

Article

Soil Substrate Characteristics for Planting Hole Greening Technology for High, Steep, Rocky Slope Vegetation in Semi-Arid Areas

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Abstract: Soil substrate plays a central role in the vegetation restoration of high and steep slopes, especially in semi-arid regions. This study aims to develop an optimal soil substrate that can provide a favorable environment for the vegetation growth of the high and steep rocky slopes in semi-arid areas. Within the framework of planting hole greening technology, we developed a synthetic substrate comprising base soil, peat, water-retaining and agglomerating agents, biochar, and controlled-release compound fertilizer. We conducted pot experiments to assess the impact of compound additions on soil properties and *Parthenocissus himalayana* growth. Field tests on exposed, high, and steep rocky slopes in a semi-arid region validated the optimal ratio of substrate components. The results showed that the base soil-to-peat ratio significantly influenced soil density, moisture, pH, organic matter, nitrogen content, and vegetation growth ($P_s < 0.05$). The controlled-release compound fertilizer significantly affected soil electrical conductivity and alkali-hydrolyzable nitrogen content ($P_s < 0.05$). Meanwhile, the water-retaining agent, biochar, and agglomerating agent had inconsequential effects on soil characteristics and plant growth. The optimal substrate composition included a 7:3 ratio of base soil to peat, 1.5 g/L of water retainer, 10 mg/L of agglomerating agent, 5 g/L of biochar, and 5 g/L of controlled-release compound fertilizer. The field verification showed that the developed optimal substrate possessed desirable pore structure, moisture, and nutrients, resulting in excellent growth of *Parthenocissus himalayana*. This optimal soil substrate could be suitable for establishing vegetation on high, steep, rocky slopes in semi-arid areas using planting hole greening technology.



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1. Introduction

Engineering construction and resource development activities, including the building of roads, hydropower facilities, and open-pit mining, have led to the formation of a large number of exposed rocky slopes [1]. These slopes can pose ecological and geo-environmental challenges, including landscape fragmentation, collapse, landslides, and debris flows [2–5]. Although traditional engineering protection methods such as dry masonry and spray anchor support initially provide effective protection, they tend to weaken over time. In contrast, revegetation technology offers a cost-effective solution for stabilizing slopes and enhancing the ecological environment, which is achieved by steadily improving slope strength through root system development [6–8]. Consequently, revegetation technologies have gained widespread acceptance for restoring rocky slopes.

Some high and steep rocky slopes in semi-arid regions, characterized by steep gradients exceeding 75° and heights exceeding 30 m, face specific challenges. These include limited precipitation with uneven seasonal distribution, poor soil consolidation, low water

and nutrient retention capacity, and harsh summer conditions with scorching and evaporation, making them susceptible to drought and poor nutrient replenishment. Modifying these slope surfaces is a well-recognized challenge in the ecological restoration of rocky slopes [9,10]. Currently, the most commonly used greening technology for rocky slopes is net spraying, which forms a continuous soil layer approximately 10 cm thick on the slope surface. It offers advantages such as high mechanization, efficiency, and rapid revegetation; however, it is generally only suitable for slopes with gradients less than 75° . Moreover, the thickness of the resulting soil substrate is limited and, under the influence of drought or heavy rainfall scouring, dislodgement and nutrient loss can be serious, resulting in poor long-term vegetation restoration success. Notably, these limitations are particularly pronounced for semi-arid slopes with steep gradients $>75^\circ$ [11–13]. As an alternative approach, planting hole greening technology involves drilling holes into rocky slope surfaces, filling them with soil, and then planting seedlings in the holes. This method has the potential to address soil substrate retention challenges and is suitable for revegetating steep and vertical slopes.

Although planting hole greening technology is a type of revegetation technology applicable to steep rocky slopes, it faces practical challenges, including moisture and nutrient deficiencies and high-temperature scorching during summer, which can limit plant survival and hinder the greening effect. In semi-arid areas, unfavorable ecological conditions, such as low moisture and nutrients, further diminish the effectiveness of this technology [14,15]. Inappropriate soil substrates may exacerbate moisture and nutrient deficiencies and lead to poor adaptability to such harsh climates. Therefore, determining the most appropriate soil substrate composition is critical for the development of planting hole greening technology.

Current research on soil substrates for rocky slope revegetation is mainly focused on spraying the soil substrate [16–19], whereas research on soil substrates for planting hole greening technology is limited. Yuan et al. [20] used loamy soil, organic matter, and composite fertilizer to create soil substrates for planting holes, applying them in plant reestablishment on high, steep slopes in the Xiaguan Mining Area of Fushan District, Yantai City, Shandong Province, China. Shao et al. [21] employed a planting hole mixture with a mass ratio of 88.2% loam, 11.2% organic fertilizer, 0.5% compound fertilizer, and 0.1% water-retention agent for vegetation establishment on steep rocky side slopes in Jinan City, Shandong Province, China. Wang [22] developed a soil substrate for planting holes with a loam-to-peat ratio (by volume) of 3:1, incorporating fertilizers for rocky slopes in Jiulonghu Park, Ningbo City, Zhejiang Province, China. However, despite these applications, soil substrates for planting holes are typically formulated based on engineering experience, with untested effects of each soil component on ecological potential, long-term performance, and adaptability. For instance, Wang et al. [14] used loess, peat, and controlled-release composite fertilizer as substrate components in planting hole revegetation of rocky slopes. They identified water deficit as the key limiting factor for plant growth during hot summers. However, their field tests only examined vegetation growth, without reporting long-term nutrient content, moisture levels, or temperature dynamics of the soil substrate. Furthermore, previous applications have primarily focused on rocky slopes in humid climatic regions, which may not be directly applicable to high, steep, rocky slopes in semi-arid areas. In these semi-arid regions, vegetation growth is constrained by factors such as moisture, temperature, and nutrient deficiencies.

Parthenocissus himalayana is a fast-growing climber with a high tolerance to drought and high temperature; it also grows well in infertile soils [22]. Therefore, to address the above-mentioned research gap, *P. himalayana* was used in our current study. The aims of our study were (1) to assess plant growth and the physicochemical properties of various soil substrates, (2) to optimize a soil substrate comprising five different components, and (3) to confirm the feasibility of this substrate's application in planting hole greening technology for restoring high, steep, rocky slopes in semi-arid regions.

2. Materials and Methods

2.1. Components of Synthetic Soil Substrates

In this study, we incorporated peat, a water-retaining agent, an agglomerating agent, biochar, and a controlled-release composite fertilizer into the subsoil (common powdered clay) to enhance soil substrate permeability, improve precipitation absorption efficiency, and enhance water and fertilizer retention.

2.1.1. Base Soil

The primary properties of the base soil derived from spoil grounds, which consisted of powdered clay, were as follows: bulk density of 1.3 to 1.4 g/cm³, organic matter content between 3% and 4%, and a pH of 8.44. Other soils with similar characteristics could serve as suitable subsoils. The selection of additional soil components depended on their eco-friendliness and cost-effectiveness.

2.1.2. Peat (Pt)

Peat is an organic mineral resource characterized by good aeration, strong water retention, high organic matter content, strong nutrient retention capacity, and small bulk weight, and it is widely used for soil improvement [23]. Peat (Klasmann-Deilmann China Co., Ltd., Shanghai, China) with a bulk density of approximately 200 g/L, a pH of 6.1, and an organic matter content of approximately 620 g/kg was used to improve the porosity and organic matter content of the soil substrates and reduce the pH of the common powdered clay soil.

2.1.3. Water-Retention Agents (WA)

Water-retention agents are synthetic polymers known for their remarkable super-absorbent and water-retaining capabilities, which hold significant application value in the ecological restoration of rocky slopes [24]. Numerous successful vegetation restorations on rocky slopes have been achieved with the addition of water-retention agents [25]. We selected an acrylamide–potassium acrylate crosslinked copolymer-type water retainer produced by SNF(SNF (China) Flocculant Co., Ltd., Taixing, China), which combines the advantages of the stability of acrylamide and the high water absorption polyacrylates. This water retainer was incorporated as a vital component of the soil substrates.

2.1.4. Agglomerating Agents (AA)

Polyacrylamide is a general term used for homopolymers and copolymers of acrylamide and its derivatives. Of these, anionic linear polyacrylamide can increase the number of soil macroaggregates, improve permeability and erosion control ability, and is widely used in soil improvement owing to its long-molecular-chain structure and other characteristics [26]. Lentz et al. [27] found that the use of anionic linear polyacrylamide as a soil conditioner increased soil aggregates and reduced the generation of soil crust so that soils maintained good permeability. In the present study, anionic polyacrylamide(Nanjing Yuanling chemical Co., Ltd., Nanjing, China) with a molecular weight of 8 million linear polyacrylamide units was selected.

2.1.5. Biochar (Bc)

Biochar is a solid by-product resulting from the low-temperature thermal conversion of biomass under anaerobic or micro-oxygen conditions. It possesses notable attributes, including high organic carbon content, porosity, alkalinity, robust adsorption capacity, and extensive applicability in agriculture. When combined with slow- and/or controlled-release fertilizers, biochar plays a crucial role in retarding the release of water-soluble fertilizers in the soil, extending the nutrient validity period, and facilitating synchronized nutrient absorption by crops. Furthermore, biochar significantly curbs nutrient loss, enhances crop nutrient uptake, and boosts fertilizer utilization rates [28]. Despite its multiple benefits in agriculture, the utilization of biochar in slope revegetation has been seldom reported. Considering the stability and porosity of biochar, as well as its capacity to work in tandem

with controlled-release compound fertilizer to mitigate fertilizer loss, we included corn stalks biochar (Henan Lize Environmental Protection Technology Co., Ltd., Zhengzhou, China) as a component in the soil substrates tested for slope greening.

2.1.6. Controlled-Release Compound Fertilizers (CCFs)

Controlled-release compound fertilizers represent an innovative approach that regulates nutrient release rates to align with crop growth and development needs. These compounds offer rapid nutrient supply during early plant growth stages while delivering long-lasting fertilization effects. They play a pivotal role in significantly reducing nutrient loss and enhancing fertilizer efficiency [29]. Controlled-release compound fertilizers have garnered considerable attention in fertilizer innovation and have been applied in agricultural soils since the 1980s. For seedling container cultivation, Osmocote, a widely used fertilizer (The Scotts Company, Marysville, OH, USA), was selected as a representative membrane compound fertilizer. It features an N:P:K ratio of 16:8:12 and provides effective fertilization for 8–9 months. The outer particles of Osmocote are coated with a semipermeable film, enabling soil water to gradually pass through. Consequently, the fertilizer inside absorbs the water and generates pressure, facilitating the gradual release of nutrients.

Leveraging the beneficial physicochemical properties of peat and the selected water-retaining agents, agglomerating agents, biochar, and controlled-release compound fertilizer, the aim of this study was to develop and assess soil substrates tailored for high, steep, rocky slopes. This endeavor involved optimizing the component ratios based on experimental findings.

2.2. Laboratory Experiments

2.2.1. Orthogonal Experimental Design

Applying an orthogonal experimental design focusing on the characteristics of each component of the soil substrate, an experiment was established with five treatment factors (base soil and peat, water-retention agent, agglomerating agent, biochar, and controlled-release composite fertilizer), each with four levels, as shown in Table 1; the base soil was used as the control treatment (CK). The composition of each of the tested soil substrates and the corresponding additive amounts of each component are shown in Table 2.

Table 1. Treatment levels used in the laboratory experiments.

Levels	Vsoil:Vpt (L/L)	WA (g/L)	AA (mg/L)	Bc (g/L)	CCF (g/L)
1	9:1	0.5	5	5	3
2	8:2	1	10	10	4
3	7:3	1.5	15	20	5
4	6:4	2	20	30	6

Table 2. Orthogonal study design.

Substrate No.	Orthogonal Design Substrates					Composition				
	Vsoil:Vpt (L/L)	WA (g/L)	AA (mg/L)	Bc (g/L)	CCF (g/L)	Vsoil:Vpt (L/L)	WA (g/L)	AA (mg/L)	Bc (g/L)	CCF (g/L)
1	1	1	1	1	1	9:1	0.5	5	5	3
2	1	2	2	2	2	9:1	1	10	10	4
3	1	3	3	3	3	9:1	1.5	15	20	5
4	1	4	4	4	4	9:1	2	20	30	6
5	2	1	2	3	4	8:2	0.5	10	20	6
6	2	2	1	4	3	8:2	1	5	30	5
7	2	3	4	1	2	8:2	1.5	20	5	4
8	2	4	3	2	1	8:2	2	15	10	3
9	3	1	3	4	2	7:3	0.5	15	30	4
10	3	2	4	3	1	7:3	1	20	20	3
11	3	3	1	2	4	7:3	1.5	5	10	6
12	3	4	2	1	3	7:3	2	10	5	5
13	4	1	4	2	3	6:4	0.5	20	10	5
14	4	2	3	1	4	6:4	1	15	5	6
15	4	3	2	4	1	6:4	1.5	10	30	3
16	4	4	1	3	2	6:4	2	5	20	4

Pt: peat, WA: water-retention agents, AA: agglomerating agents, Bc: biochar, CCF: controlled-release compound fertilizers.

2.2.2. Experimental Setup

The 2-year-old *Parthenocissus himalayana* cutting seedlings, which were chosen due to their almost uniform growth, were selected as the study plants. The various soil substrates were loaded into 3 L pots, each containing one *P. himalayana* plant, with three replicates for each substrate, as shown in Figure 1. The pots were initially saturated with water and subsequently monitored and rehydrated daily. The experiment commenced on 15 March 2022, and after two months, the number and length of vegetation branches were measured. Furthermore, the different soil substrates were placed in pots, watered, and maintained for 20 days. Subsequently, soil bulk density, saturated moisture, field capacity, and water loss ratio were determined. The moisture loss test involved using a 100 cm³ ring knife to obtain soil samples, which were soaked for 12 h to reach saturation and then left indoors to naturally dry. Moisture loss measurements were recorded every 2 days from 20 May to 9 June 2022 (temperature 27.2–28.3 °C, humidity 35–40%). The moisture loss ratio was calculated as the cumulative moisture loss divided by the total net moisture content of each sample.

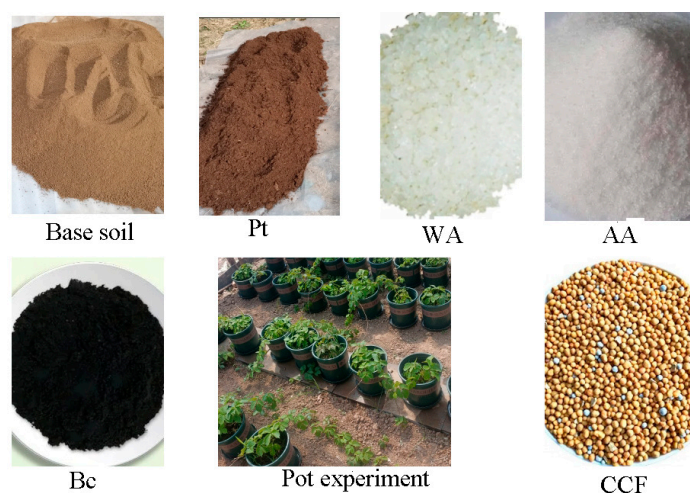


Figure 1. The graphs of laboratory experiment setup.

2.3. Field Test

2.3.1. Site Description

The study area used for field testing was located in Jiaozuo City, Northwest Henan Province, China, and had a continental warm-temperate semi-arid monsoon climate with four distinct seasons: moderate temperatures and a dry, windy spring; hot and rainy summers; warm days and cool nights in the fall; and cold and dry winters. The average temperature was 15.2 °C, the absolute maximum temperature was 43.2 °C, the absolute minimum temperature was −16.9 °C, the effective cumulative temperature was 4633 °C, the frost-free period was 231 d, and the average annual sunshine hours were 2484 h. According to data from the Jiaozuo Meteorological Station spanning from 1956 to 2010, this site has consistently received an average annual precipitation of around 580 mm; however, this precipitation is unevenly distributed throughout the year due to the influence of monsoon patterns. The majority of the precipitation, approximately 70% of the annual total, occurs between June and September. Within this period, July and August are the peak months, accounting for 45% of the annual total [30]. The field test was conducted on an exposed, steep, rocky slope, situated at the mining elevation of a cement plant, with a height of 40 m and a gradient of approximately 80°. Its predominant lithology was limestone and it exhibited relatively stable overall conditions, as shown in Figure 2a.

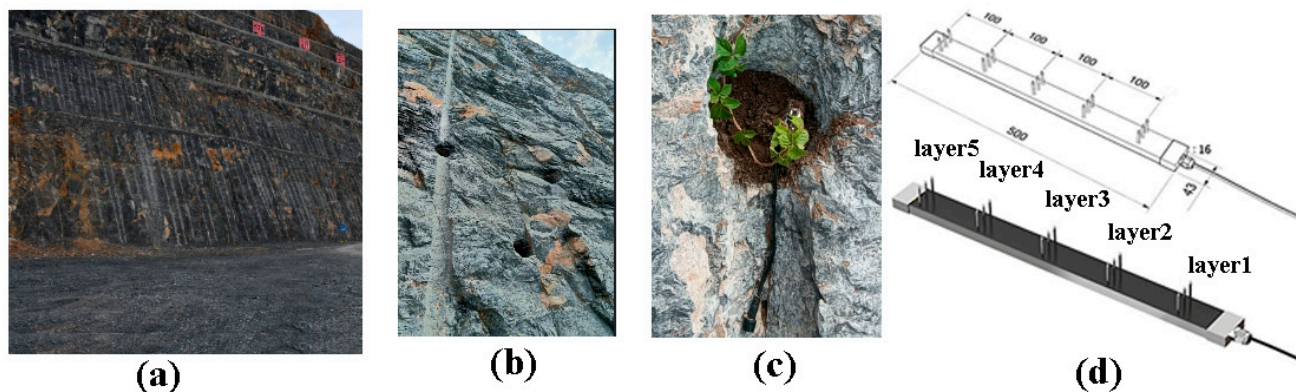


Figure 2. The graphs of field test setup. (a) Exposed high and steep rocky slope; (b) planting holes in rocky slopes; (c) *Parthenocissus himalayana* in the planting hole; (d) automatic temperature and humidity monitor.

2.3.2. Field Test Setup

At the end of April 2022, a submerged drilling rig was employed to create multiple holes on the slope surface with a diameter of 120 mm and a depth of 500 mm, each at a 45° angle. These holes were spaced horizontally at 3 m and vertically at 2 m, as illustrated in Figure 2b. On 3 June 2022, a *P. himalayana* specimen displaying uniform growth was planted in each hole, as shown in Figure 2c. Based on the findings of our laboratory experiments (Section 3.2), the soil substrate composition consisted of a base soil-to-peat volume ratio of 7:3, 1.5 g/L of a water-retaining agent, 10 mg/L of a granulating agent, 5 g/L of biochar, and 5 g/L of fertilizer. The bottom of the planting holes was filled with approximately 5 cm of slag stone with a particle size ranging from 2 to 3 mm. After one month of manual maintenance, the plants were allowed to establish naturally. Extreme months (August and January) and varying rainfall conditions (heavy and light) were selected to monitor the dynamic changes in moisture and temperature in the soil substrates at different depths. Regular *P. himalayana* growth indicator measurements were taken, and soil samples were collected to analyze the physical and chemical properties of the soil. This testing cycle continued until June 2023.

2.4. Measurement Methods

Soil bulk density was determined using the ring knife method; soil saturated moisture and field capacity were determined using the indoor ring knife method; soil moisture loss was determined using the weighing method; soil pH was measured using the potentiometric method; soil conductivity was measured using time-domain reflectance; soil organic carbon (organic matter) was measured using the oxidative spectrophotometric method using potassium dichromate; soil total nitrogen was measured using the Kjeldahl method; soil hydrolytic nitrogen was measured using the alkali diffusion method [31]; plant branching was measured by counting the total number of branches; and total branch length was determined using a tape measure. Additionally, an automatic temperature and humidity monitor was employed to measure the temperature and humidity at various soil depths within the planting holes, specifically at depths of 3 (layer 1), 13 (layer 2), 23 (layer 3), 33 (layer 4), and 43 cm (layer 5), as shown in Figure 2d. These measurements were recorded automatically every 30 min.

2.5. Data Analysis

All data were analyzed using SPSS 26.0 software (IBM, Armonk, NY, USA) and a one-way analysis of variance was performed to analyze the differences in individual indicators between the 16 treatments with a significance threshold of $p < 0.05$.

3. Results and Discussion

3.1. Physicochemical Properties of Synthetic Soil Substrates

Compared with the control blank soil, the soil bulk density of the different synthetic soil substrates decreased significantly, the soil saturated moisture and field capacity increased significantly, and the water loss ratio decreased significantly (Table 3). The volume ratio of base soil to peat was the main factor affecting the soil bulk density, saturated moisture, field capacity, and water loss ratio, and the soil bulk density, saturated moisture, field capacity, and water loss ratio at different levels of this factor were significantly different ($p < 0.05$). The water-retention agent, agglomerating agent, biochar, and controlled-release compound fertilizer all affected the physical characteristics of the synthetic substrate but not significantly. Overall, an increase in peat effectively increased the porosity, reduced the bulk weight, improved the water-holding performance, and reduced water loss from the substrate material.

Compared with the control soil, the pH values of the different synthetic soil substrates were lower, and the organic matter content, conductivity, total nitrogen, and alkaline-dissolved nitrogen content increased significantly. The volume ratio of soil to peat emerged as the primary factor influencing soil substrate pH, organic matter content, and total nitrogen content; these differences were statistically significant ($p < 0.05$) across different treatment levels. Controlled-release compound fertilizer played a pivotal role in influencing the conductivity and alkaline-dissolved nitrogen content of the substrate materials, with significant differences ($p < 0.05$) observed among the treatment levels. Water-retention agents, agglomerating agents, and biochar exerted some impact on substrate pH, organic matter content, conductivity, total nitrogen, and alkaline-dissolved nitrogen; however, these differences were not statistically significant. In summary, increasing the amount of peat in the substrate material resulted in a substantial decrease in pH and an increase in organic matter content. Similarly, increasing the content of controlled-release composite fertilizer led to a substantial increase in substrate salt and quick-acting nutrient content.

3.2. Determination of the Optimal Soil Substrate

The optimization of soil substrates for the revegetation of steep rocky slopes should use the plant growth index as the priority index based on the extreme ecological conditions of steep rocky slopes in semi-arid areas, such as water and nutrient shortages. The water retention and nutrient properties of soil substrates are also key factors that should be considered. Here, the optimal soil substrate was determined based on plant growth, as well as the soils' water-holding capacity and organic matter content.

Table 3. Soil substrate properties for 16 experimental combinations and one control.

Factor	Level	BD (g/cm ³)	SM (%)	FC (%)	MR (%)	pH	OM (g/kg)	EC (μS/cm)	TN (mg/kg)	AN (mg/kg)
Vsoil:VPt	1	1.23 ± 0.0056 ^a	40.45 ± 0.90 ^d	27.84 ± 0.89 ^d	94.50 ± 0.65 ^a	7.64 ± 0.022 ^a	51.56 ± 2.55 ^c	407.5 ± 84.40 ^a	2329.25 ± 137.37 ^c	307 ± 43.66 ^a
	2	1.11 ± 0.0093 ^b	48.71 ± 0.41 ^c	34.50 ± 0.77 ^c	92.75 ± 1.03 ^a	7.44 ± 0.022 ^b	59.45 ± 2.97 ^c	415 ± 51.24 ^a	2797.5 ± 60.28 ^{ab}	256.25 ± 48.61 ^a
	3	1.04 ± 0.023 ^c	56.04 ± 2.22 ^b	39.81 ± 1.24 ^b	91.00 ± 1.63 ^a	7.41 ± 0.024 ^c	78.72 ± 4.25 ^b	447.5 ± 32.76 ^a	2515 ± 59.52 ^{bc}	325.25 ± 37.94 ^a
	4	0.92 ± 0.026 ^d	68.86 ± 3.05 ^a	48.97 ± 2.12 ^a	86.00 ± 1.08 ^b	7.23 ± 0.050 ^d	126.00 ± 1.54 ^a	487.5 ± 54.83 ^a	2945 ± 232.41 ^a	352.5 ± 13.53 ^a
WA	1	1.07 ± 0.062 ^a	51.73 ± 5.28 ^a	36.87 ± 4.02 ^a	91.50 ± 1.26 ^a	7.46 ± 0.074 ^a	74.98 ± 17.12 ^a	435 ± 89.58 ^a	2568.5 ± 114.25 ^a	302.75 ± 38.66 ^a
	2	1.07 ± 0.082 ^a	54.00 ± 8.17 ^a	38.29 ± 5.75 ^a	91.00 ± 2.48 ^a	7.42 ± 0.119 ^a	81.00 ± 16.61 ^a	435 ± 52.04 ^a	2740 ± 353.94 ^a	295.25 ± 26.31 ^a
	3	1.08 ± 0.057 ^a	53.56 ± 5.15 ^a	38.39 ± 3.53 ^a	90.00 ± 2.38 ^a	7.44 ± 0.063 ^a	78.06 ± 17.62 ^a	437.5 ± 59.63 ^a	2573.5 ± 68.19 ^a	330.75 ± 26.95 ^a
	4	1.08 ± 0.068 ^a	54.76 ± 6.14 ^a	37.58 ± 4.98 ^a	91.75 ± 2.17 ^a	7.40 ± 0.090 ^a	81.71 ± 16.18 ^a	450 ± 28.58 ^a	2704.75 ± 76.50 ^a	312.5 ± 66.26 ^a
AA	1	1.07 ± 0.065 ^a	53.74 ± 6.50 ^a	38.06 ± 5.01 ^a	89.75 ± 2.06 ^a	7.40 ± 0.095 ^a	75.48 ± 16.68 ^a	390 ± 74.94 ^a	2657 ± 174.06 ^a	287.5 ± 27.72 ^a
	2	1.08 ± 0.060 ^a	53.64 ± 5.76 ^a	37.79 ± 3.98 ^a	90.25 ± 1.89 ^a	7.48 ± 0.082 ^a	77.89 ± 16.81 ^a	435 ± 46.64 ^a	2474.5 ± 161.17 ^a	347.5 ± 35.55 ^a
	3	1.06 ± 0.080 ^a	56.02 ± 7.56 ^a	39.37 ± 5.51 ^a	90.50 ± 2.251 ^a	7.41 ± 0.105 ^a	81.90 ± 17.93 ^a	490 ± 48.48 ^a	2853.5 ± 261.82 ^a	286.75 ± 59.56 ^a
	4	1.10 ± 0.064 ^a	50.66 ± 4.80 ^a	35.91 ± 3.70 ^a	93.75 ± 1.60 ^a	7.44 ± 0.066 ^a	80.48 ± 16.13 ^a	442.5 ± 57.79 ^a	2601.75 ± 83.68 ^a	319.5 ± 33.34 ^a
Bc	1	1.05 ± 0.080 ^a	55.96 ± 8.42 ^a	39.29 ± 5.96 ^a	91.25 ± 2.59 ^a	7.38 ± 0.106 ^a	67.76 ± 19.67 ^a	385 ± 87.80 ^a	2781.75 ± 296.92 ^a	316.5 ± 50.35 ^a
	2	1.08 ± 0.069 ^a	52.72 ± 5.38 ^a	36.74 ± 4.05 ^a	91.00 ± 1.78 ^a	7.46 ± 0.090 ^a	73.28 ± 19.91 ^a	462.5 ± 48.02 ^a	245.75 ± 161.92 ^a	273.25 ± 55.04 ^a
	3	1.09 ± 0.059 ^a	52.83 ± 5.61 ^a	38.07 ± 4.12 ^a	91.25 ± 1.93 ^a	7.44 ± 0.095 ^a	84.15 ± 20.38 ^a	482.5 ± 44.98 ^a	2606.75 ± 129.18 ^a	331.5 ± 24.92 ^a
	4	1.09 ± 0.058 ^a	52.55 ± 5.14 ^a	37.03 ± 4.10 ^a	90.75 ± 2.25 ^a	7.45 ± 0.055 ^a	94.77 ± 20.82 ^a	427.5 ± 35.91 ^a	2722.75 ± 85.68 ^a	320 ± 26.49 ^a
CCF	1	1.11 ± 0.054 ^a	50.78 ± 5.514 ^a	35.30 ± 4.22 ^a	92.25 ± 2.43 ^a	7.48 ± 0.061 ^a	83.23 ± 17.24 ^a	320 ± 47.08 ^c	2482.25 ± 47.08 ^a	238.5 ± 46.85 ^b
	2	1.08 ± 0.065 ^a	52.74 ± 6.24 ^a	38.17 ± 4.62 ^a	91.50 ± 2.02 ^a	7.43 ± 0.108 ^a	74.89 ± 18.76 ^a	397.5 ± 30.10 ^{bc}	2575.25 ± 196.21 ^a	273.25 ± 14.53 ^b
	3	1.07 ± 0.061 ^a	53.9 ± 4.91 ^a	37.81 ± 3.31 ^a	91.00 ± 0.82 ^a	7.42 ± 0.072 ^a	79.62 ± 15.67 ^a	490 ± 38.94 ^{ab}	2647.75 ± 119.52 ^a	367.25 ± 29.89 ^a
	4	1.05 ± 0.083 ^a	56.64 ± 7.81 ^a	39.85 ± 5.78 ^a	89.50 ± 2.60 ^a	7.40 ± 0.104 ^a	78.01 ± 15.61 ^a	550 ± 15.81 ^a	2281.5 ± 248.88 ^a	362.25 ± 9.17 ^a
CK	/	1.33 ± 0.018	32.36 ± 0.82	22.02 ± 0.21	105.92 ± 1.71	8.44 ± 0.0029	32.75 ± 1.45	175 ± 6.46	1546 ± 15.32	59 ± 3.25

BD: bulk density, SM: saturated moisture, FC: field water content, MR: moisture loss ratio, OM: organic matter, EC: electrical conductivity, TN: total nitrogen, AN: alkaline nitrogen, different letters represent significant differences ($p < 0.05$).

3.2.1. Effect of the Volume Ratio of Base Soil to Peat on Vegetation Growth and Substrate Properties

The volume ratio of base soil to peat had a significant effect ($p < 0.05$) on the number of *P. himalayana* branches, branch length, substrate field water-holding capacity, and organic matter content (Figure 3). Adding peat to the soil effectively enhanced the growth indices of *P. himalayana* and improved the water-holding properties and organic matter content of the substrate compared to those of blank soil. For example, when the soil-to-peat ratio was reduced from 9:1 to 6:4, the field water-holding capacity of the substrate increased from 27.9% to 49.0% and the organic matter content increased from 51.6 to 126 g/kg. However, the number of *P. himalayana* branches and branch length exhibited an increase followed by a decrease as the volume ratio of soil to peat was reduced, with the highest values achieved at a soil-to-peat volume ratio of 7:3. When this volume ratio changed from 7:3 to 6:4, the number of branches decreased from 6.68 to 6.43 and the branch length decreased from 83.65 to 79.13 cm. This suggests that an excessive amount of peat is detrimental to the growth of *P. himalayana*. Therefore, a soil-to-peat volume ratio of 7:3 was selected as the optimal ratio. The present study showed that a volume ratio of 7:3 yielded optimal growth for *P. himalayana*, whereas higher proportions of peat constrained growth. Similarly, Ma et al. [32] observed that a higher peat proportion increased water-holding capacity but impaired permeability in planting substrates, negatively impacting root system development and overall plant growth. Consequently, a base soil-to-peat volume ratio of 7:3 is considered the optimal substrate for cultivating *P. himalayana* in planting holes on rocky slopes.

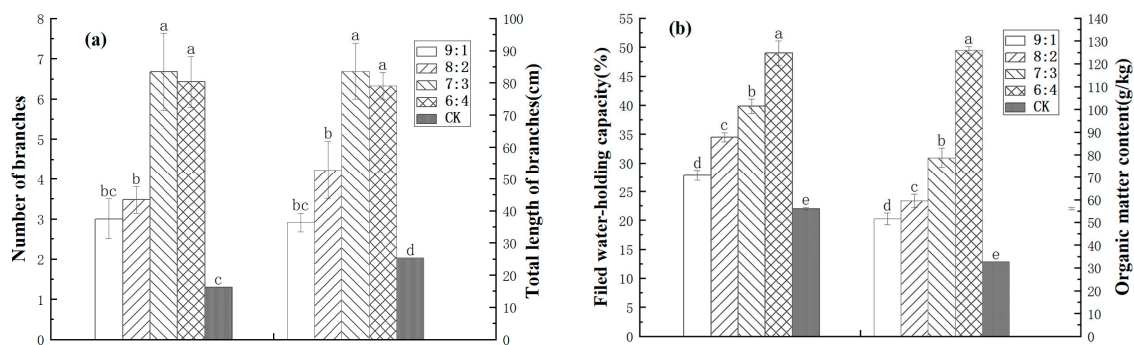


Figure 3. Effects of the volume ratio of base soil to peat on (a) vegetation growth and (b) substrate properties. Different letters indicate significant differences (ANOVA, $p < 0.05$); CK, control.

3.2.2. Effects of Water-Retaining Agent Content on Vegetation Growth and Substrate Properties

The addition of a water-retaining agent had significant effects ($p < 0.05$) on the number of branches and branch length of *P. himalayana* (Figure 4a). Compared with the control soil, the synthetic soil substrates with added water-retaining agent effectively improved the growth indices of *P. himalayana* and improved the water-holding properties and organic matter content of the substrate (Figure 4b). When the amount of water-retaining agent was increased from 0.5 to 2 g/L, the field water-holding capacity increased from 36.57% to 40.58%, although this was not statistically significant. Furthermore, as the amount of water-retaining agent was increased, the organic matter content of the substrate did not change significantly; there was no clear pattern of response. With an increase in the water-retaining agent content, the number of *P. himalayana* branches and branch length first increased and then decreased, with 1.5 g/L resulting in the highest number and length of branches. Increasing the content of the water-retaining agent from 1.5 to 2 g/L reduced the number and length of branches from 5.6 to 5.35 and from 72.48 to 72.18 cm, respectively. This indicates that above a certain level, the addition of an excessive amount of water-holding agent is unfavorable for *P. himalayana* growth. Thus, 1.5 g/L of water retention agent was identified as the optimal amount. This study showed that the addition of 1.5 g/L of water-retaining agent increased the soil substrate field water-holding capacity

and optimized *P. himalayana* growth while increasing the dosage to 2 g/L limited growth. Similarly, Li et al. [33] showed that excessive water-retaining agent levels led to excessive water storage, hampering permeability and causing root rot, thus impeding plant growth. Therefore, a water-retaining agent dose of 1.5 g/L is considered optimal for promoting the growth of *P. himalayana* in planting holes on rocky slopes.

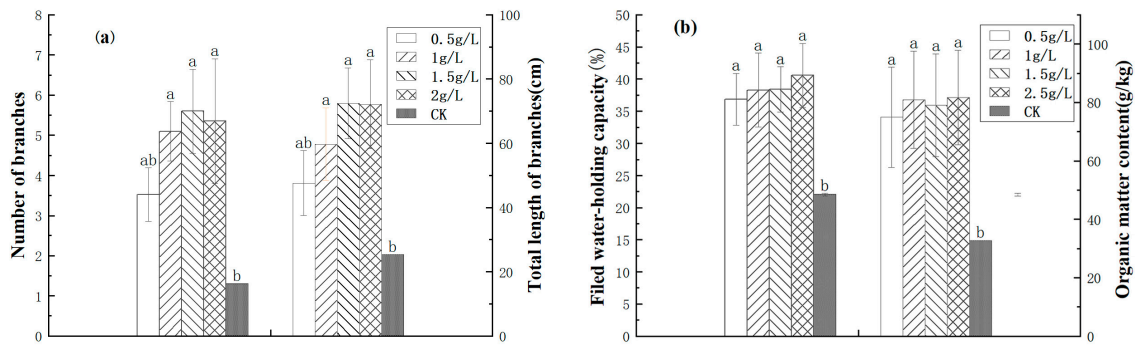


Figure 4. Effects of water-retaining agent content on (a) vegetation growth and (b) substrate properties. Different letters indicate significant differences (ANOVA, $p < 0.05$); CK, control.

3.2.3. Effects of Agglomerating Agent Content on Vegetation Growth and Substrate Properties

The addition of an agglomerating agent had significant effects on the number of *P. himalayana* branches and branch length ($p < 0.05$; Figure 5a) and improved the water-holding performance and organic matter content of the substrate relative to the control soil ($p < 0.05$, Figure 5b). There were no significant differences between the synthetic soils with different amounts of the agglomerating agent. When the agglomerating agent was added at a rate of 10 mg/L, the number of *P. himalayana* branches was the maximum but reduced from 5.9 to 4.4 when more was added; branch length varied between 61.4 and 65.2 cm, with the higher values associated with an application rate of 5 mg/L. Thus, an agglomerating agent addition rate of 10 mg/L was determined as the optimal value. In January 1995, the U.S. Department of Agriculture issued interim specifications for the use of water-soluble anionic polyacrylamides for controlling ditch irrigation erosion, stipulating an agglomerant application rate of 10 mg/kg [34]. Similarly, in this study, *P. himalayana* growth was optimal with an agglomerant addition rate of 10 mg/L of substrate.

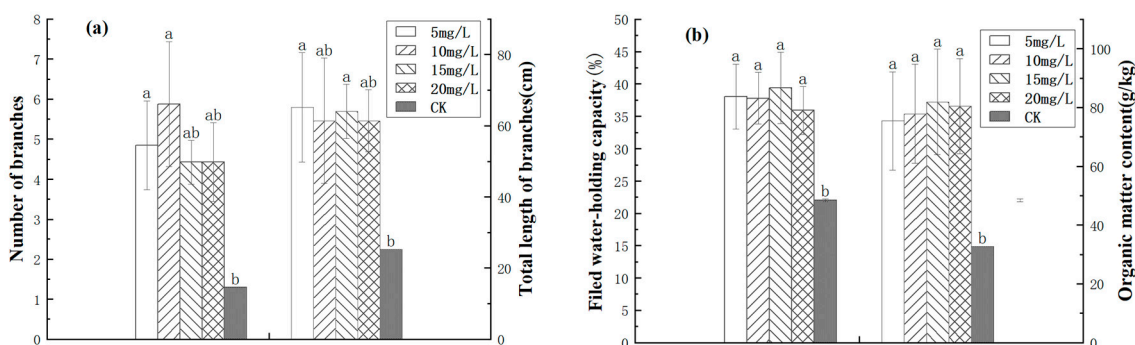


Figure 5. Effects of agglomerating agent content on (a) vegetation growth and (b) substrate properties. Different letters indicate significant differences (ANOVA, $p < 0.05$); CK, control.

3.2.4. Effects of Biochar Content on Vegetation Growth and Substrate Properties

Compared to the control soil, the synthetic substrates enriched with biochar demonstrated a notable enhancement in the growth parameters of *P. himalayana* (Figure 6a) and improved the water-holding capacity and organic matter content within the substrates (Figure 6b). As the quantity of biochar increased, there was a tendency for the substrate's

field water-holding capacity to decrease, although this difference did not reach statistical significance. When the rate of biochar addition escalated from 5 to 20 g/L, the organic matter content of the substrate increased from 67.76 to 94.76 g/kg. Interestingly, the application rate of 5 g/L had the most pronounced impact on the number and length of *P. himalayana* branches ($p < 0.05$). It is noteworthy that higher rates of biochar addition were associated with diminished growth (Figure 6a). Consequently, 5 g/L of biochar was identified as the optimal quantity. This study also revealed that the growth indices of *P. himalayana* declined with increasing biochar addition. Biochar has been shown to promote NH_3 and NH_4^+ adsorption [35,36] but may have limited the initial N utilization by *P. himalayana* roots. The higher C/N ratio of biochar might have exacerbated competition among soil microbes for N. Consequently, the lowest level of biochar addition (5 g/L) is considered suitable for planting holes on rocky slopes for greening purposes. However, further in-depth research is warranted to elucidate the effects of biochar addition.

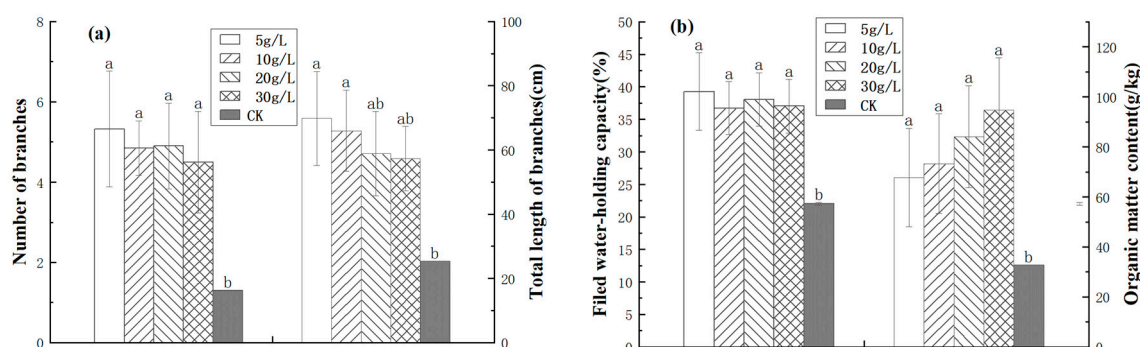


Figure 6. Effects of biochar content on (a) vegetation growth and (b) substrate properties. Different letters indicate significant differences (ANOVA, $p < 0.05$); CK, control.

3.2.5. Effects of Controlled-Release Compound Fertilizer Content on Vegetation Growth and Substrate Properties

Compared with the control soil, the addition of the controlled-release composite fertilizer effectively improved the growth indices of *P. himalayana* (Figure 7a) and improved the water-holding performance and organic matter content of the soil substrates (Figure 7b). Although there were no significant differences in field water-holding capacity and organic matter content between the treatment levels, an increase in the amount of controlled-release compound fertilizer tended to increase the field water-holding capacity but reduced the organic matter content (Figure 6b). The addition of controlled-release composite fertilizer had a significant effect on the number of *P. himalayana* branches ($p < 0.05$), falling from 5.4 to 3.1 with an increase from 5 to 6 g/L, while there were no differences in branch length between the treatment levels (Figure 6a). Given these results, a controlled-release compound fertilizer addition amount of 5 g/L was selected as the optimal amount. Inorganic fertilizers provide nutrients for plant growth during the early stages of rocky slope revegetation. However, considering the negative effects of excessive inorganic fertilizers on plants and the environment, especially groundwater [37,38], as well as the cost of restoration efforts, it is important to determine the optimal level of fertilizer addition. In this experiment, a controlled-release compound fertilizer addition rate of 5 g/L was optimal for *P. himalayana* growth, while 6 g/L limited growth. This follows the evidence of Rufat et al. [39], who showed that the fine roots of containerized seedlings decreased with an increase in effective nutrients in the seedling substrate, which in turn negatively affected plant growth. Therefore, a fertilizer addition rate of 5 g/L is considered most appropriate for planting hole substrates.

Based on the experimental results, the optimal soil substrate composition, as subsequently used in the field trial, was determined to have the following properties: 7:3 soil-to-peat ratio by volume, 1.5 g/L of water-retention agent, 10 mg/L of agglomerating agent, 5 g/L of biochar, and 5 g/L of controlled-release composite fertilizer.

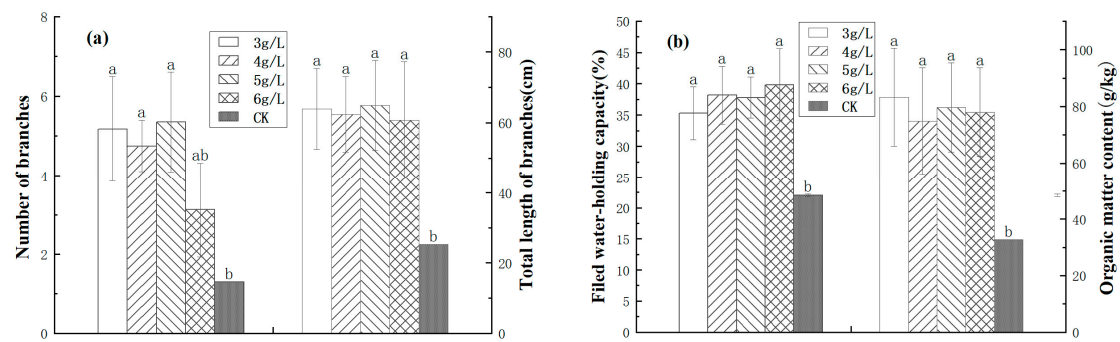


Figure 7. Effects of controlled-release compound fertilizer content on (a) vegetation growth and (b) substrate properties. Different letters indicate significant differences (ANOVA, $p < 0.05$); CK, control.

3.3. Properties of the Optimal Soil Substrate in the Field Test

3.3.1. Moisture Content Dynamics and Their Response to Rainfall

Figure 8 illustrates the moisture content of the optimal soil at various depths within the drilled planting holes on the rocky slope, recorded at 30 min intervals, and the daily rainfall under extreme monthly conditions. During the representative summer months, the moisture content of the soil substrate at different depths varied from 6.3% to 47%. In representative winter months, the moisture content at different depths varied between 3.2% and 25%. Overall, it is evident that the moisture content of the soil substrate varied more during the summer months than in the winter months, with summer rainfall contributing to higher moisture levels within the substrates.

The uppermost layer had the lowest moisture content, with relatively lower moisture content in the second and fifth layers. In contrast, the third and fourth layers showed relatively high moisture content, with the fourth layer having the highest moisture levels, which indicates that the soil substrate effectively retained water. Notably, during two consecutive drought periods, spanning from 12 August to 23 August and from 31 August to 8 September, the soil moisture content at different depths experienced a decrease ranging from 10% to 14%. The second layer reached a low of 11%, while the fourth layer decreased from 46% to 32%. During two successive dry periods, spanning from 1 January to 13 January and 19 January to 30 January, the moisture content of the second layer was $>7\%$ and that of the third through fifth layers was $>10\%$, while root growth mainly occurred in the second to fourth soil layers in the planting holes (depth = 13–33 cm), in which the soil moisture content (volumetric) ranged from 11% to 47% in August and from 7.4% to 25% in January. Xia [40] investigated the photosynthetic efficiency in response to moisture and light in 14 major woody liana vines in North China and found that a soil moisture range of 8.9–22.8% maintained high rates of photosynthesis. Zhang et al. [41] found that the photosynthetic rate of climber leaves was highest with a volumetric soil moisture content of 12.6–20.7%. These studies indicate that the moisture-retaining properties of the optimized planting substrate were suitable for *P. himalayana*.

Rainfall events of 4.1 mm (light rain) on 25 August and 32.6 mm (heavy rain) on 28 August 2022 were selected to examine the effect of rainfall amount on the moisture content at different depths of the soil substrate in the planting holes (Figure 9). When rainfall was light (Figure 9a), the moisture content of the first and second layers was strongly affected, with a particularly rapid increase in the first layer, and a smaller impact on the third, fourth, and fifth layers. When rainfall was heavy (Figure 9b), the moisture content rose rapidly across the first to the fourth layers, particularly in the fourth layer (which was close to the field water-holding capacity of the optimal soil substrate), while the water content of the fifth layer increased the least. When the rainfall was heavy, the average moisture content of the soil substrate was 30%, which may have led to water retention and accumulation in the planting holes; this is not conducive to optimal plant growth. Therefore, appropriate consideration should be given to the drainage of planting holes exposed to high amounts of rainfall.

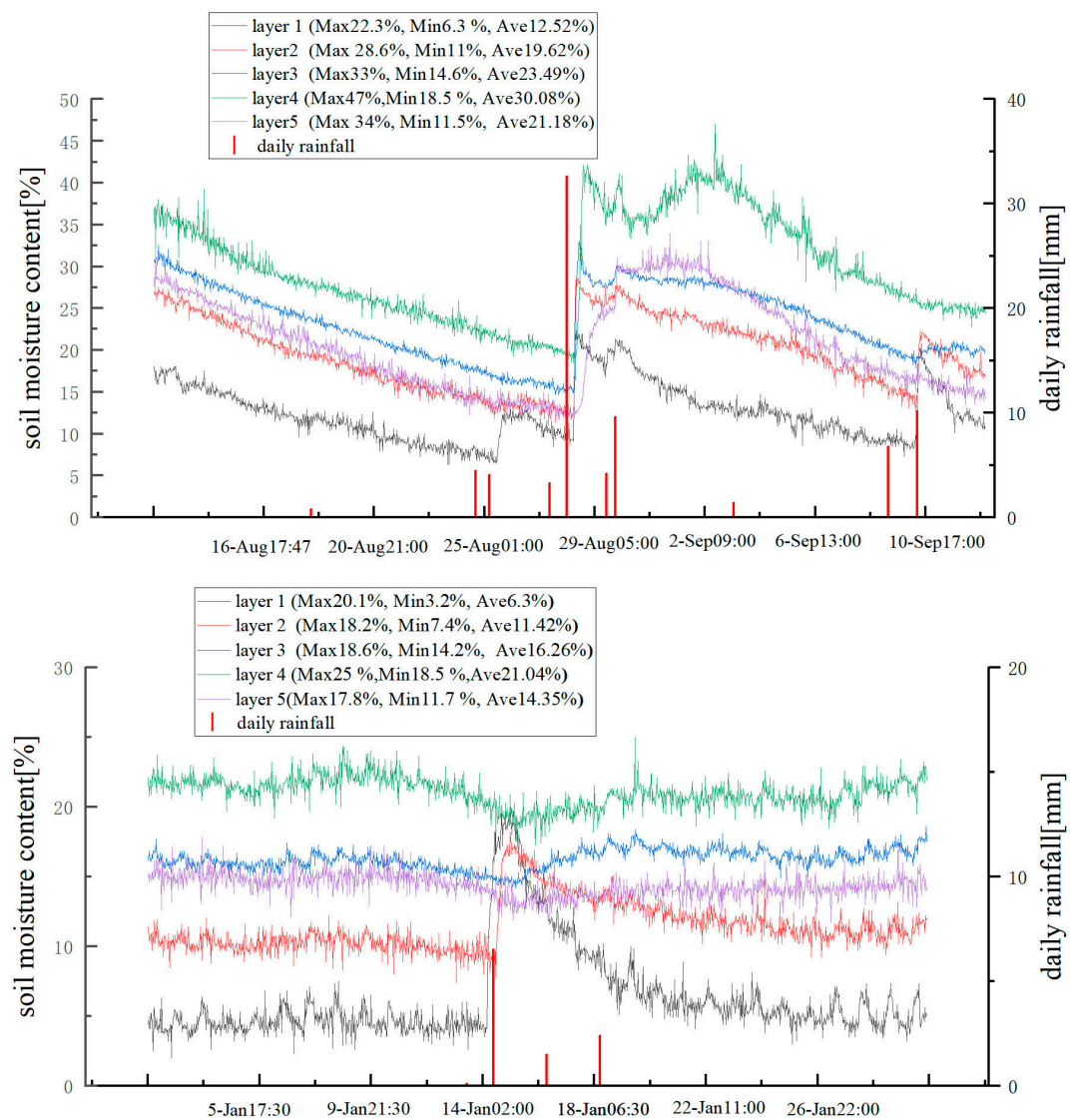


Figure 8. Characterization of soil substrate moisture content changes under extreme monthly conditions.

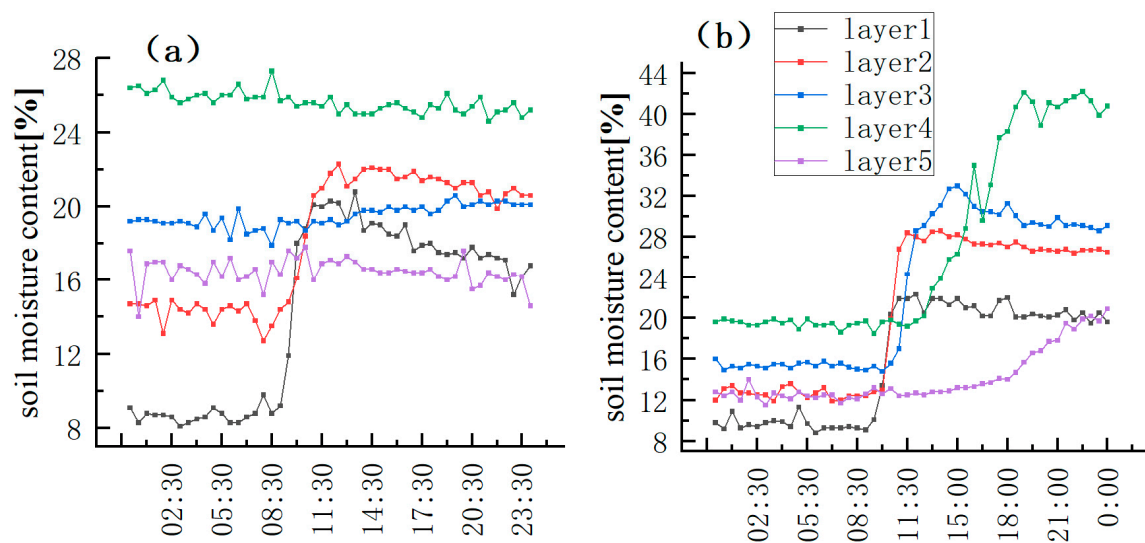


Figure 9. Effect of (a) light and (b) rainfall events on the moisture content of soil substrates at different depths in planting holes.

3.3.2. Physical and Chemical Properties of the Optimal Soil Substrate

Soil samples from the planting holes were collected at 7, 120, 210, and 300 days after the commencement of the experiment. The soil substrate material exhibited a low density, falling within the range of 1.08–1.13 g/cm³. Porosity levels varied between 56% and 59%, and the pH remained neutral (as indicated in Table 4). Notably, any soil washing out from the holes during rainstorms was minimal and the nutrient content surpassed that of China's secondary agricultural soil, according to the Grading Criteria for agricultural soil (when comparing values in Table 4 with those of secondary agricultural soil, which typically maintains a total nitrogen content of 0.15%, an available phosphorus content exceeding 20 mg/kg, an available potassium content exceeding 150 mg/kg, and an organic matter content exceeding 3%). Consequently, throughout the duration of the experiment, the substrate material retained relatively high levels of nitrogen, phosphorus, potassium, and organic matter. These findings affirm that the selected substrate soil material was suitable to meet the growth requirements of vegetation on barren rocky slopes. During the first growing season, from June to October, the nutrient content of the substrate decreased, indicating absorption during plant growth; however, the nutrient content of the soil substrates subsequently increased. This was likely due to nutrient release from dead branches and leaves, as well as recharge from slope runoff or growth of the root system, which compensated for the nutrient depletion of plant growth during the growing season.

Table 4. The results of physical and chemical properties of the optimal soil substrates.

Time (d)	BD (g/cm ³)	Porosity (%)	pH	OM (g/kg)	TN (mg/kg)	AN (mg/kg)	TP (mg/kg)	AP (mg/kg)	AK (mg/kg)
7	1.08	59	7.35	75.94	2537	428	1102	105	834
120	1.10	58	7.59	47.92	1717	193	981	136.6	590
210	1.13	56	7.40	50.20	2254	1050	1038	124.2	861
300	1.09	58	7.66	44.41	2510	724	846	122.3	719

BD: bulk density, OM: organic matter, TN: total nitrogen, AN: alkaline nitrogen, TP: total phosphorus, AP: available phosphorus, AK: available potassium.

3.3.3. *P. himalayana* Growth in the Optimal Soil Substrate

On 3 June 2022, the test site was planted; new shoots began to grow on the plant stems after 15 d. Watering was carried out according to the weather conditions during the first month after planting and was stopped thereafter to allow natural growth. In October 2022, the average number of *P. himalayana* leaves was 233 ± 35 , the number of branches was 8 ± 3 , the total length of branches was 290 ± 150 cm, and the length of the main stem was 100 ± 12 cm. On 6 May 2023, after the winter, the average number of leaves had reached 584 ± 177 , the number of branches was 15 ± 4 , the total length of branches was 700 ± 169 cm, and the length of the main stem was 128 ± 8 cm. The vegetation grew well and began to cover the slope (Figure 10a,b). Notably, the survival rate of the plants was 95%. After 360 days, the vegetation survival rate was high and began to cover the bare slopes. Meanwhile, soil nutrition was able to support the growth of vegetation, similar to that of vegetation on a natural slope.

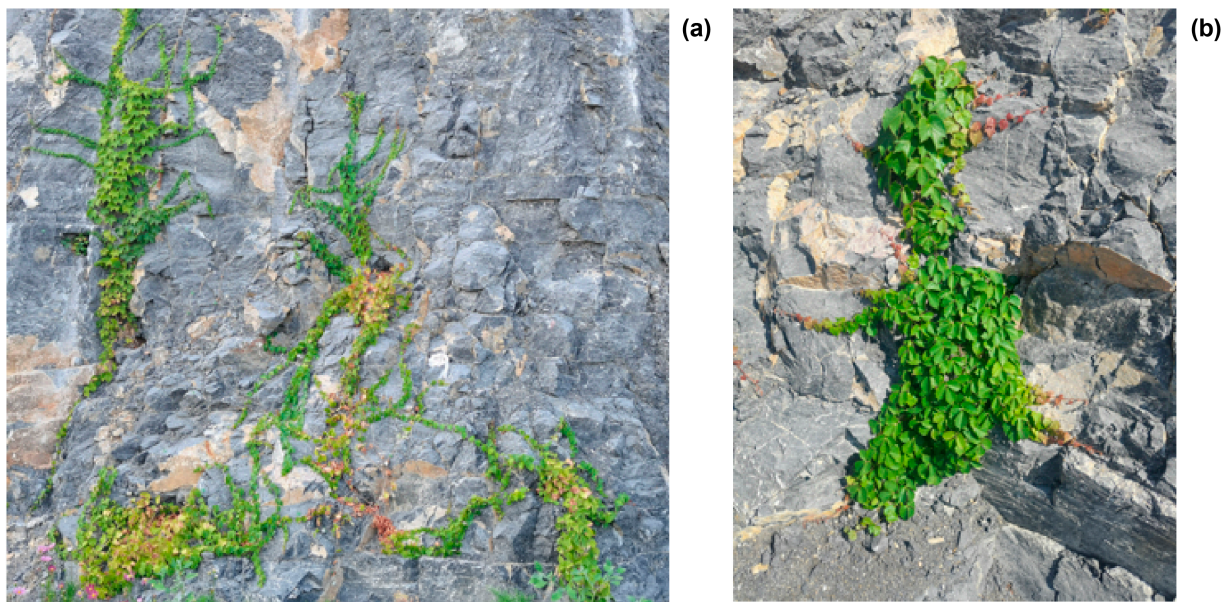


Figure 10. Growth of *Parthenocissus himalayana* planted in drilled holes filled with a synthetic soil substrate in a rock slope. (a) Vegetation growth of local area, (b) growth of individual plant.

3.3.4. Temperature Dynamics of the Optimal Soil Substrate under Extreme Monthly Conditions

Figure 11 presents data on the temperature at various depths of the soil substrate within the planting holes recorded at 30 min intervals alongside the average air temperature during extreme monthly conditions. During representative summer, the soil temperature exhibited a range of 19.8–35.5 °C in the second to fourth soil layers (depth = 13–33 cm). In winter, the air temperature range in the second to fourth soil layers was 3.9–27.2 °C. Notably, the first layer displayed the highest thermal amplitude, whereas the other layers gradually experienced a weakening of this effect with increasing depth. Temperature peaks in each layer positively correlated with the average daily air temperature. Moreover, the soil substrates underwent cyclic temperature variations throughout each day. Minimum values were typically observed around 8:30 and, as the air temperature began to rise, the first layer reached its maximum temperature around 15:00, with the second, third, fourth, and fifth layers reaching their thermal maxima at approximately 17:00. Subsequently, temperatures started to decline, reaching their minimum values at the beginning of the following day. The diurnal temperature range was most pronounced in the first layer due to its rapid cooling and warming characteristics, whereas the ranges of the second, third, fourth, and fifth layers were lower and decreased with increasing depth. Li [42] investigated that perennial vegetation requires a temperature of no less than 2–4 °C for the root system during the winter dormant period and no more than 30 °C during the summer growth period. This indicates that the optimal soil substrate temperature is generally suitable for plant growth; however, the soil temperature is higher than the suitable temperature in the summer. Therefore, it is recommended that cooling measures such as drip irrigation or other measures should be considered.

Based on this field verification test, the optimal soil substrate provided the ideal moisture, temperature, nutrient content, and physical and chemical properties required to establish and maintain vegetation on the semi-arid, high, steep, rocky slope.

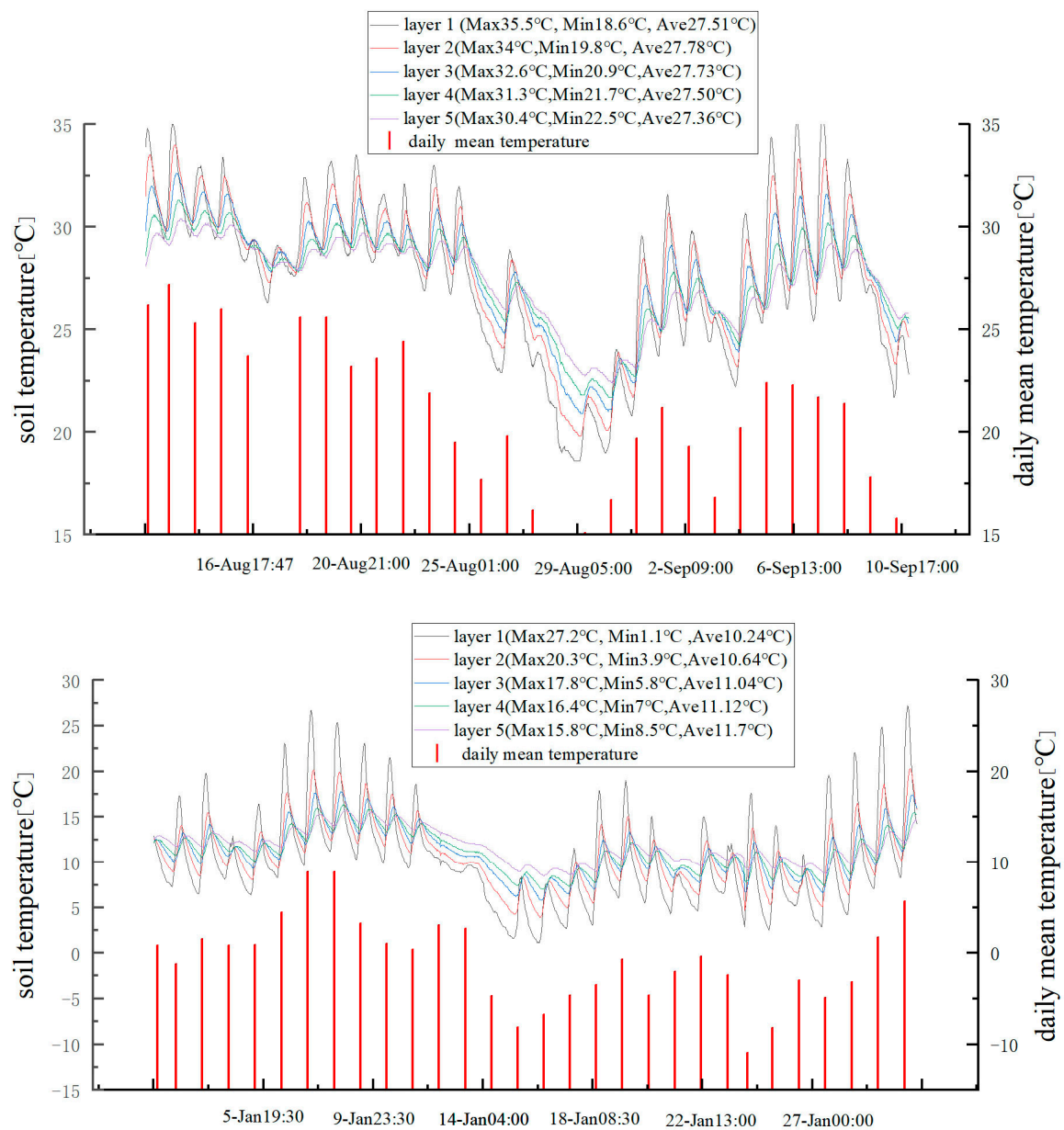


Figure 11. Characterization of temperature changes at different depths of optimal soil substrates in planting holes on a rocky slope under extreme monthly conditions.

4. Conclusions

In this study, we employed orthogonal methods to formulate distinct soil substrates and investigated the impact of individual compound additions on soil properties and the growth of *P. himalayana*. Our research encompassed both pot experiments and field validation tests conducted in a semi-arid region, with the objective of determining the optimal ratio of substrate components. The volume ratio of base soil to peat exhibited significant effects on various attributes of the planting hole soil substrate, including bulk density, water-holding and water-retention performance, pH, organic matter content, total nitrogen content, and vegetation growth indices. In contrast, the controlled-release composite fertilizer exerted a noteworthy influence on soil substrate conductivity and alkaline-dissolved nitrogen content. The water-retention agent, biochar, and agglomerating agent exhibited some influence on the physicochemical properties of the soil substrates and plant growth, although without statistical significance.

The optimal composition of a soil substrate intended for planting on rocky slopes contained a base soil-to-peat volume ratio of 7:3, 1.5 g/L of water-retaining agent, 10 mg/L of agglomerating agent, 5 g/L of biochar, and 5 g/L of controlled-release composite fertilizer. This optimal substrate possessed an acceptable pore structure, with moisture content meeting the requirements for plant growth and water retention in the intermediate layers of the substrate. Furthermore, the thermal performance of the optimal soil substrate was suitable and its nutrient content was high, resulting in excellent plant growth. Based on this evidence, the developed optimal soil substrate is considered suitable for the greening technique in planting holes, particularly on high, steep, rocky slopes within semi-arid areas.

In conclusion, this study successfully developed a synthetic soil substrate tailored for the greening technology of planting holes on high, steep, rocky slopes in semi-arid areas. It is imperative to conduct further research to assess the applicability of this substrate for other plant species and to investigate the long-term nutritional persistence of the soil substrate within the planting holes.

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Conflicts of Interest: The authors declare no conflict of interest.

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