

Article

Comprehensive Evaluation of Soil Improvement Benefits of Biological Retention Facilities Based on AHP-CRITIC

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Abstract: Biological retention facilities are widely used in the construction of new urban infrastructure because of the increasingly serious problems of urban waterlogging and rainwater pollution. At present, a common method to resolve these problems is to improve the treatment performance of these facilities to improve the soil filling layer. How to evaluate the comprehensive benefits of the improved soil filling layer is a problem that cannot be ignored. In this paper, data from seven groups of soil improvement schemes were collected through laboratory tests, and an evaluation method based on AHP-CRITIC was proposed. Firstly, the evaluation indexes of soil improvement in biological retention facilities were determined, and their subjective and objective weights were determined by the AHP method and CRITIC method, respectively, and the comprehensive weights were further calculated. A comprehensive evaluation model was established by the TOPSISI method. Finally, the AHP-CRITIC evaluation model determined that 10% zeolite-amended soil had the best comprehensive evaluation effect, followed by 20% zeolite-amended soil and 10% gravel-amended soil. The results show that the evaluation model can comprehensively assess the benefits of soil improvement in bioretention facilities from the levels of infiltration, purification, and economy and can then select the optimal program for use in actual engineering practice.

Keywords: infrastructure construction; LID; bioretention facility; AHP; CRITIC; comprehensive evaluation



Citation: Liang, H.; Wu, M.; Jia, X.; Yang, Q. Comprehensive Evaluation of Soil Improvement Benefits of Biological Retention Facilities Based on AHP-CRITIC. *Buildings* **2024**, *14*, 780. <https://doi.org/10.3390/buildings14030780>

Academic Editor: Eugeniusz Koda

Received: 21 January 2024

Revised: 28 February 2024

Accepted: 5 March 2024

Published: 13 March 2024



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1. Introduction

With the increase in urbanization levels, the urbanization “heat island effect” has appeared in cities all over the world, which not only causes frequent rainstorm events but also causes a large number of urban waterlogging disasters. The reason is that the rapid development of urbanization causes the original natural surface that can conserve water to be replaced by an impervious surface, which in turn changes the natural drainage mode and pattern and ultimately leads to great changes in the hydrological mechanism in the natural state [1]. The main features include an increased runoff volume from extreme rainfall events, shorter confluence times, and increased burden on urban drainage systems. The results of research on the flooding situation in 351 cities across China showed that 62% of the cities in the country had experienced waterlogging of varying degrees during the period from 2008 to 2010, of which 137 cities, accounting for 39% of the total number of cities, had a frequency of flooding disasters of more than three times [2].

At the same time, the shortage of water resources and the problem of pollution are also problems that need to be urgently solved in the urbanization of China. At present, the per capita resources of 16 provinces and districts in China are below the line of severe water shortage, and 6 provinces and districts are below the line of extreme water cut-off. In addition, the existing urban rainwater runoff contains a large number of pollutants from human life and natural processes, mainly including suspended solids, oils and fats, nutrients, heavy metals, toxic organisms and pathogenic bacteria, etc. [3,4], and these

pollutants go through the process of infiltration and enter into the groundwater, which not only pollutes the surrounding environment but also jeopardizes human health.

In view of the situation of “rainwater flooding, water shortage, and dirty water”, there is an urgent need to effectively control and utilize urban rainwater runoff, and this can then play an important role in building a sustainable water cycle system [5]. In view of this, General Secretary Xi put forward the construction of “sponge cities with natural accumulation, natural infiltration, and natural purification” in 2013, which also set off a wave of sponge city construction in China. In addition, countries around the world have also carried out active theoretical exploration and practice, such as best management practices (BMPs) and low-impact development (LID) in the United States, “sustainable urban drainage” in the United Kingdom, “water-sensitive urban design” (WSUD) in Australia, “Water Square” in the Netherlands, and the “Active Beautiful and Clean Waters Programme” (ABC Programme) in Singapore.

In low-impact development systems, bioretention ponds are widely used because of their excellent runoff pollution control effect, runoff volume regulation effect, and flood flow reduction effect. These facilities are particularly effective in runoff water purification [6,7]. In terms of runoff regulation, at the University of Maryland, College Park, MD, USA, through two sets of bioretention facilities that monitored 49 storm events, it has been proven that bioretention ponds could effectively reduce the adverse hydrological effects in a city [8]. Dietz and Clausen [9] built on-site rain gardens in the US state of Connecticut after more than a year of monitoring, and the monitoring showed that there was an infrequent permafrost winter cycle of freezing–thawing. Li [10] and Hunt [11] investigated and monitored the hydraulic performance of a number of bioretention ponds and found that about 20–50% of the runoff rainwater flowing through the bioretention ponds was reduced by evaporation, transpiration, and infiltration within the system, while the average reduction in runoff volume was the highest in the summer months. Pilot tests conducted by Yingying Meng and others [12] showed that the peak flow reduction rates of the pilot bioretention pond were 84.3%, 25%, and 30.7% when the simulated rainfall was 6.38–32.8, 6.74–45.5, and 5.46–76.5 mm, respectively.

In terms of the water purification effect, the removal effect of bioretention ponds on TSS is very significant, mainly through the combined effect of physicochemical precipitation and the adsorption filtration of filler, and the removal amount can reach more than 80% in most cases [13]. The study by Ying Mei [14] also showed that most of the retention-type LID measures have the best effect on the removal of TSS, the removal rate of heavy metals is higher than 90%, and the average removal rate of *E. coli* can also reach 88%. In terms of nitrogen removal, Davis Ap [15] found that the removal rate of ammonia nitrogen was relatively stable and could reach 70%, while the removal rate of nitrate nitrogen varied greatly and was prone to the phenomenon of drenching. The removal rates of TN concentrations in the clear water tests conducted by Lucke et al. [16] were all negative, and TP could be effectively removed. In addition to this, many scholars have carried out studies on their effectiveness in removing heavy metal ions, perfluorinated compounds, and various drug-resistant bacteria [17–19]. Overall, bioretention ponds have a good removal effect on a variety of pollutants in stormwater runoff.

In the existing research, the common bioretention ponds can be divided into aquifers, filler layers, sand layers, and gravel drainage layers according to their structure, of which, the filler soil layer is the core structure of the treatment and purification of surface runoff. Its main role is to make the surface rainfall infiltrate along the filler soil layer of the internal gap, and the infiltration process can remove pollutants in the runoff through their own material properties so that the rainwater runoff water quality can be improved. However, the traditional natural soil not only has a low permeability coefficient but it is also prone to consolidation over prolonged use, which reduces the porosity of the soil and decreases the treatment performance. Therefore, it is difficult to carry out the long-term and efficient use of bioretention ponds. In response, technical associations and scholars in various countries have improved and optimized the fill layer within bioretention ponds.

The earliest optimization of filler soils in LID facilities originated from the Prince George's County design manual [20], which recommended the use of natural soils, loamy sandy soils, and sandy loam soils. While loamy soils are considered to be a suitable soil choice for LID facilities, they tend to solidify during long-term use, resulting in a reduction of soil void ratio and treatment performance. Therefore, it is necessary to limit the content of organic matter in the fill. In North Carolina the recommended fill combination is 85% to 88% sand, 8% to 12% clay and silt, and 3% to 5% organic matter, whereas the recommended fill combination for use in Delaware is a mix of sand, peat, and organics according to a ratio of 1:1:1 [21]. The Facility for Advancing Water Biofiltration (FAWB) in Australia stipulates that the organic matter content should not exceed 5% at the most. Simultaneously, FAWB stipulates that the nutrient content of the filler soil should be less than 1000 mg/kg of nitrogen and 80 mg/kg of phosphorus. Additionally, the filler should contain a certain percentage of clay in the mix. FAWB recommends that this clay should be less than 3% [22]. In addition to this, recently Hoy, Menglim, et al. proposed using natural rubber latex (NRL) as a replacement material for soil. They investigated its performance in enhancing cement-stabilized laterite and recycled material mixtures [23–25].

Domestic research on retention facilities mostly focuses on the decontamination performance of various modified media. Huang Chenzhe [26] and Gao Xiaoli [27] compared the purification capacity, infiltration capacity, and water-holding capacity of various filler media by conducting soil column infiltration tests on multiple fillers. Their findings highlighted that loam, sand, gravel, and slag were relatively excellent in each performance. Wang's [28] filler soil grading design is 65% construction yellow sand, 25% soil, 5% wood chips, and 5% water supply plant sludge as filler soil in the improved medium, and the results showed that the addition of a water supply plant sludge retention zone can reduce the trend of eutrophication in the receiving water body. Qi Navy [29] further investigated the grading design involving natural soil, slag, and zeolite, and the test concluded that an appropriate increase in the void ratio of the filler soil could improve the runoff reduction performance of the facility. In addition, Wanhe Liu and Shaoying Hu conducted optimization studies on region-specific bioretention ponds [30,31].

It can be seen that a single medium of filler soil struggles to meet the performance requirements of retention facilities. Consequently, a prevailing approach involves combining natural soil, sand, and improved media, with the addition of a certain amount of organic matter. Existing research mainly considers the improvement effect of the filler from two aspects: permeability and purification effect, and subjectively evaluates its advantages and disadvantages, so as to provide reference for the actual construction. However, in the actual construction and promotion of bioretention ponds, performance factors related to the filler layer structure are not the sole considerations. Other crucial factors, such as economic costs and plant survival rates, must also be integrated. Unfortunately, existing evaluations of filler improvement often overlook critical aspects, resulting in a lack of universality. Moreover, the current evaluation methods are rough and subjective, and it is difficult to reflect the gap between the schemes. Consequently, significant errors may occur in the final results. Therefore, in order to enhance the application of improved filler in bioretention pool construction, it is an urgent problem to comprehensively consider the various factors needed in the construction, accurately weigh the correlation and importance between the factors, and objectively and accurately select the optimal bioretention pool improved soil.

At present, when addressing the comprehensive effect evaluation of multiple factors, AHP and CRITIC empowerment methods have achieved good results by different scholars in diverse fields. Xu Tong et al. [32] carried out a comprehensive evaluation of three cooling system programs, considering economic, construction, and energy-saving aspects. Wenbo et al. [33] identified fire risk indicators of high-bay warehouses using the PSR model and combined it with the 4M theory. They employed the fuzzy comprehensive evaluation method to assess the fire safety level. Shang Jin et al. [34] performed a comprehensive evaluation to impact ground pressure using the improved AHP-CRITIC model. Lu Chao et al. [35] optimized the optimal mix design of honeysuckle tea drink

based on AHP-CRITIC. The experimental results were also subsequently confirmed. Zhang Lanqi [36] constructed a single tree-cutting index based on the AHP-CRITIC combination weighting method and realized the optimization and adjustment of the spatial structure of natural forest in the Changbai Mountains.

Therefore, in order to study the comprehensive benefits and promotional value of soil improvement through biological retention ponds under multiple factors, this study proposes a comprehensive evaluation method for assessing soil improvement benefits of biological retention facilities based on AHP-CRITIC. The factors required for a comprehensive evaluation were determined using the expert consultation method. Subsequently, subjective and objective weights were assigned to various indicators of the improved fillers in this study. The comprehensive weights corresponding to each index were then determined, leading to the final realization of the comprehensive benefit evaluation of the improved soil structure. The research method and results can objectively and effectively provide support for the construction and promotion of improved fill layer bioretention ponds in the future. This can further advance the construction of green, efficient, and economically viable sponge cities.

2. Research Method

This paper presents a comprehensive evaluation of bioretention pond improvement based on the AHP-CRITIC theory. The improvement process involved six groups of improvements, with corresponding experiments conducted on the structures. Upon completion of the experiments, relevant data were obtained. The comprehensive evaluation utilized the AHP for subjective weighting and CRITIC for objective weighting, followed by the completion of the comprehensive evaluation. The evaluation process consists of three main parts: experiments and data collection, subjective and objective assignment, and comprehensive evaluation.

2.1. Experiments and Data Collection

Before this study was carried out, experiments and pre-analysis were first conducted on the soil in the study area. The sieving method was used to determine the gradation of the soil, and the corresponding gradation curves were plotted, as shown in Figure 1. The liquid limit and plastic limit were further determined using the combined liquid limit and plastic limit method. Based on the two points mentioned above, the USCS was utilized to determine the pertinent properties of the in situ soil and classify it accordingly.

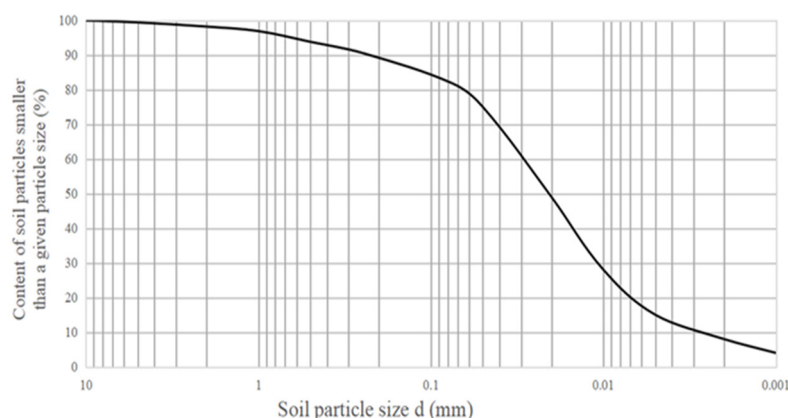


Figure 1. Grading curves for raw soils.

From the above figure, it can be seen that more than 50% of the soil particles are less than 0.075 mm, so it is a fine-grained soil. Additionally, the liquid limit of this soil is 30.7% and the plastic limit is 18.4%. According to the USCS, raw soil belongs to the CL category. This type of soil exhibits characteristics of easy saturation and viscosity when encountering water. It forms an aquiclude after saturation, which obstructs rainwater

infiltration. Therefore, if the soil is directly used as the filling material of the bioretention ponds, during periods of intense rainfall, the rainwater may overflow before infiltration, which will lead to poor runoff control and pollutant removal effect of the bioretention ponds. Therefore, in order to enhance the comprehensive performance of the raw soil, we developed two soil improvement programs: zeolite particles and coarse sand.

For the selection of particle size, considering that the average particle size of coarse sand is more than 0.5 mm, in order to make the experimental object and the results more accurate, based on GB/T 14684-2022 [37], the standard sieve apertures of 0.60 mm and 1.18 mm are used to sieve zeolite particles and river sand, and the relevant particles of 0.60–1.18 mm are obtained. Zeolite and coarse sand were purchased.

When it comes to the proportion of improved filler, in general, the smaller the proportion of improved material, the less noticeable the effect will be. Conversely, the larger the proportion, the more pronounced the effect will be. However, this will also result in increased construction costs. Therefore, in order to ensure the economy and effectiveness of the improved filler, filler ratios of 10%, 20%, and 30% were established to investigate the comprehensive performance of the improved filler across various ratios. Subsequently, using the indoor column simulation method, the soil infiltration and purification effects under different improvement programs were simulated. The specific experimental process is outlined as follows:

2.1.1. Experimental Group and Filler Properties

Two soil amendment structures were designed for this study, including zeolite particles and coarse sand with a particle size range of 0.60–1.18 mm. The proportions of fillers in this experiment are shown in Table 1 below.

Table 1. Experimental group filler ratios.

Specimen Number	Zeolite (%)	Coarse Sand (%)	Raw Soil (%)
#1	10	0	90
#2	20	0	80
#3	30	0	70
#4	0	10	90
#5	0	20	80
#6	0	30	70
#7	0	0	100

In order to better reflect the properties of the raw materials used in this experiment, the main physical characteristics, chemical characteristics, and chemical composition of the three fillers are shown in Table 2 below.

Table 2. Characteristics of different fillers.

Type of Filler	Main Physical Properties	Main Chemical Properties	Chemical Composition
Raw soil	Color: 5GY/7 Porosity: 49% Soil structure: non-hydrostable Water content: 14%	PH: 8.02 Organic matter content: 12.37 g kg ^{−1}	SiO ₂ ; Al ₂ O ₃ ; H ₂ O (crystallization); Fe ₂ O ₃ ; CaO; MgO;
Zeolite	Color: brown Mohs hardness: 5 Density: 2.1 g/cm ³	Adsorptive, ion-exchange, catalytic	[Al ₂ SiO ₄] _n H ₂ O; aluminosilicate mineral
Coarse sand (river sand)	Color: white, brown Grain size range: 0.60–1.18 mm Fineness modulus: 3.1~3.3	Firmness: excellent Alkali aggregate reaction: alkali–silica reaction Methylene blue value: none	SiO ₂ ; aluminate mineral

2.1.2. Improved Soil Permeability Experiments

Experimental Apparatus: The main structure of the experimental device is an infiltration cylinder and a rainwater collection device. When the aperture of the cylinder is small, there may be a capillary phenomenon, which affects the seepage and observation. Therefore, we selected a cylinder with an external diameter of 110 mm, an internal diameter of 104 mm, and a length of 1 m for the experiment. A disc with a 5 mm hole was customized to be placed at the bottom of the cylinder for seepage. Additionally, a permeable gauze was placed between the cylinder and the disc to prevent soil leakage. The rainwater collection device consisted of a funnel and a beaker to gather rainwater for measuring infiltration.

Experimental Method: First, the amended soil was added into the experimental cylinder with a thickness of 5 cm, followed by manual compaction and then compaction with a high-head water rammer. At the beginning of the experiment, the water level added to the experimental cylinder was 50 mm (marked on the tube). When the funnel at the bottom of the cylinder started discharging water, the timer was started. According to specific time intervals of 1, 2, 3, 4, 5, 7, and 10 min, the water seepage under the infiltration pipe is collected and recorded. Each time the amount of seepage is recorded, the head is promptly raised to 50 mm to maintain a specific pressure gradient.

Data Collection and Analysis: During the experiments, rainwater was collected from the bottom of the infiltration tubes at specific time intervals using beakers and measuring cylinders. The volume of rainwater was then manually recorded. The experimental data were recorded and imported into a computer. The volume of rainwater was divided by the cross-section of the cylinder to obtain the corresponding infiltration height. Subsequently, the infiltration height was divided by the corresponding time interval to calculate the initial and stable infiltration coefficients of the different amended soils.

2.1.3. Improved Soil Purification Experiment

Experimental Apparatus: The equipment for this experiment is almost the same as the previous experimental equipment, but it is necessary to use 1-liter opaque white plastic bottles to preserve the rainwater collected.

Experimental Method: To assess the purification effect, it is important to note that bioretention ponds are more effective at removing particulate pollutants from actual runoff. Therefore, evaluating the removal efficiency of amended soil on dissolved pollutants can provide a more direct indication of its purification capacity. In this study, the pollutants were manually configured to simulate natural rainfall (Table 3). Different concentrations of pollutants were prepared to spray the soil layer with a specific rainfall intensity, and the rainfall lasted for 1 hour. Once the rainfall commenced, the purified rainwater at the bottom of the soil layer was collected and sampled. The sampled water was then sent to a professional organization for testing after the rainfall ended. This was carried out to investigate the purification capacity of the amended soil under different pollutant loads. The purification capacity of the improved soil was measured under varying pollutant loads.

Table 3. Table of pollutant counterparts for test configurations.

Added Substance	Modeled Pollutant Indicators
Glucose	COD
Sodium dihydrogen phosphate	TP
Ammonium chloride	NH ₄ ⁺ -N

Data Collection and Analysis: The COD, TP, and NH₄⁺-N contents of the initial natural rainwater and purified rainwater were obtained through professional testing organizations. The pollutant contents of the purified rainwater were compared with those of the initial natural rainwater to obtain the removal rate of the corresponding pollutants.

The instruments required for the experiments in this study as well as the experimental site are shown in Figure 2.

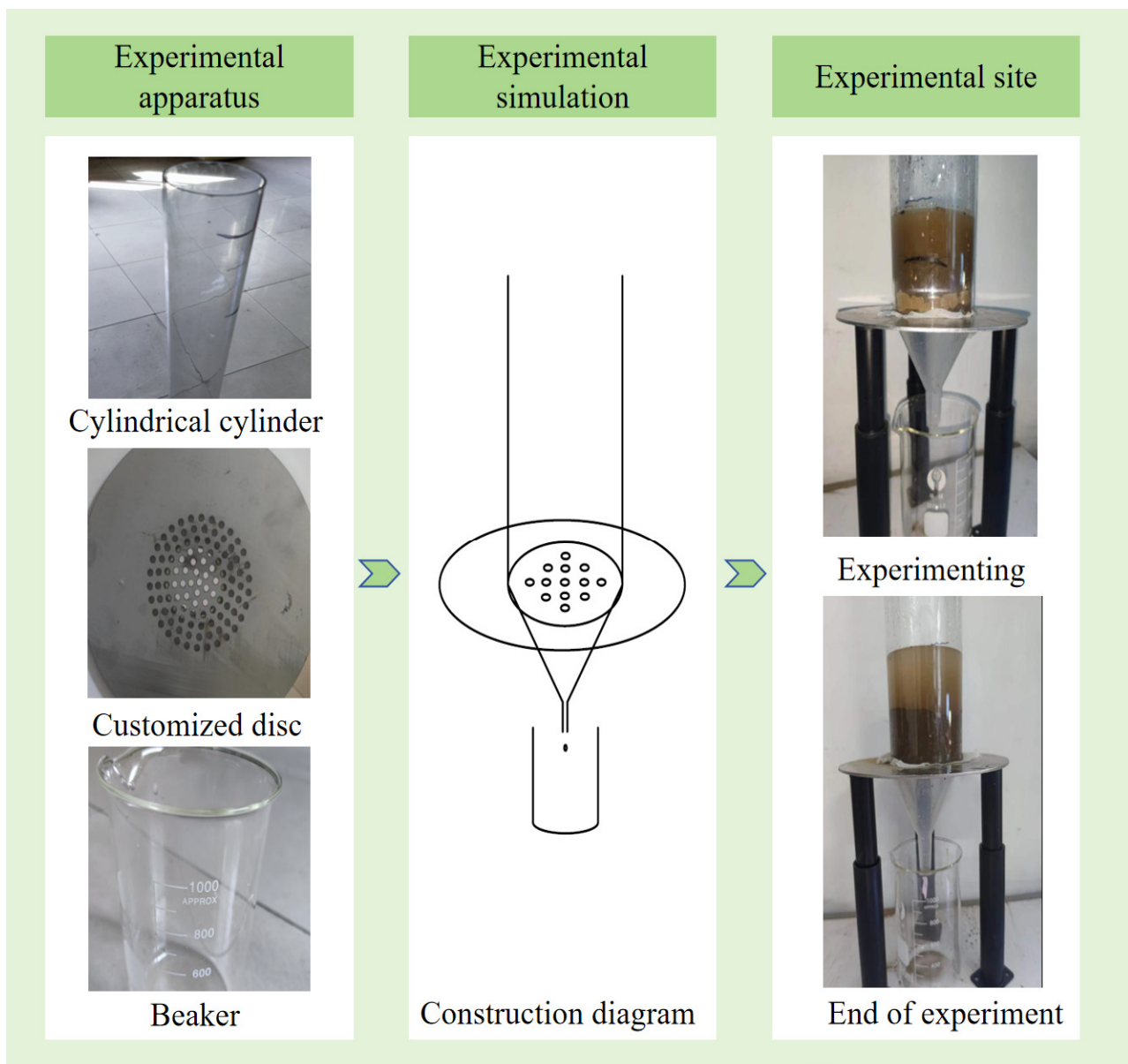


Figure 2. Instruments required for the experiment and the experimental site.

2.2. Establishment of Subjective and Objective Assignments

This section includes three aspects: determination of subjective weights, determination of objective weights, and determination of comprehensive weights. The comprehensive indicator evaluation system for soil improvement by bioretention facilities first determines the evaluation indicators through qualitative analysis. Subsequently, AHP was used to subjectively assign weights to the indicators (Section 4.2) and test their consistency. The indicators were further objectively assigned based on the raw data, and finally, the Lagrange multiplier method was used to determine the comprehensive weights.

2.3. Comprehensive Evaluation

According to the weights of the indicators calculated in the previous section, the TOPSIS method was used to evaluate the different improvement schemes individually. On the basis of constructing the dimensionless judgment matrix Z , the positive and negative ideal solutions of each scheme are calculated. Subsequently, the relative closeness of each

scheme is further determined and ranked. Finally, the fill layer improvement scheme with the highest relative proximity is recommended for practical engineering construction.

In summary, the comprehensive evaluation framework for this study is shown in Figure 3.

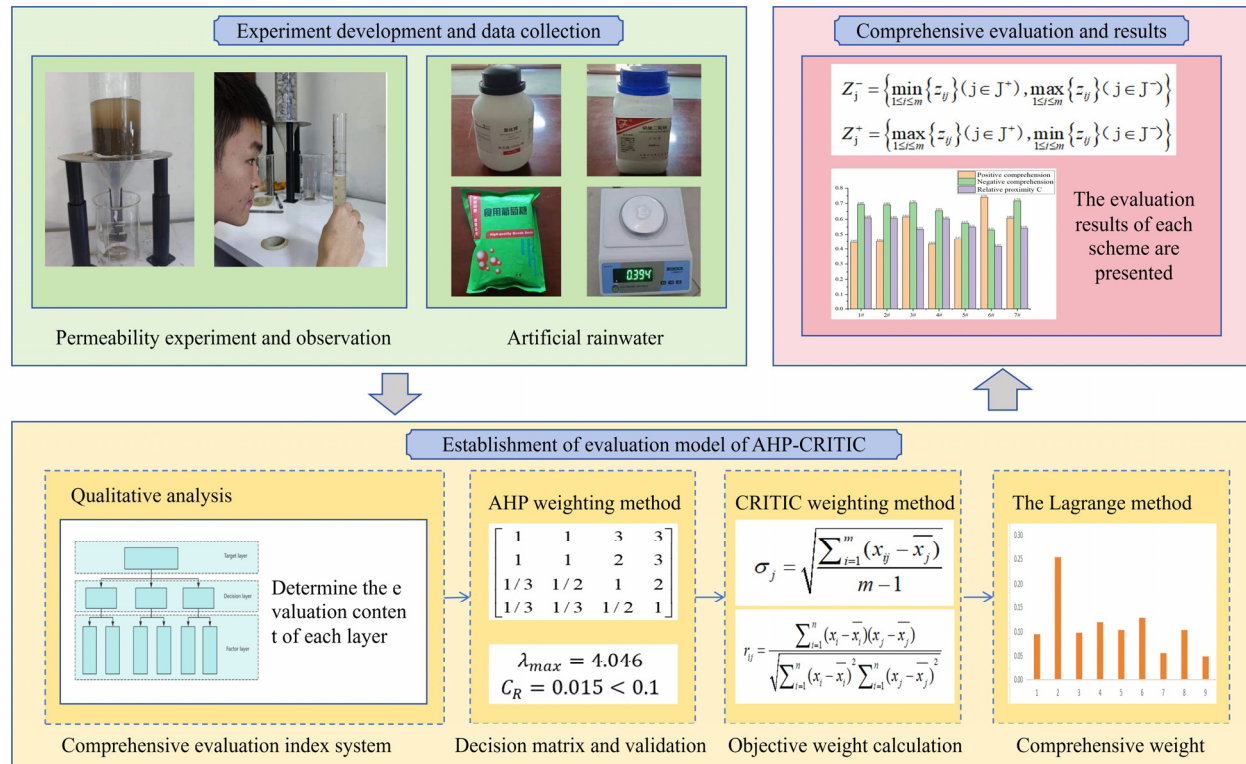


Figure 3. Modeling Framework for Integrated Evaluation of Biological retention facilities for Soil Improvement.

3. Evaluation Modeling of Bioretention-Amended Soil Models

3.1. Evaluation Process for Bioretention Cell Fill Layer Modification

The effectiveness of bioretention cell soil improvement is generally influenced by the performance of the improved material itself, including factors like adsorption, microstructure, and catalytic properties. It is also influenced by the structure of the improved soil, such as porosity, pore size distribution, pore shape, particle arrangement density, and the degree of pore connectivity. However, the aforementioned factors are inherent to the structure and do not intuitively reflect the advantages and disadvantages of the improvement effect. In this study, we conducted preliminary literature research and consulted with relevant experts to determine the comprehensive evaluation of the influencing factors of bioretention pond soil improvement, focusing on aspects such as penetrating quality, purification effect, and so on (Figure 4).

Further, when evaluating the actual effects, the analytic hierarchy process (AHP) was first introduced to summarize the assessment indicators for the advantages and disadvantages of soil improvement benefits and determine the subjective weights of the corresponding indicators. Based on the experimental data, the CRITIC method was used to calculate the differences and conflicts and determine the objective weights. Subsequently, the Lagrangian method was used to calculate the combined weights under subjective and objective criteria. Finally, the correlation coefficients of each improvement scheme were calculated and ranked using the TOPSIS method, which led to the construction of a comprehensive benefit evaluation model for the improved packing layer of bioretention ponds, based on the AHP-CRITIC method. The research idea of comprehensive evaluation in this section is shown in Figure 5.

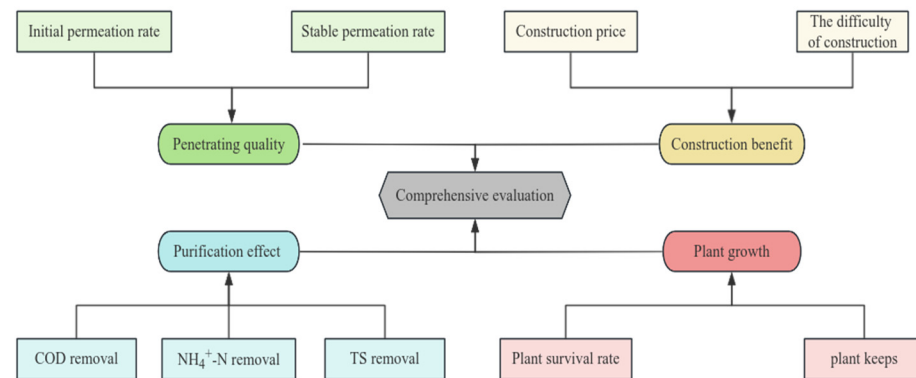


Figure 4. Factors affecting the comprehensive evaluation of soil amendment in Biological retention facilities.

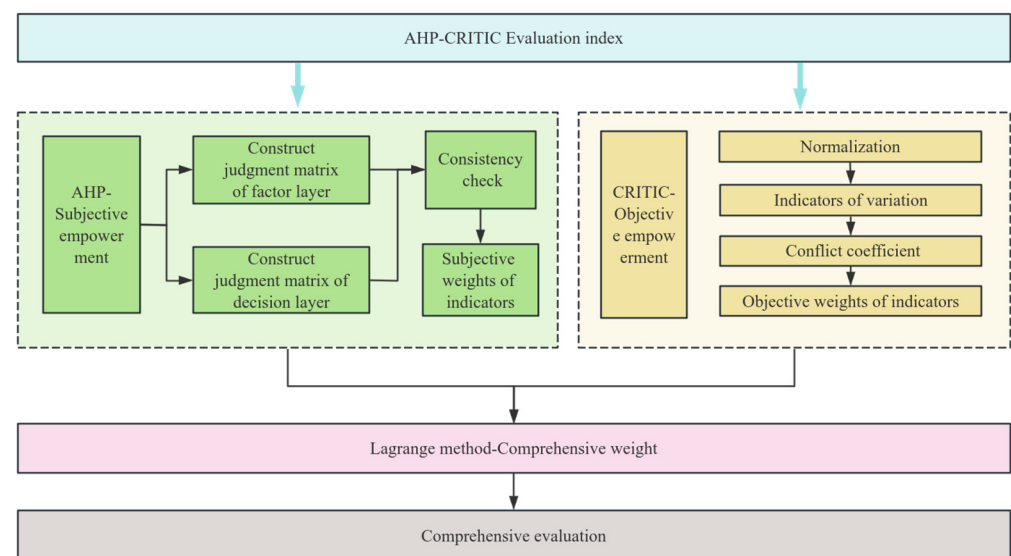


Figure 5. Flow chart for comprehensive assessment of bioretention pond improvements.

3.2. Selection of Indicators for the Assessment Methodology

Based on the beneficial factors affecting the effectiveness of soil improvement, an analysis was conducted to identify the factors that are most representative of the benefits of soil improvement and those that contribute the most. Firstly, the permeability coefficient was filtered out because a higher permeability coefficient can be visualized as indicating better permeability. Subsequently, the evaluation index for the pollutant removal rate was chosen from a wide range of indexes. In previous studies, the pollutant removal rate of rainwater was mainly considered in terms of COD, SS, ammonia nitrogen, total nitrogen, total phosphorus, and metal ions. At the same time, this study needs to consider not only the benefits of improved soil itself but also how to make the improved soil materials more applicable and popular. The economic cost of construction, plant survival, and ease of construction were also considered. By summarizing the above evaluation factors, the evaluation factors for bioretention soil improvement were comprehensively obtained, resulting in a total of 9 indicators as follows in Table 4.

Table 4. Indicator system for integrated benefits of bioretention soil improvement.

Target Layer	Decision Layer	Factor Layer
Indicator system for comprehensive benefits of soil improvement in biological retention facilities	A Permeability	A_1 Initial permeability rate
		A_2 Stabilized permeability rate
	B Purification effect	B_1 COD removal rate
		B_2 Ammonia nitrogen removal rate
		B_3 Total phosphorus removal
	C Vegetative growth	C_1 Planting survival rate
		C_2 Vegetative state
	D Construction benefit costs	D_1 Unit price for soil improvement
		D_2 Ease of construction

3.3. Determination of Subjective Weights for the AHP Hierarchical Analysis Method

Hierarchical analysis is a systematic method that combines qualitative and quantitative analysis techniques. It breaks down the problem into different constituent factors and according to the interrelated influence of these factors and their affiliation based on different levels of aggregation and combination. This forms a multilevel analysis of the structural model, ultimately simplifying the problem to the lowest level in relation to the highest level. This helps determine the relative importance of weights or the relative advantages and disadvantages for ranking purposes. The specific steps are as follows:

3.3.1. Create an Initial Judgment Matrix

When analyzing the target problem, if there are m evaluation targets and n evaluation indicators for each evaluation target, the judgment matrix is constructed as shown below:

$$D = \begin{bmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1n} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{nm} \end{bmatrix} = \begin{bmatrix} D_1(X_1) \\ \vdots \\ D_2(X_2) \\ \vdots \\ D_m(X_m) \end{bmatrix} \quad (1)$$

where: D is the evaluation objective, $X_1, X_2, \dots, X_m$ is the evaluation program; $x_{11}, x_{ij}, \dots, x_{mn}$ are the evaluation indicators; and x_{ij} denotes the importance weight of factor i compared to factor j , which is usually quantified using a 1~9 scale (Table 5).

Table 5. AHP Nine-Level Method of Comparison Scale.

Explanation of the Results of the Comparison of Indicators	Contrast Scale
Both factors are equally important	1
The former is slightly more important than the latter when comparing the two factors	3
When comparing the two factors, the former is significantly more important than the latter	5
The former is very important compared to the latter	7
The former is particularly more important than the latter when comparing the two factors	9
Midway between two levels	2, 4, 6, 8

3.3.2. Judgment Matrix Normalization

Data standardization for indicators in the indicator system:

$$\bar{x}_{ij} = \frac{x_{ij}}{\sum_{i=1}^n x_{ij}} (i = 1, 2, \dots, n; j = 1, 2, \dots, m) \quad (2)$$

The standard judgment matrix is then regularized to obtain the weight coefficients.

$$w_i = \frac{\bar{w}_i}{\sum_{i=1}^m \bar{w}_i} \quad (3)$$

where $\bar{w}_i = \sum_{j=1}^n \bar{x}_{ij}$, w_i is the indicator weight.

3.3.3. Calculating Eigenvalues

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^n \frac{(DW)_i}{W_i} \quad (4)$$

where $\lambda_{\max}$ is the matrix maximum.

3.3.4. Test the Consistency of the Decision Matrix to Ensure the Accuracy of the Evaluation Results

$$\begin{cases} CI = \frac{\lambda_{\max} - n}{n-1} \\ CR = \frac{CI}{RI} \end{cases} \quad (5)$$

where: CI is the consistency index, $\lambda_{\max}$ is the maximum characteristic root of the judgment matrix, RI is the average stochastic consistency index, the value of which is referred to in Ref. [38].

If $CR < 0.1$, the judgment matrix is considered consistent, otherwise it is not.

In this study, six experts specializing in the research field of biological detention facilities were consulted. Judgment matrices were constructed, and consistency tests were conducted. The weight calculation for each layer is shown in Table 6.

Table 6. AHP weighting table.

Evaluation Layer	Content	Evaluation Matrix	Consistency Test
Decision layer	A, B, C, D	$\begin{bmatrix} 1 & 1 & 3 & 3 \\ 1 & 1 & 2 & 3 \\ 1/3 & 1/2 & 1 & 2 \\ 1/3 & 1/3 & 1/2 & 1 \end{bmatrix}$	$\lambda_{\max} = 4.046$ $CR = 0.015 < 0.1$
	A_1, A_2	$\begin{bmatrix} 1 & 8 \\ 1/8 & 1 \end{bmatrix}$	$\lambda_{\max} = 2$ $CR = 0 < 0.1$
Factor layer	B_1, B_2, B_3	$\begin{bmatrix} 1 & 1/2 & 1/2 \\ 2 & 1 & 2 \\ 2 & 1/2 & 1 \end{bmatrix}$	$\lambda_{\max} = 3.054$ $CR = 0.027 < 0.1$
	C_1, C_2	$\begin{bmatrix} 1 & 4 \\ 1/4 & 1 \end{bmatrix}$	$\lambda_{\max} = 2$ $CR = 0 < 0.1$
	D_1, D_2	$\begin{bmatrix} 1 & 6 \\ 1/6 & 1 \end{bmatrix}$	$\lambda_{\max} = 2$ $CR = 0 < 0.1$

The calculation results in Table 6 show that each matrix constructed meets the requirements of the consistency test and can be calculated in the next step. Subsequently, each evaluation matrix is normalized and calculated. The weights between evaluation layers and the weights between indicators of each program layer are then determined. Finally, by

multiplying the interindicator weights corresponding to $A_1, A_2, B_1 \dots$ and their respective weights, the AHP indicator weight summary in Table 7 is obtained.

Table 7. Summary table of AHP indicator weights.

	Weight		Interindicator Weights	Actual Weight
Permeability	0.38	A_1 Initial permeability rate	0.11	0.04
		A_2 Stabilized permeability rate	0.89	0.34
Purification effect	0.34	B_1 COD removal rate	0.25	0.07
		B_2 Ammonia nitrogen removal rate	0.43	0.17
		B_3 Total phosphorus removal	0.32	0.10
Vegetative growth	0.17	C_1 Planting survival rate	0.80	0.14
		C_2 Vegetative state	0.20	0.03
Construction benefit costs	0.11	D_1 Unit price for soil improvement	0.86	0.09
		D_2 Ease of construction	0.14	0.02

From the results of AHP calculations, it is evident that different indicators have different weights, in which the stabilized infiltration rate A_2 holds the highest subjective weight at 34%, followed by the ammonia nitrogen removal rate at 15%, the plant planting survival rate of 15%, and the price of the unit of improved soil at 9%. This phenomenon can be attributed to:

During rainfall, the initial permeability rate plays a minor role in the overall infiltration process, occupying only a short period, while the stabilizing permeability rate plays a role throughout the middle and later stages of rainfall. Therefore, its influence on the overall permeability effect is greater and carries more weight.

In terms of purification effectiveness, both COD and ammonia nitrogen can significantly harm water quality. In bioretention facilities, high levels of ammonia nitrogen can lead to an increase in photosynthetic microorganisms, primarily algae. This can result in eutrophication of the water body, ultimately causing blockage of the bioretention pond pores. Therefore, the increase in ammonia nitrogen content will not only affect the purification efficiency but also result in decreased permeability.

In addition, the successful survival of plants can reduce soil erosion. The roots of plants can absorb some of the pollutants and improve the purification effect. Therefore, it also occupies a more important proportion. Finally, whether the improvement program can actually be promoted and implemented is considered. Therefore, its economic factors also need to be considered and the economic cost is also an essential factor.

3.4. Determination of Objective Weights for the CRITIC Method

The CRITIC method is an improvement of the entropy weight method, which is a type of objective weight assignment method. This method measures the degree of difference between the indicators themselves and the mutual influence and intrinsic connection between multiple indicators through the standard deviation and correlation coefficient of the indicator data. It aims to comprehensively assess the relationship between the indicators, determine the amount of information each indicator contains, and consequently establish the objective weight of each indicator. The evaluation steps are as follows.

3.4.1. Data Normalization Process

First, the relevant raw data of the program are listed (Table 8). The raw data calculation method is based on expert ratings, statistical data, and relative standards. The data in the comparison matrix are standardized and divided into forward and reverse processing. In forward processing, the larger the value, the better; in reverse processing, the smaller the

value, the better. Specifically, the choice is made based on the scoring criteria, and the data-processing process is as follows:

Normalization:

$$b_{ij} = \frac{\max x_j - x_{ij}}{\max x_j - \min x_j} \quad (6)$$

Reverse

$$b_{ij} = \frac{\max x_j - x_{ij}}{\max x_j - \min x_j} \quad (7)$$

where: x_{ij} represents the raw data in the matrix, x_j represents the maximum value of the row to which the original data belongs, and b_{ij} is the result of normalizing the original data in the matrix.

Table 8. Experimental program raw data.

	#1	#2	#3	#4	#5	#6	#7
A ₁ Initial permeability rate	3.777	4.495	6.495	3.495	4.895	6.095	3.036
A ₂ Stabilized permeability rate	0.682	0.835	0.988	0.741	0.811	0.906	0.413
B ₁ COD removal rate	0.746	0.728	0.673	0.679	0.650	0.610	0.699
B ₂ Ammonia nitrogen removal rate	0.679	0.676	0.65	0.668	0.646	0.556	0.662
B ₃ Total phosphorus removal	0.711	0.708	0.697	0.690	0.674	0.646	0.706
C ₁ Planting survival rate	0.7	0.64	0.58	0.72	0.68	0.6	0.8
C ₂ Vegetative state	7	7.5	6	7	7	6	8
D ₁ Unit price for soil improvement	66.8	81.6	96.4	59.8	67.6	75.4	52
D ₂ Ease of construction	6	6.3	6.5	5.9	6.1	6.1	5

3.4.2. Calculation of the Variational Index of the Evaluation Indicator x_j

The larger the value of the standard deviation, the greater its variability, the more information it contains, and the higher the weight. The standard deviation of the evaluation index x_j is calculated.

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^m (x_{ij} - \bar{x}_j)^2}{m - 1}} \quad (8)$$

where: m is the evaluation objective.

3.4.3. Calculation of Correlation Coefficients between Evaluation Indicators (Conflictual)

The correlation coefficient r_{ij} between indicators is calculated. The larger the value of the correlation coefficient between indicators, the higher the degree of correlation, indicating a more uniform amount of information contained and a smaller weight. The correlation coefficient r_{ij} is calculated by the following formula.

$$r_{ij} = \frac{\sum_{i=1}^n (x_i - \bar{x}_i)(x_j - \bar{x}_j)}{\sqrt{\sum_{i=1}^n (x_i - \bar{x}_i)^2 \sum_{i=1}^n (x_j - \bar{x}_j)^2}} \quad (9)$$

where: n is the evaluation objective.

3.4.4. Calculation of Objective Weights

By calculating the variational indicators and relative coefficients, and then determining the objective weights corresponding to each indicator X_j , the corresponding calculation formula can be expressed as follows:

$$w_{2j} = \frac{c_j}{\sum_{j=1}^n c_j}, \text{ and } C_j = \sigma_j \sum_{j=1}^n (1 - r_{ij}) \quad (10)$$

Through the processing of raw data and the calculation of variability and conflict, the objective weights of the indicators based on the CRITIC method were finally obtained. The calculation process and results are shown in Table 9.

Table 9. CRITIC assignment method evaluation of layer indicator weights.

	A_1	A_2	B_1	B_2	B_3	C_1	C_2	D_1	D_2
Variability	0.378	0.324	0.339	0.345	0.358	0.366	0.343	0.330	0.321
Conflictual	12.117	11.479	6.317	5.975	6.254	6.210	6.256	6.955	7.774
Weights	0.19	0.16	0.09	0.08	0.09	0.10	0.09	0.10	0.10

3.5. Comprehensive Weighting Calculation and Comprehensive Evaluation Methodology

On the basis of obtaining the subjective and objective weights, it is necessary to analyze the correlation between the two. This involves determining whether the subjective weight obtained by the AHP method and the objective weight obtained by the CRITIC method are significantly correlated. This is carried out through a test of significance of the p value. If the p value is greater than 0.05, it means that the two weights are not correlated. In other words, the contents reflected in these two methods of empowerment are independent of each other and do not exhibit repetitive patterns.

Regarding the Pearson correlation coefficient, specific analysis reveals that the correlation value coefficient between subjective and objective weights is 0.263, which is close to 0. The p value is 0.494, which is greater than 0.05. This suggests that there is no correlation between X and Y , meeting the requirements for calculating the composite weights.

When calculating the comprehensive weights, the Lagrange multiplier method is used to find the extreme value of a multivariate function whose variables are constrained by one or more conditions. This method can be used to solve the optimal combination of weights assigned by the AHP and CRITIC methods, resulting in the comprehensive weights. The comprehensive weights accounted for by each index are presented in Table 10.

$$w_j = \frac{\sqrt{w_{1j}w_{2j}}}{\sum_{j=1}^n \sqrt{w_{1j}w_{2j}}}, j = 1, 2, \dots, n \quad (11)$$

where: w_j is the combined weight, w_{1j} is the subjective weight, and w_{2j} is the objective weight.

Table 10. Lagrangian method of combining weights.

	A_1	A_2	B_1	B_2	B_3	C_1	C_2	D_1	D_2
Weights	0.09	0.25	0.09	0.13	0.10	0.13	0.06	0.10	0.05

Subsequently, this paper utilizes the TOPSIS integrated evaluation method to comprehensively evaluate a series of bioretention ponds for amended soils. The method combines the advantages of both AHP and CRITIC methods. On the basis of determining the comprehensive weights using the AHP-CRITIC method, TOPSIS was employed to calculate the Euclidean distance of the positive ideal solution and the Euclidean distance of the negative ideal solution for the amelioration schemes. Subsequently, the relative proximity was further calculated to rank the schemes, ultimately identifying the amelioration scheme with the best comprehensive benefits.

4. Comprehensive TOPSIS Evaluation of Modified Biological Retention Facilities

4.1. TOPSIS Comprehensive Evaluation Calculations

The TOPSIS method is a ranking method that approximates the ideal solution. It only requires the utility functions to be monotonically increasing or decreasing in nature. At the same time, the TOPSIS method is commonly used and effective in multiobjective decision analysis. It is also known as the technique for order of preference by similarity to ideal solutions. Therefore, it is applicable to the comprehensive evaluation in this study. Its basic principle is to rank evaluation objects by detecting their distance from the optimal solution and the worst solution. If the evaluation object is closest to the optimal solution and farthest from the worst solution simultaneously, then it is considered the best; otherwise, it is deemed suboptimal. The final result is determined by the correlation coefficient, and the larger the correlation coefficient, the better the solution.

Before conducting a comprehensive evaluation of the seven improvement program groups using the TOPSIS method, it is necessary to normalize the raw data because in the raw data, the larger the value of the evaluation indexes $A_1, A_2, B_1, B_2, B_3, C_1, C_2$, the better the performance of this aspect. Therefore, it is necessary to carry out forward processing. Conversely, the larger the value of the evaluation indexes D_1, D_2 , the worse the performance of this aspect, so it is necessary to carry out inverse processing. The results of the treatment are shown in Table 11.

Table 11. Normalization of experimental data.

	#1	#2	#3	#4	#5	#6	#7
A_1 Initial permeability rate	0.214	0.422	1.00	0.133	0.537	0.884	0
A_2 Stabilized permeability rate	0.468	0.734	1.000	0.571	0.693	0.857	0
B_1 COD removal rate	1.000	0.868	0.463	0.507	0.294	0.000	0.654
B_2 Ammonia nitrogen removal rate	1.000	0.976	0.764	0.911	0.732	0.000	0.862
B_3 Total phosphorus removal	1.000	0.955	0.788	0.682	0.439	0.000	0.924
C_1 Planting survival rate	0.545	0.273	0.000	0.636	0.455	0.473	1.000
C_2 Vegetative state	0.500	0.750	0.000	1.000	0.500	0.267	0.5
D_1 Unit price for soil improvement	0.667	0.333	0.091	0.824	0.649	0.091	1.000
D_2 Ease of construction	0.333	0.133	0.000	0.400	0.267	0.008	1.000

4.1.1. Determining Positive and Negative Ideal Solutions

On this basis, the dimensionless judgment matrix Z is constructed and the positive and negative ideal solutions are further determined as shown in the following equation:

$$Z_j^- = \left\{ \min_{1 \leq i \leq m} \{z_{ij}\} (j \in J^+), \max_{1 \leq i \leq m} \{z_{ij}\} (j \in J^-) \right\} \quad (12)$$

$$Z_j^+ = \left\{ \max_{1 \leq i \leq m} \{z_{ij}\} (j \in J^+), \min_{1 \leq i \leq m} \{z_{ij}\} (j \in J^-) \right\} \quad (13)$$

where: J^+ denotes an extreme value indicator, J^- denotes a very small value indicator, and Z_{ij} denotes the elements within the matrix.

4.1.2. Calculating the Positive Ideal Solution D^+ and the Negative Ideal Solution D^- for Each Scheme

$$D_i^+ = \sqrt{\sum_{j=1}^n (z_{ij} - z_j^+)^2} \quad (14)$$

$$D_i^- = \sqrt{\sum_{j=1}^n (z_{ij} - z_j^-)^2} \quad (15)$$

4.1.3. Determining the Relative Proximity C

The relative proximity C is calculated and ranked.

$$D_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (16)$$

Here, $D_i \in [0, 1], i = 1, 2, \dots, m$.

The final calculation of the relevant content according to the above formula and its calculation results are shown in Figure 6 below.

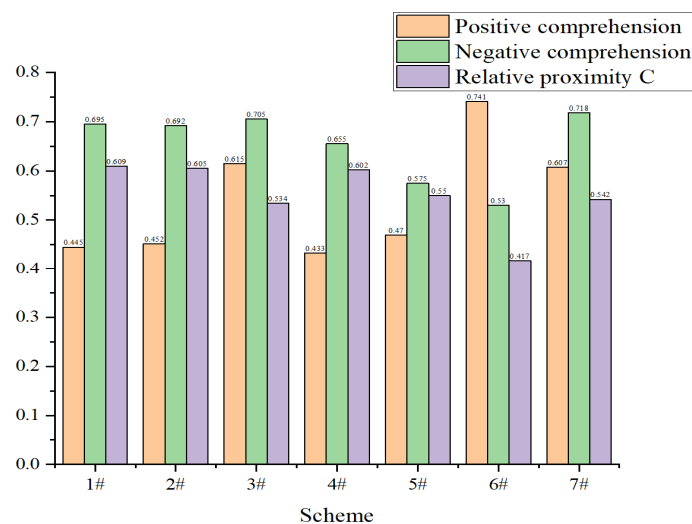


Figure 6. Map of comprehensive evaluation results for each program.

The calculations reveal that the correlation coefficient (C) for scheme #1 is 0.609, for scheme #2 it is 0.605, for scheme #3 it is 0.534, for scheme #4 it is 0.602, for of scheme #5 it is 0.550, for scheme #6 it is 0.417, and for scheme #7 it is 0.542. The rankings of each scheme are shown in Table 12 below.

Table 12. Ranking table of schemes.

Rank	Relative Proximity C	Scheme
1	0.609	#1
2	0.605	#2
3	0.602	#4
4	0.550	#5
5	0.542	#7
6	0.534	#3
7	0.417	#6

4.2. Analysis of Results by Program

In summary, scheme #1 is more beneficial for utilization in engineering practice. The results of the calculations show that scheme #1, i.e., 10% zeolite-amended soil, has the best overall performance. However, the comprehensive score of scheme #4 and scheme #2, which involve 10% gravel-amended soil and 20% zeolite-amended soil, respectively, is not significantly different from that of scheme #1. The reason may be that scheme #1 has achieved good results in the main weighting parameters, such as stabilized permeability rate, purification effect, and construction cost. Therefore, the comprehensive score is the highest. For scheme #4 and scheme #2, the main reason for the slight difference compared to scheme #1 is that both of them achieved good results in the primary weighting parameters, some even better. However, when considering economic cost factors and plant growth factors, there is a lack of similarity in these aspects, resulting in an overall score that is not higher than that of scheme #1. In summary, scheme #1 is more worthwhile to be used in engineering practice.

In addition, the results of this experiment are consistent with those of Liao Jiang [39] in that the infiltration rate of the filler can be directly increased with the increase in the proportion of soil amendment filler, but it will also negatively affect the purification effect of the amended filler and the plant growth. Therefore, it should be comprehensively considered in the improvement of the biological retention facilities. However, the qualitative analysis of Liao Jiang's improvement plan differs from that of the present study. The two studies utilized different types of native soil, modified gravel, and zeolite particle size. The present study considered more and more specific factors, including economic costs, construction difficulty, and other related factors. Therefore, from a comprehensive perspective, the selection results of this study are more convincing and accurate.

According to the evaluation results of AHP-CRITIC for the improvement program, it provides an important reference basis for understanding the strengths and weaknesses of the bioretention pond soil improvement effect, as well as for guiding future construction and promotion efforts. With the development of sponge city construction and biological retention facilities, an increasing number of soil improvement programs will continue to emerge. Although this method may not be the best comprehensive evaluation program, the operation and principle of this study are simple and it can be used as one of the important selection criteria for different subsequent studies.

5. Conclusions and Outlook

The seepage effect of bioretention facilities is closely related to the composition of the filler layer. Improving the filler layer of bioretention facilities can effectively improve the runoff control and purification effects. Therefore, this method is widely utilized in the construction of sponge cities. At present, numerous studies focus on the improvement of bioretention facility filler. With future development, there will be more and more bioretention facility filler improvement programs. Therefore, it is necessary to select the most suitable improvement program based on the comprehensive evaluation.

In this paper, a comprehensive evaluation was conducted for seven groups of experimental programs. Firstly, the index evaluation system was determined by combining the AHP method and the expert consultation method. Secondly, the judgment matrix was constructed using the AHP method to calculate the subjective weights of the indexes. Subsequently, the raw data underwent dimensionless processing through the CRITIC method to obtain the objective weights. Finally, the comprehensive weights were further calculated by the Lagrangian method. On this basis, the comprehensive weights are combined with the comprehensive evaluation method to obtain the evaluation results. The study yields the following conclusions:

1. In the weighting of the indicators, the stabilized permeability rate of 25% accounted for the largest proportion, followed by the plant survival rate of 13% and the removal rate of ammonia nitrogen of 12%.

2. The comprehensive evaluation results showed that the soil improved by 10% zeolite had the best comprehensive effect, followed by the soil improved with 10% sand and 20% zeolite. The optimal scheme has a more stable permeability rate, purification effect, and construction cost, but not all indicators show superior performance. The reason is that the proportion of zeolite in the optimal scheme is lower. As a result, the performance of infiltration storage and purification effects is not as good as in other schemes with a higher improvement ratio. However, this also leads to the advantage of lower construction costs for the scheme. Therefore, it can be seen from the conclusion of this study that relevant scholars should consider other factors in addition to their own stable permeability rate and purification effect when improving the filler layer. In this way, the comprehensive benefits of improved soil can be better, and then the application and promotion of improved schemes can be carried out.
3. The evaluation model proposed in this study is able to effectively measure the relationship between various factors by looking at factors such as permeability performance, purification effect, economic cost, and construction. Subsequently, it successfully identifies the soil amendment structure with the best comprehensive benefits for bioretention facilities. At the same time, the methods and ideas of this study are generalizable and can be used not only for the comprehensive evaluation of soil improvement in bioretention facilities but also for the comprehensive benefit evaluation of other LID facilities.
4. In the research experimental program, specific indicators are determined based on literature research and consultation with relevant experts, so they have a certain degree of subjectivity. At the same time, errors in the experimental process can also result in insufficient precision in the raw data. However, on the whole, the comprehensive evaluation ideas and methods in this paper will not be changed as a result, and they are of great significance.
5. In the future, the methodology of this study can provide support for the construction and promotion of future improved fill layer bioretention ponds and other LID facilities. This will further advance the construction of green, efficient, and economical sponge cities.

Author Contributions: H.L.: Determined the research ideas and theoretical methods of the whole study, designed different improvement schemes, and carried out related experiments and data collection work. M.W.: According to different improvement schemes, put forward specific evaluation indexes, corresponding AHP-CRITIC evaluation method, and comprehensive evaluation model. X.J.: Collated, analyzed, and calculated the data collected in the experiment. Q.Y.: Responsible for organizing all data and editing the article. All authors have read and agreed to the published version of the manuscript.

Funding: Key Research and Development Program of Shaanxi Province, S2022-YF-LLRH-10-0022.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: The conduct of the experiment in this article meets the requirements of moral ethics and has obtained moral approval. At the same time, all participants gave their consent.

Data Availability Statement: All data generated or analyzed during this study are included in this published article.

Conflicts of Interest: Author Hui Liang and Meng Wu were employed by the company Shaanxi Huashan Road and Bridge Group Co., Ltd., and Shaanxi Zhengcheng Road and Bridge Engineering Research Institute Co., Ltd., The remaining 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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