 109.36% and 99.15%, respectively, with a mean increase of 104.26% (Figure 3c).

Compared to R2, R1 exhibited 19.06% less cumulative runoff and 53.77% lower cumulative sediment yield, with a 5.13% increase in cumulative infiltration (Figure 3b). These results demonstrate that the ecological restoration measure of hanging net soil spraying on excavated rock slopes offers superior soil and water conservation benefits in the early stage.

The results indicated that ecological restoration is effective in reducing runoff and sediment loss, as well as enhancing soil water retention, compared to the unrestored slopes.

3.2. Hydrodynamic Characteristics

The shear stress (τ) for slope W was 7.01 Pa. For slopes R1 and R2, τ decreased by 47.60% and 41.98%, respectively, compared to W, with a mean reduction of 44.79% (Figure 4a). The stream power (ω) for slope W was 2.05 W·m^{-2}, while for slopes R1 and R2, ω decreased by 59.05% and 54.94%, respectively, resulting in an average reduction of 56.99%. The unit runoff energy (E) for slope W was 0.33×10^4 W·m^{-2}, and for slopes R1 and R2, E decreased by 90.16% and 85.48%, respectively, with an average reduction of 87.82%. The total runoff energy (SE) for slope W was 0.90 W, while for slopes R1 and R2, SE decreased by 88.34% and 84.67%, respectively, with a mean reduction of 86.51% (Figure 4b). Compared to R2, the τ, ω, E, and SE for slope R1 were reduced by 43.61%, 9.12%, 32.25%, and 23.94%, respectively.

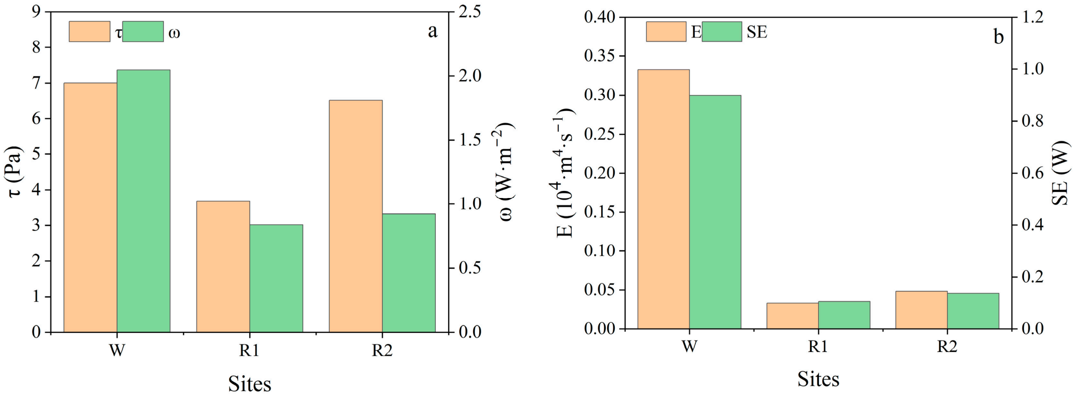

Figure 4. Hydrodynamic characteristics of different slopes. W: unrepaired slope, R1: repaired excavated slope, R2: repaired filled slope. (**a**) Shear force (τ) and stream power (ω) of different slopes, (**b**) unit runoff energy (E) and total runoff energy (SE) of different slopes.

Shear stress, stream power, unit runoff energy, and total runoff energy analyses indicate that ecological restoration effectively reduces slope hydrodynamic forces, with the most pronounced reduction observed on excavated rock slopes.

3.3. Runoff and Sediment Processes

In the runoff process (Figure 5a), runoff gradually decreased over time, particularly after 6 min, with a significant difference compared to the runoff before 6 min ($p < 0.05$). However, the runoff process for the restored slopes differed from that of the W slope, initially increasing and then decreasing with time, reaching its peak at 5 min. The primary difference between W and the restored slopes (R1 and R2) occurred within the first 0–6 min, with minimal variation after 6 min. At all stages, the runoff for the R2 slope was higher than that of R1.

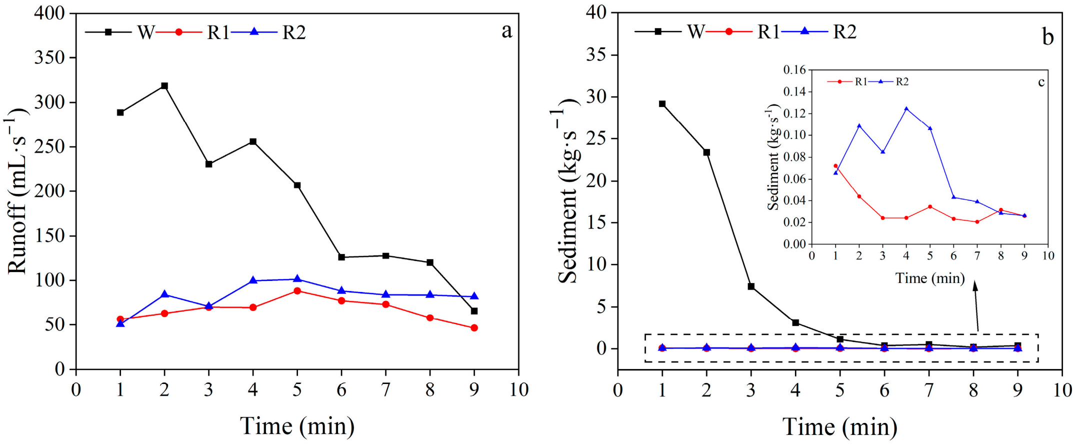

Figure 5. Runoff and sediment production processes on different slopes. W: unrepaired slope, R1: repaired excavated slope, R2: repaired filled slope. (**a**) Runoff process of different slopes, (**b**) sediment process of different slopes, (**c**) sediment process of repaired slopes.

In the sediment production process (Figure 5b), the sediment yield on the W slope initially decreased and then stabilized with time, particularly after 6 min, with a significant difference compared to the sediment yield before 6 min ($p < 0.05$). The differences between W and the restored slopes (R1 and R2) were primarily concentrated in the first 0–6 min, with minimal variation after 6 min. On the R1 slope, sediment yield decreased initially and then stabilized, whereas on the R2 slope, sediment yield increased first and then decreased. The main difference between R1 and R2 slopes occurred during the 0–6 min period. In summary, the differences in runoff and sediment yield across different slopes were most pronounced during the first 0–6 min.

3.4. Relationship of Runoff and Sediment

The slope of the linear relationship between runoff and sediment can serve as an indicator of soil erodibility [27,28]. Based on this principle, linear regression analysis of slope W (R^2 = 0.56) yielded an erodibility parameter of 0.0998 g·mL^{-1} (Figure 6a).

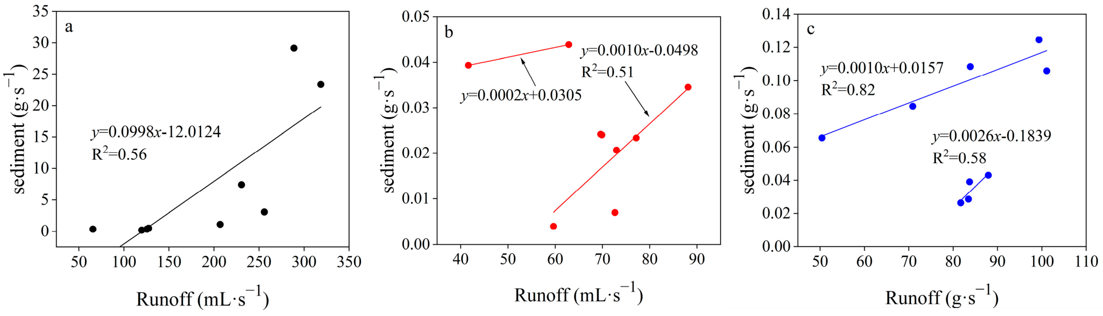

Figure 6. Relationship between runoff and sediment on different slopes. (**a**) Unrepaired slope (W), (**b**) repaired excavated slope (R1), (**c**) repaired filled slope (R2).

For the R1 slope, the correlation between runoff and sediment was weaker, primarily due to changes in the runoff–sediment relationship between the 0–2 min and 3–9 min intervals. The erodibility parameters for these intervals were 0.002 g·mL^{-1} and 0.0010 g·mL^{-1}, respectively, with a mean value of 0.0006 g·mL^{-1}. Similarly, for the R2 slope, changes in the runoff–sediment relationship were observed between 0–5 min and 6–10 min, yielding erodibility parameters of 0.0010 g·mL^{-1} and 0.0026 g·mL^{-1}, with a mean value of 0.0018 g·mL^{-1}.

In summary, ecological restoration altered the runoff–sediment relationship compared to the unrestored slope, reducing soil erodibility by 98.80%. Additionally, the excavated slope showed a more pronounced variability in the runoff–sediment relationship compared to the filled slope following ecological restoration.

4. Discussion

4.1. Effects of Ecological Restoration on Runoff and Sediment

Compared to the unrepaired slope, the ecologically restored slopes exhibited significantly lower runoff and sediment yields, consistent with findings from previous studies [29,30]. Li et al. [7] further reported that spraying techniques can reduce sediment yields of rocky slopes by over 90%. In this study, in addition to netting and soil spraying, a plant blanket was applied to the surface of the slope (Figure 1b).

The use of hanging nets enhances shear resistance on steep and high slopes, significantly improving slope stability and creating favorable conditions for plant growth [31]. Soil spraying materials typically contain water-retaining agents and adhesives. The adhesives bond soil particles to each other and to the slope surface, enhancing the erosion resistance of the slope soil. Meanwhile, water-retaining agents significantly increase the soil's water retention capacity and reduce runoff [32]. Planting blankets adhere to the soil surface, forming numerous micro-depressions that trap runoff and sediment. Additionally, they increase surface roughness, reduce runoff velocity and erosion energy, enhance infiltration [28], and decrease soil detachment [33]. Furthermore, planting blankets help maintain soil temperature and moisture, improve soil fertility and erosion resistance (Figure 5), and prevent seed washout, thereby facilitating vegetation recovery [34].

After vegetation recovery on the slope, plant roots provide significant reinforcement. Compared to bare soil, roots increase soil shear strength by 2.5% to 139.4% [35], leading to a 41.69% to 99.00% reduction in soil detachment [36]. Additionally, plant roots enhance infiltration and water retention capacity [21], thereby reducing runoff and helping to retain moisture. The ecological restoration in this study involved a combination of hanging nets, soil spraying, planting blankets, and vegetation recovery (Figure 7), providing effective slope protection. As a result, runoff was reduced by 61.38%, and sediment yield decreased by 99.28%.

Figure 7. Composition of ecological restoration measures. (**a**) Hanging nets, (**b**) planting blankets, (**c**) vegetation recovery.

Continuous monitoring has demonstrated that the ecological restoration measures have yielded positive results. Compared to the 45-day restoration plot, the 76-day restoration plot exhibited superior vegetation growth (Figure 8). Further monitoring will continue to assess the vegetation growth and soil and water conservation effectiveness, with the aim of evaluating the long-term sustainability and stability of these restoration measures. In the plot restored for 76 days, the main species were *Cosmos bipinnatus*, *Medicago sativa*, and *Lolium perenne*. Therefore, these three plants can serve as long-term monitoring candidates, to evaluate the effects of vegetation and the sustainability of restoration.

Figure 8. Plots of different ecological restoration periods. (**a**) Restored 45 d, (**b**) restored 76 d.

Compared to filled slopes, excavated rocky slopes exhibit lower runoff and sediment yields during the early stages of ecological restoration. This can be attributed to the presence of numerous fissures in the rock slopes (Figure 9), which facilitate water loss through the matrix soil layer during ecological restoration. Consequently, runoff volumes are lower on rocky slopes, which in turn reduces the erosion energy and leads to decreased sediment production.

Figure 9. Fissures in rock slopes.

For the unrepaired slope (W), runoff decreased with increasing scouring time, which is consistent with the runoff pattern observed by Liu et al. [37] on a restored 2a spoil heap slope. This slope is a fill slope predominantly composed of a mixture of soil and gravel, with numerous pores between the gravel and soil [38]. The soil cannot become saturated in a short time, leading to a continuous loss of runoff and a decreasing runoff trend over time.

In contrast, for the ecologically restored slopes (R1, R2), the runoff initially increased, followed by a subsequent decline. In the early stages of erosion, as the substrate soil layer gradually saturated, surface runoff increased, which aligns with the findings of several studies [28,39]. However, the ecologically restored slopes have a dual structure, with a surface layer of substrate soil and a lower layer of accumulated material or fractured rock. Once the infiltration exceeds the water-holding capacity of the matrix soil layer, water continues to percolate into the highly permeable lower layer. This process creates downward infiltration channels, increases infiltration volume, and reduces surface runoff. In the later stages, runoff tends to approach that of the unrepaired slope, indirectly confirming this hypothesis.

For the sediment yield process, it exhibits a trend of initially decreasing and then subsequently stabilizing with erosion time in the unrestored slope (W). This result aligning with the findings of Ma et al. [40] and Li et al. [7]. This behavior can be attributed to two main factors: first, the reduction in runoff during the later stages of erosion diminishes the erosion energy; second, the depletion of readily erodible materials at later stages weakens the sediment response to runoff. Under the combined influence of these two factors, sediment yield in the later stages of erosion remains low and relatively stable.

For the filled slope (R2), its sediment yield process is consistent with the runoff trend, showing an initial increase followed by a decrease. Notably, the sediment peak occurs earlier than the runoff peak, indicating that a substantial portion of soil particles is detached and transported before the runoff reaches its maximum. Despite increasing runoff, sediment production declines sharply thereafter. For the excavated slope (R1), the sediment yield demonstrates a trend of initially decreasing and then stabilizing over time, consistent with the conclusions drawn by Lu et al. [41] on spoil heap slopes. In the early erosion phase, although runoff is minimal, the presence of loose material on the slope provides an abundant source of sediment, leading to higher sediment production. Additionally, the R1 slope, located on a shaded aspect, exhibits higher soil moisture content (Table 1) and better soil cohesion, resulting in reduced erosion. These underlying surface conditions lead to a rapid stabilization of sediment production.

4.2. Effects of Ecological Restoration on the Relationship Between Runoff and Sediment

For the unrepaired slope (W), sediment production increased proportionally with runoff, consistent with findings from studies on bare slopes [27]. In the case of ecologically restored slopes, a unique pattern was exhibited during the initial stages of scouring, particularly within the first six minutes. During this period, a large amount of loose material present on the surface led to high sediment yields even under lower runoff conditions. This pattern aligns with that observed on unrestored slopes. However, during the later stages of erosion, most loose surface materials are detached away, and sediment yield primarily arises from the erosive force of runoff acting on the slope surface [40]. In these later stages, higher runoff correlates with greater erosion energy, enabling the detachment and transport of more material. Consequently, the differing underlying surface conditions between restored and unrestored slopes resulted in distinct runoff–sediment dynamics on the ecologically restored slopes.

For the excavated rock slope and the filled slope, the transition points in the runoff–sediment relationship occurred at 3 min and 6 min, respectively. However, there was no significant differences in the runoff dynamics over time between the two slopes. This suggests that variations in the underlying surface properties are the primary drivers of these differences. The relatively low erosion observed on the excavated rock slope indicates a scarcity of loose material on its surface, allowing the sediment production process to reach a stable phase more rapidly. In contrast, the higher erosion rate on the filled slope delays the stabilization of the sediment production process.

4.3. The Limitation and Significance of This Study

The development of slope ecological restoration in China began relatively late, and research on restoration technologies remains in the exploratory stage. A series of mature technologies, such as hanging net and soil spraying, vegetative belts, geogrid vegetative slope protection, and honeycomb grid vegetative slope protection, has formed. Among these, spraying techniques are widely applied due to their excellent restoration effect, simple construction, and cost-effectiveness [20]. Notably, advancements such as reinforced macromat, eco-substrate, and high-bonded particle spraying techniques [42] have significantly improved the effectiveness of slope ecological restoration. However, current ecological restoration technologies face numerous challenges when applied to steep rocky slopes. It is mainly reflected in serious soil erosion, low vegetation survival rate, and inability to form a self-stable ecosystem with a single vegetation structure [5]. Therefore, investigating the application of a combined hanging net and soil spraying technique on rocky slopes provides valuable guidance for the restoration of steep rocky slopes.

This study primarily examines the influence of slope conditions on the effectiveness of ecological restoration under specific flow, slope, and restoration measures, providing valuable guidance for the selection of site-specific restoration strategies. However, runoff and sediment yield on slopes are also influenced by slope and vegetation types. For example, Cui et al. [43] demonstrated that the vegetation types most effective for soil and water conservation vary between steep and gentle slopes.

In this study, the objective was to evaluate the effects of slope condition on ecological restoration outcomes. To ensure comparability, restoration timelines, slope angles, and soil types were kept consistent across the selected sites. However, other slope types exist within the mining area, such as more steeply excavated rock slopes (slopes more than 70°), where similar ecological restoration measures have been applied. Future studies will focus on these slopes to assess the impact of slope gradient on the effectiveness of ecological restoration.

The ecological restoration measures applied in this study primarily involved netting and soil spraying. The efficiency of soil and water conservation is also significantly influenced by the type of restoration measures employed [44]. Additionally, varying rainfall intensities drive distinct erosion dynamics. In general, higher rainfall intensities result in increased soil and water loss on slopes [45], raising the question of whether soil and water conservation effects diminish under extreme rainfall conditions. These issues merit further investigation.

Moreover, this study focused on the soil and water conservation effects during the early stages of ecological restoration. As restoration progresses, the erosion reduction effects of vegetation are expected to intensify, further shaping the outcomes of ecological restoration [39]. In the future, the effects at different stages of restoration would be examined. Meanwhile, several models can be employed to analyze the long-term effects of ecological restoration. For example, the WEPP model can assess the potential reduction in soil erosion, while the MIKE model can analyze changes in erosion dynamics. The SCS-CN method is useful for simulating runoff processes, and the InVEST model can evaluate the ecological outcomes.

The findings of this study provide valuable insights for guiding ecological restoration efforts across different slope conditions. The netting and soil spraying method is simple and cost-effective, and particularly effective for the restoration of excavated rock slopes, making it well-suited for such conditions. However, for filled slopes, due to differences in slope characteristics, the effectiveness of this method is lower compared to excavated slopes. Therefore, alternative, more suitable restoration measures should be explored for this slope type.

5. Conclusions

This study demonstrated that ecological restoration measures significantly reduced runoff and sediment by 61.38% and 99.28%, respectively. Ecological restoration increased soil infiltration by 104.26%, which is likely the primary factor contributing to the reduction in runoff. and the soil erodibility and runoff erosion energy decreased by 98.80% and 86.51 %, respectively, which might be the primary factor contributing to the reduction in sediment.

Ecological restoration also altered the relationship between runoff and sediment on the slopes. Over time, runoff on the unrestored slope gradually decreased, while sediment yield initially declined before stabilizing. On the restored slopes, runoff exhibited an initial increase followed by a decrease, with sediment yield varying according to specific slope conditions.

Slope conditions also influence the effectiveness of ecological restoration. Compared to the filled slope, the excavated rocky slope exhibited lower runoff erosion energy and sediment yield after ecological restoration. Furthermore, the runoff–sediment relationship on the excavated slope was more responsive to changes, resulting in reduced runoff and sediment yields in the later stages.

From the perspective of soil and water conservation, ecological restoration, of netting and soil spraying, proves to be an effective measure for high and steep excavated rocky slopes. The suitability of this approach for filled slopes requires further investigation. However, this study focused exclusively on the early stage of ecological restoration when vegetation effects were minimal. Future research will explore the impact of different restoration stages on the soil and water conservation benefits of slopes.

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Conflicts of Interest: Authors Xiaofeng Zhao, Xin Li and Yajun Chen were employed by the company China Nonferrous Metal Industry Xi'an Survey and Design Institute Co., Ltd. Author Haibo Li and Qian Dai were employed by the company Luanchuan County Longyu Molybdenum Industry Co., Ltd. All authors declare no conflicts of interest.

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