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Evaluation for Suitability of Urban Roof Greening in Arid Areas of Northwest China

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Abstract:

Roof greening is an effective method which can improve urban ecological environment, and the suitability evaluation of roof greening is of great significance to improve the quality of human dwelling environment in semi-arid areas of Northwest China. Firstly, five factors including cost attribute, building attribute, roof attribute, greening attribute and facility attribute were chosen in this paper to construct the suitability evaluation index system of urban roof greening in semi-arid area of Northwest China. Secondly, the AHP was used to calculate the weight, and the multi-level fuzzy analysis method was used to establish the suitability evaluation model of urban roof greening. Finally, the suitability evaluation of 32 samples of urban roof greening in Lanzhou was conducted. The results indicated that only 2 samples were in the suitable grade, 8 samples were in the grade secondary to suitable grade, 22 samples were in the unsuitable grade, and the overall suitability degree of the samples was low. The suitability evaluation index system of roof greening has strong applicability for semi-arid areas of Northwest China, and the research results are expected to provide decision-making basis for urban artificial ecosystem construction in semi-arid areas.

Keywords: *The semi-arid areas of Northwest China; Roof greening; Suitability evaluation*

I. INTRODUCTION

As one of the effective ways of improving urban ecological environment, roof greening is related to the quality of human dwelling environment and the social sustainable development, and its importance has been widely concerned by all sectors of society [1, 2]. In recent years, with the rapid development of urban construction, the effective green space area in high-density areas has been constantly lacking, and ecological problems including rainstorm runoff and heat island effect are becoming more and more serious. How to use roof greening to increase greening rate and improve urban ecological function has become a research hotspot of relevant scholars [3]. At the same time, drought, as the main factor restricting the growth and development of plants, leads to the urban roof greening of semi-arid areas lagging far behind that of humid areas in the aspects of construction process and research heat, etc. Therefore, the present

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situation of roof greening in semi-arid areas is evaluated using the suitability evaluation method, which provides important decision support for planning and popularizing urban roof greening in semi-arid areas.

At present, the roof greening research in academic circles is mainly carried out from the aspects of roof greening structure technology, comprehensive benefits, plant screening [4], construction type [5], landscape configuration [6], maintenance management [7] and policies and regulations [9], etc. At present, the research on potential evaluation method of roof greening suitability mostly focuses on the attribute analysis of single building. Eight indicators including building location, roof direction, roof height, roof slope, roof load, sustainability and maintenance level of plant cultivation and formation were extracted by WILLKINSO [9] et al. to evaluate the potential of roof greening of existing buildings. After screening and introducing roof ownership, shading area and equipment area with reference to this standard, Shao Tianran et al. [10], Wang Xinjun et al. [11] and Luo Tianqing et al. [12] respectively conducted the suitability analysis of roof greening of existing buildings in Futian, Southern Jiangsu and Shanghai. In addition, from the perspective of urban planning, some scholars evaluate the spatial resource potential of roof greening. For example, Dong Liang et al. [13] discussed the problem of climate (wind and thermal environment) adaptability planning of roof greening system in Chengdu from the urban scale; Dong Jing et al. [14] summarized the evaluation system of implementation potential of roof greening in high-density urban areas from two aspects of planning zoning and building classification. It is indicated by the current research situation that the research of suitability evaluation of roof greening is an important reference for developing urban roof greening construction, but the existing evaluation index system mostly focuses on the research object in humid areas, and there are some limitations in the aspects of development and the decision-making of roof greening in semi-arid areas. Therefore, on the basis of climate characteristics in semi-arid areas, discussing the suitability of roof greening is necessary to improve the scientificity of urban roof greening and the feasibility of decision-making and development in semi-arid areas of Northwest China.

On the basis of the constraint of cold and arid conditions in semi-arid areas of Northwest China on roof greening, the evaluation factors that have important influence on the suitability of roof greening are selected. Considering that there are many factors which affect roof greening, in this study, the fuzzy comprehensive evaluation method is introduced, and the suitability evaluation model of roof greening is constructed, providing reference for scientific and reasonable roof greening utilization, roof greening construction site selection and relevant policy formulation in the semi-arid areas of Northwest China.

II. ESTABLISHING A COMPREHENSIVE EVALUATION INDEX SYSTEM

In this paper, based on investigating, analyzing the natural, economic and related technical regulations of the study area, according to the construction index associated with regional urban greening, by comprehensively referring to the index content of the evaluation system of roof greening suitability of existing buildings, the suitability evaluation of urban roof greening in semi-arid area of Northwest China was discussed so as to determine the suitability degree of roof greening construction of samples, and screen the factors affecting the suitability of roof greening and construct the evaluation index system from

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five aspects including cost attribute, building attribute, roof attribute, greening attribute and facility attribute. (As shown in Figure 1)

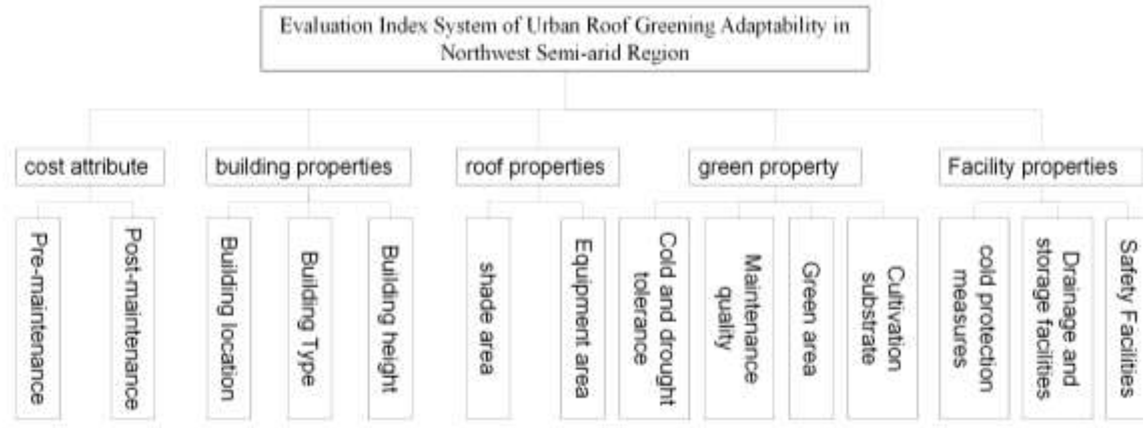

Fig 1: Suitability assessment index system for the urban roof greening in semi-arid areas of Northwest China

III. ESTABLISHING A MULTI-LEVEL FUZZY COMPREHENSIVE EVALUATION MODEL

3.1 Determination of Weights

After establishing the evaluation index, choosing the appropriate method to determine the weight of the evaluation index is the key of the rationality of the evaluation results. In this study, analytic hierarchy process was used to determine the weight of evaluation index, and the steps are as follows:

3.1.1 Constructing judgment matrix

The overall goal was divided into two levels of indicators in this study. Comparing the importance of each factor in the same level with that of one factor in the upper level, the index of "cost attribute" was taken as an example to construct a judgment matrix.

$\boldsymbol{A}=(\boldsymbol{a}_{ij})_{n\times n}$ is shown in table I, where the common values of $\boldsymbol{a}_{ij}$ are shown in table II.

TABLE I. Cost attribute importance level

	Pre-investment	Post-maintenance
Pre-investment	1	3
Post-maintenance	1/3	1

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TABLE II. The meaning of scaling

Bi to Bj	Same	Slightly stronger	Strong	Very strong	Absolutely strong	Same	Slightly weak	Weak	Very weak	Absolutely weak
aij	1	3	5	7	9	1	1/3	1/5	1/7	1/9

From the same to absolutely strong, it can be quantized as 2, 4, 6, 8 in turn between every two grades, that means $\boldsymbol{a}_{ij}$ can take 1, 2, …, 9 or their reciprocals, and be satisfied.

$$a_{ij} = 1,\ a_{ji} = \frac{1}{a_{ij}}, 1, 2, \ldots, n \tag{1}$$

A judgment matrix A can be obtained after comparing all indicators of “cost attribute” in pairs:

$$A = \begin{bmatrix} 1 & 3 \\ \frac{1}{3} & 1 \end{bmatrix} \tag{2}$$

3.1.2 Determining the index weight

The sum method is used to calculate the weight of each factor $\boldsymbol{A}$=(0.7500, 0.2500)

According to Table III, it can be indicated that the *RI* of 2-order judgment matrix is 0, so the judgment matrix meets the requirements of consistency test, and this group of weights can be accepted.

TABLE III. Average random consistency index

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

The weight aggregation of suitability evaluation of urban roof greening in semi-arid areas of Northwest China can be constructed after obtaining the weights of indexes at all levels. As shown in Table IV.

TABLE IV. Summary of comprehensive evaluation weights for roof greening in semi-arid areas of Northwest China

Factor layer	Factor weight	Indicator layer	Index weight
Cost attribute	0.2276	Pre-investment	0.7439
		Post-maintenance	0.2561
Architectural attribute	0.1558	Building location	0.2975
		Type of building	0.5396
		Building height	0.1629
Roof property	0.1462	Shading area	0.3333
		Equipment area	0.6667
Greening attribute	0.3633	Cold and drought resistance	0.2628

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		Maintenance quality	0.1439
		Green area	0.4524
		Cultivation medium	0.1409
Facility attribute	0.1071	Cold protection measures	0.2990
		Water drainage and storage facilities	0.5373
		Safety facilities	0.1637

3.2 Establishing the Evaluation Standard of Suitability Evaluation Index of Urban Roof Greening in Semi-Arid Area of Northwest China

3.2.1 Determining the evaluation index set

According to the suitability evaluation index system of urban roof greening in semi-arid area of Northwest China, the evaluation factors are taken as follows:

U={U1, U2, U3, U4, U5}={cost attribute, building attribute, roof attribute, roof attribute, greening attribute, facility attribute}

$U_1=\{U_{11}, U_{12}\}$

$U_2=\{U_{21}, U_{22}, U_{23}\}$

$U_3=\{U_{31}, U_{32}\}$

$U_4=\{U_{41}, U_{42}, U_{43}, U_{44}\}$

$U_5=\{U_{51}. U_{52}, U_{53}\}$

3.2.2 Determining the comment set and value set

The suitability degree of roof greening in semi-arid area of Northwest China is divided into three grades (as shown in Table V), that means $\boldsymbol{V}=\{v_1$(suitable), v_2(secondary to suitable), v_3(unsuitable) $\}$, which is quantitatively expressed as $\boldsymbol{V}=(100, 80, 60)^T$.

TABLE V. Evaluation standard of roof greening in semi-arid areas of Northwest China

Evaluation standard	Status rating
The comprehensive score is above 80 points	Appropriate
The comprehensive score is between 80 and 60 points	Secondary to suitable
The comprehensive score is below 60 points	Inappropriate

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3.3 Fuzzy Comprehensive Evaluation

Fuzzy comprehensive evaluation method is a very effective multi-factor decision-making method, which makes a comprehensive evaluation of things affected by many factors applying the principle of fuzzy relation synthesis [15]. This paper adopted a three-level fuzzy comprehensive evaluation model.

3.3.1 Primary hierarchical fuzzy comprehensive evaluation

According to Formula 5, the discriminant matrix of the index can be obtained

$$r_{ij}=\frac{c_{ij}}{\sum_{j=1}^{4} c_{ij}}\ (j=1,2,3) \tag{5}$$

Where c_{ij} is the number of people $\sum_{j=1}^{4} c_{ij}=10$ who are support that the index i chooses evaluation v_j as the number of judging teams.

10 roof greening experts were invited to grade each evaluation factor in cost attribute, building attribute, roof attribute, greening attribute and facility attribute according to the suitability evaluation of roof greening in Lanzhou. The "cost attribute" discriminant matrix was taken as following:

$$R_1=\begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \end{bmatrix} \tag{6}$$

The weight value of the cost attribute (U_1={U_{11}, U_{12}}) is A_1, and the weight vector is $\boldsymbol{A}1$; Then the evaluation result of cost attribute $\boldsymbol{B}_1=\boldsymbol{A}_1\bullet\boldsymbol{R}_1$. By the same token, the evaluation results of "building attribute", "roof attribute", "greening attribute" and "facility attribute" can be calculated.

3.3.2 Overall fuzzy comprehensive evaluation

The first factor set $U=\{U_1, U_2, U_3, U_4, U_4, U_5\}$, whose weight is A, and its total single factor evaluation matrix is

$$\mathbf{R}=\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix}=\begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \\ b_{41} & b_{42} & b_{43} \\ b_{51} & b_{52} & b_{53} \end{bmatrix} \tag{7}$$

Making overall comprehensive evaluation, and $\boldsymbol{B}=\boldsymbol{A}\bullet\boldsymbol{R}$ can be taken.

3.3.3 Calculating fuzzy comprehensive evaluation score

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Quantifying the grade of the evaluation set by percentile system, and weighting and averaging the evaluation results, the comprehensive score of the green roof of the sample can be obtained. Therefore, the comprehensive evaluation score of roof greening ***F*** is:

$$F=B\bullet V=(b_1, b_2, b_3)\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \tag{8}$$

IV. ENGINEERING CASES

4.1 Overview of the Study Area

The semi-arid areas of Northwest China is located in the north part of 32°N and the east part of 110°E, and it includes the south-central area of the Yellow River in Gansu Province, the north-central area of Shaanxi Province, Ningxia and the central area of Qinghai [16], and the topography in these areas mainly includes plateau, basin and mountain. Roof greening has always been a difficult point in ecological construction in semi-arid areas of Northwest China, and the characteristics of scattered distribution, small scale and single type have been formed in the special geographical environment. As a typical semi-arid city in Northwest China, Lanzhou is located inland with less precipitation. In addition, the influence of valley topography leads to obvious urban heat island effect and the ecological environment is fragile [17]. Therefore, Anning District, Qilihe District and Chengguan District of Lanzhou City were taken as the main research scope in this study.

4.2 Data Sources

The data used in the study were taken from the field investigation of roof greening in Lanzhou from December 2020 to January 2021 in winter and June 2020 to July 2020 in summer, and 32 samples were selected for data collection. The construction of roof greening was inspected and recorded in the field. The data of daily maintenance were obtained, and the questionnaire survey of green plant maintenance status was carried out for maintenance and management personnel by consulting the maintenance and management records of sample green roofs. The evaluation team was composed of 10 professionals and scholars in roof greening, and their evaluation was indicated by using the method of scoring, and the corresponding single factor evaluation matrix was obtained.

4.3 Determination of Evaluation Matrix

By taking the roof greening of Wangfujing Department Store Commercial Complex in Lanzhou as an example, the fuzzy comprehensive evaluation is carried out now, and the discriminant matrix of "cost attribute" can be obtained from Table VI:

$$R_1=\begin{bmatrix} 1.0000 & 0.0000 & 0.0000 \\ 0.0000 & 1.0000 & 0.0000 \end{bmatrix} \tag{9}$$

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TABLE VI. Expert's judgment on roof greening of Wangfujing Department Store Commercial Complex

Element layer	Indicator layer	Appropriate	Secondary to suitable	Inappropriate
Cost attribute	Pre-investment	10	0	0
	Post-maintenance	0	10	0
Architectural attribute	Building location	6	4	0
	Type of building	10	0	0
	Building height	6	4	0
Roof attribute	Shading area	0	10	0
	Equipment area	0	10	0
Greening attribute	Cold and drought resistance	1	5	4
	Maintenance quality	1	3	6
	Green area	0	10	0
	Cultivation medium	1	2	7
Facility attribute	Cold protection measures	1	2	7
	Water drainage and storage facilities	3	5	2
	Safety facilities	3	4	3

The weight value of the cost attribute (U_1={U_{11}, U_{12}}) is A_1=0.2276, and the weight vector is $\boldsymbol{A}1$=(0.7439, 0.2561); Then the evaluation result of cost attribute $\boldsymbol{B}_1=\boldsymbol{A}_1\bullet\boldsymbol{R}_1$=(0.7439, 0.2561, 0.0000).

By the same token, the evaluation results of "building attribute", "roof attribute", "greening attribute", "facility attribute" and "regional land use index attribute" can be calculated as follows:

The evaluation result of building attribute is $\boldsymbol{B}_2=\boldsymbol{A}_2\bullet\boldsymbol{R}_2$=(0.8158, 0.1842, 0.0000);

The result of roofing attribute is $\boldsymbol{B}_3=\boldsymbol{A}_3\bullet\boldsymbol{R}_3$=(0.0000, 1.0000, 0.0000);

The result of green attribute is $\boldsymbol{B}_4=\boldsymbol{A}_4\bullet\boldsymbol{R}_4$=(0.0548, 0.6552, 0.2901);

The result of judging facility attribute is $\boldsymbol{B}_5=\boldsymbol{A}_5\bullet\boldsymbol{R}_5$=(0.2402, 0.3939, 0.3659);

4.4 Overall Fuzzy Comprehensive Evaluation

The first factor set U={U_1, U_2, U_3, U_4, U_4, U_5, U_6}, its weight is $\boldsymbol{A}$=(0.2276, 0.1558, 0.1462, 0.3633, 0.1071), and the total single factor evaluation matrix is

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$$\mathbf{R}=\begin{bmatrix}B_1\\B_2\\B_3\\B_4\\B_5\end{bmatrix}=\begin{bmatrix}0.7439 & 0.2561 & 0.0000\\0.8158 & 0.1842 & 0.0000\\0.0000 & 1.0000 & 0.0000\\0.0548 & 0.6552 & 0.2901\\0.2402 & 0.3939 & 0.3659\end{bmatrix} \tag{10}$$

The overall comprehensive evaluation is taken to get $\boldsymbol{B}=\boldsymbol{A}\bullet\boldsymbol{R}$=(0.3420, 0.5134, 0.1446).

4.5 Calculate the Fuzzy Comprehensive Evaluation Score

The comprehensive evaluation score of roof greening of Wangfujing Department Store Commercial Complex $\boldsymbol{F}$ is:

$$F=(0.3420, 0.5134, 0.1446)\begin{bmatrix}100\\80\\60\end{bmatrix}=83.95 \tag{11}$$

The suitability evaluation grade of roof greening of Wangfujing Department Store Commercial Complex is “suitable”. There are more prominent performances in the cost attributes, building attributes and roof attributes, but there are slight deficiencies in the green attributes and facilities attributes. Among them, there are reasonable overall planning of cost attribute in the early stage, moderate the input cost, and rich plant species, and the later maintenance investment is 10% of the standard cost economy; Among the architectural attributes, Wangfujing Commercial Complex is located in the main urban area of Lanzhou City, with superior geographical position and large flow of people; The commercial part has 7 floors, and the influence of wind power was reduced by the suitable floor height; Roof property equipment occupies no more than 40% of the roof area, which is suitable for the growth of surrounding plants.

4.6 Result Analysis

The suitability evaluation grades of 32 samples of roof greening in Lanzhou were finally obtained using the above methods, as shown in Table VII. Among them, 2 samples are suitable, 8 samples are secondary to suitable for roof greening suitability evaluation, and the evaluation results with the largest proportion are unsuitable, so the overall suitability is low. In this paper, 10 roof greening samples which are “suitable” and “secondary to suitable” will be analyzed, and their scores are shown in Table VIII.

TABLE VII. Evaluation results of roof greening in Lanzhou

Class	Number of samples	Percentage of total samples/%
Appropriate	2	6.25
Secondary to suitable	8	25
Inappropriate	22	68.75
General situation	The overall suitability is low	

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TABLE VIII. Evaluation results are suitable and more suitable samples

Ranking	Location	Location	Buildings Category	Types of roof greening	Comprehensive score
1	Lanzhou Central Commercial Complex	Qilihe District	Commerce	Garden style	84.32
2	Wangfujing shopping center	Chengguan District	Commerce	Garden style	83.95
3	Qiaomen Building	Chengguan District	Office	Garden style	77.52
4	Reader building	Chengguan District	Office	Garden style	75.23
5	Taohai Student Apartment	Anning District	Dwelling	Simple formula	74.16
6	Sunshine Home	Qilihe District	Dwelling	Garden style	72.58
7	Huafu Swiss Haoting	Chengguan District	Dwelling	Garden style	71.39
8	Jing'an Building	Qilihe District	Office	Simple formula	68.47
9	Lanzhou Municipal government	Chengguan District	Office	Garden style	65.61
10	Gansu Science and Technology Museum	Anning District	Recreation	Simple formula	63.22

From the table, it can be seen that the areas with higher evaluation scores of roof greening suitability are mainly concentrated in Chengguan District of Lanzhou City, and the following one is Qilihe District, which mainly benefits from the superiority of regional infrastructure and economic strength. The number of roof greening of buildings which were built in Anning District is very small, and there are only two with high suitability scores. The development of roof greening is limited by the far way from the city center and regional planning. In other areas, there are fewer buildings with roof greening, and the suitability level is not high, so it was not included in the research scope during the preliminary screening period.

The “suitable” grades belong to commercial buildings, especially the flow of people with obvious advantages, economic strength and regional location, and mature development conditions from the perspective of building categories. Through “garden-style” roof greening, commercial buildings can attract the flow of people, and its proceeds can be used for daily maintenance of green plants. Most of the “secondary to suitable” grades belong to public buildings, and very few of them are residential buildings. Among them, although Gansu Science and Technology Museum can attract a certain flow of people, it lacks funds for roof greening “cost attribute” as a public welfare infrastructure project, and its traffic accessibility is average, which makes its suitability score low; Although the input cost of roof greening is not high and the green plant area is not large, the Sunshine Home in Qilihe District of low-rise residential buildings has good floor height and infrastructure construction, and its suitability score is high.

From the general perspective, there are a large number of “unsuitable” grades, and the scores of each evaluation factor are low. The flow of people, infrastructure construction and regional location of this kind of buildings are not dominant.It is found by comparing various indicators that “cost attribute”, “greening attribute” and “building attribute” are quite different. Except Lanzhou Center and Wangfujing Department

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Store, other buildings are "secondary to suitable" or "unsuitable", while "roof attribute" and "facility attribute" have little overall differences. It can be seen that "cost attribute", "greening attribute" and "building attribute" have become the main limiting conditions for the suitability of urban roof greening in semi-arid areas of Northwest China.

V. CONCLUSION

The following conclusions are drawn through the application of suitability evaluation of urban roof greening in semi-arid area of northwest China in Lanzhou:

1. On the basis of the analytic hierarchy process (AHP), the suitability evaluation index system of urban roof greening in semi-arid areas of Northwest China was constructed in this paper by selecting five factors including cost attribute, building attribute, roof attribute, greening attribute and facility attribute. The suitability evaluation index system of roof greening has strong suitability to the semi-arid area of Northwest China, and the reference for the suitability evaluation of roof greening in other cities in the semi-arid area of Northwest China can also be provided.

2. For aspect of the semi-arid area of Northwest China, the suitability of roof greening is low. "Cost attribute", "greening attribute" and "building attribute" are the main limiting conditions for the suitability of urban roof greening in semi-arid areas of Northwest China. It should be pointed out that its generally good plant ecological adaptability provides the basis for roof greening to exert ecological benefits, but at the same time, there are some deficiencies in the aspects of substrate selection, maintenance quality and investment, facility configuration and maintenance, etc., which are restrictive factors affecting the exertion of ecological benefits.

3. Roof greening in semi-arid area is an ecological maintenance activity improving urban environment by using engineering means, and the external environmental conditions and corresponding technologies and facilities should be fully considered. On the basis of this, the suitability of roof greening in Lanzhou can be improved from three aspects:(1) The improved soil should be popularized and used as cultivation substrate, and the water-retaining light nutrient substrate suitable for roof greening in arid areas should be adopted to improve soil physical and chemical characteristics, reduce weight and increase covering soil thickness.(2) The domestic water should be replaced with reclaimed water or greening water for irrigation to reduce plant maintenance costs and increase investment in maintenance including fertilization, pesticide spraying and pruning, and facilities including wind and cold protection.(3) The engineering technology means should be improved and the aquifer structure should be introduced into roof greening design.

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