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Original Research

A Preliminary Exploration of Different Planting Combinations of Extensive Green Roof in Warm Temperate Semi Humid Climate Zone

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Abstract

The construction methods of extensive green roof are different in different regional climate conditions, which are directly affected by weight load bearing capacity, planting substrate, plant species and other factors. In order to explore the planting types of extensive green roof suitable for warm temperate semi humid region, 12 plant species and 5 planting substrates were selected to conduct the experiment on the roof of the Architectural Art Museum (36°40'37"N, 117°11'25"E) of Shandong Jianzhu University, Licheng District, Jinan City, Shandong Province, China in March to October in 2019, and each plant species was planted on 5 planting substrates on the roof, respectively. By measuring the basic foundation layer load parameters, substrate bulk density and plant unit weight in the process of construction, the increase of planting weight load bearing capacity was calculated. After 4 weeks, the plant physiological indexes were tested. Finally, based on fuzzy mathematics subordinate function value method, combined with the plant physiological indexes, all combination types were comprehensively evaluated. The results showed that the unit weight of 12 plant species was divided into three categories, and the change trend of the weight load bearing capacity increase of each plant combined with the five planting substrates was similar to that of the five planting substrates. According to the comprehensive evaluation, 12 planting combinations were considered to be suitable for application on the extensive green roofs in warm temperate semi-humid areas. Compared with the plant weight, in the early stage of extensive green roof construction, the weight of planting substrate is the main factor leading to the change of weight load bearing capacity increase.

Keywords: warm temperate semi humid region, extensive green roof, weight load bearing capacity, planting substrate, plant species

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Introduction

As the population increases and urbanization continues to develop and expand [1], the land for green infrastructure on the ground is becoming increasingly tense; the green space is constantly squeezed, various urban ecological environment problems occur frequently, the natural structure is unbalanced, and the urban ecosystem is more fragile [2, 3]. In 2021, the extreme rainfall in Zhengzhou, China, which is rare for thousands of years, completely uncovered the urban ecological environment problems faced by major cities all over the world. Green infrastructure is usually defined as an "Internet" with natural or semi natural attributes, including green space, trees, water body, green roof and vertical greening. These green infrastructures provide a wide range of ecosystem services, especially climate regulation [4]. As an air green infrastructure, green roof can effectively alleviate the shortage of urban land resources and has a variety of ecological functions. It is an important strategic means to create a flexible and sustainable city [3]; meanwhile, as an artificial ecosystem, it can provide ecological, economic and social benefits for cities [5], which have attracted extensive attention [6-8].

Plant is the key component of green roof, and it is also one of the most important factors affecting the quantity and quality of rainfall on green roof. The combination of four species of Sedum and two planting modes shows that *Sedum lineare, Sedum aizoon* and *Sedum spectabile* are considered to be suitable for green roofs [9]. 230 species of plants were investigated in 51 green roofs in Helsinki metropolitan area, of which 7 are red listed species [10]. In the Mediterranean climate, only 4 species (*Sedum acre, Sedum album, Sedum reflexum* and *Sedum sexangulare*) of Sedum can survive in the 3-year study cycle of the seed mixture of Sedum [11]. The analysis of plant characteristics provides a list of potential plant species for green roof for French-Mediterranean climate type [12]. The study of six Mediterranean plant species under water deficit conditions found that *Sedum sediforme* performed best, but its growth and water consumption were low, which limited its use in rainfall management; Finally, it is considered that *Brachypodium phoenicoides* and *Limonium virgatum* can be used as a supplement to *Sedum sediforme* [13]. Comparing the grassland plants and *Sedum plants* planted on the green roof in the central continent of the United States, it is found that Bouteloua dactyloides grows better due to the strong aggression, but the survival rate and coverage rate of *Sedum reflexum* are poor [14]. The survival rate of 14 of the 15 native plants used for lightweight green roof in the coastal area of Canada reaches more than 80% and the coverage rate of 10 species lives up to more than 90% [15]. Moreover, except for considering the load bearing capacity, substrate depth, functional characteristics and low maintenance of the green roof, the parameters on which plants depend to survive will be beneficial to the special plant planning required by the green roof [10].

The composition of substrates plays an important role in the growth and development of plants as well as the ecological function of green roof. Further, the different depths of the same substrate of green roof will also affect the above- mentioned contents. The viability of turf planted in cocopeat is better than that of commercial green roof substrate [16]. The interspecific competitive relationship of green roof leads to the reduction of species diversity. Substrate depth and effective water use have different effects on *Festuca rubra* and *Sedum acre*, and the two species competitive relationship is obvious. By designing different substrate depth, habitat species is improved. Moreover, substrate depth heterogeneity is more conducive to interspecific coexistence than homogeneity, and the plant species biodiversity of green roof ecosystem is greater [17]. Under the Mediterranean climate, the mixed seeds of two groups of different Sedum plants were planted in the substrate with the depth of 6 cm and 12 cm, and the irrigation methods were different. The ability of these Sedum plants to maintain growth decreased, especially in summer and water stress period [11]. *Silene vulgaris* and *Lagurus ovatus* seeds were planted in compost-soil-bricks (CSB) (1:1:3; v:v:v) and compost-bricks (CB) (1:4; v:v) with the 5 cm and 10 cm planting depth under the Mediterranean semi-arid climate, respectively. They were divided into irrigation and drought groups. It was found that *Silene vulgaris* and *Lagurus ovatus* in the 10 cm deep substrate exhibits better coverage under irrigation conditions [18]. 25 species of succulent plants were planted in 2.5, 5.0 and 7.5 cm deep substrates, after 7 years, it was found that the long-term performance of plants is also an important factor in the evaluation, in addition to the depth of planting substrate, thus, this needs to be seriously considered in the planning and design stage of green roof [19]. 18 non succulent perennial herbs were planted in three different depth substrates (10 cm, 15 cm and 20 cm). During water stress period, the plant survival rate was higher in deeper planting substrates [20]. Herbs and shrubs were planted in 12 cm and 20 cm deep substrates. It was found that the design of optimizing the thermodynamic characteristics of green roofs requires a deep enough planting substrate [21].

In addition to screening the types suitable for the application of green roof, most of the current studies are based on giving full play to the ecological service function of green roof. In terms of urban rainwater and flood management, compared with non green roofs, green roofs can change storm runoff due to their rainwater interception capacity [22]. Under simulated heavy rainfall conditions, extensive green roofs play a positive role in rainwater management [23]. Green roofs help reduce peak levels and flood risk in extreme weather conditions [24]. The water interception capacity of green roofs in the Mediterranean region is about 52% [25]; it will greatly contribute to reduce urban flood peaks and waterlogging. Simulating the soil depth of 5-160 cm on the green roof, shallow soil or extensive green roof is better than deep soil in attenuating rainwater peak due to lightweight [26]. During heavy rainfall, although the substrate depth is different, shrubs and herbs intercept and store 90% of the rainfall, which does not show significant difference [21]. Nagase and Dunnett monitored the effect of plant diversity and plant structure of 12 plant species applied on extensive green roof on the rainwater runoff. There is a significant difference in amount of water runoff between vegetation types; grasses are the most effective for reducing water runoff, followed by forbs and sedum [27]. Li et al. also obtained the above similar conclusions [28]. *Sedum sediforme*, *Origanum onites* and *Festuca arundinacea* were combined with two substrates with different depths (8 cm and 16 cm) on the green roof. It was found that *Origanum onites* planted in 16 cm substrate have the potential to alleviate runoff [29]. The average amount of rainwater retention of *Sedum spectabile, Sedum lineare,* mixed plants, *Sedum aizoon* and *Sedum spurium 'Coccineum'* are 90.98% and 91.38%, 88.51%, 83.42% and 84.17%, respectively [9].

Similarly, many achievements have been made in the research on water purification by green roof. Green roof isolates pollutants and improves water purification. As a filter layer, green roof structure can improve the pH value of water quality caused by acid rain and reduce the pollution level of traditional roof metals and artificial materials [24]. *Sedum lineare* shows higher sedimentation and enrichment capacity of total nitrogen (TN) and nitrate nitrogen (NO_3^--N) than other Sedum plant species. However, the combination of different Sedum plant species represent higher sedimentation and enrichment capacity of ammonium nitrogen (NH_4^+-N) and total phosphorus (TP) [9]. In addition, many works on green roof have also been carried out in resolving urban heat island effect, energy conservation and emission reduction, carbon fixation and oxygen release. The thermal performance of green roofs is generally studied by simply analyzing the relationship between microclimatic parameters (indoor thermal comfort), substrate characteristics (albedo, emissivity, temperature, moisture, depth) and plant composition (foliage density and species), so as to compare the effects of traditional and cooling roofs [4]. If the green roof is developed according to the urban scale level, the urban atmospheric temperature can be reduced by 0.3-3 K on average [30]. The direct way of carbon fixation of green roof can be through plants and substrates, while the indirect way is through long-term energy conservation and emission reduction of buildings, so it can finally reduce global CO_2 emissions [31].

The construction modes of green buildings are different because of different regional climatic conditions and the development strategy. It is found that the construction of green roof involves civil structure engineering, architecture, materials science, architecture landscape, gardens, horticulture, ecology, environment, municipal administration, water conservancy and other interdisciplinary studies. Based on the current problems faced by urban ecological environment and the development of green buildings, the experiment was carried out to explore construction mode of extensive green roof suitable for regional climate environment. It is expected to find a reasonable construction method, so as to provide scientific data parameters for solving the problems of urban ecological environment, and better promote the construction of smart low-carbon and sponge city.

Materials and Methods

General Situation of the Study Area

Jinan is located in the middle region of Shandong Province, China, between 36°02′~37°54′ N and 116°21′~117°93′ E. It is adjacent to Mount Tai in the South and across the Yellow River in the north. It is located on the junction zone between low mountains and hills in Central and Southern Shandong and alluvial plain in Northwest Shandong. The terrain is high in the south and low in the north. The terrain can be divided into three zones: Yellow River belt in the north, piedmont plain in the middle and hilly mountain area in the south. The total area is 10244.45 km^2. Jinan is a warm temperate continental monsoon climate zone with four distinct seasons and sufficient sunshine. The annual average temperature of the whole city is 14.2ºC. January is the coldest, with an average temperature of –0.2ºC; The temperature is the highest in July, with an average temperature of 28.3ºC. The average annual precipitation is 548.7 mm [32].

Research Location and Experimental Methods

The research site is located on the roof of the Architectural Art Museum (36°40'37"N, 117°11'25"E) of Shandong Jianzhu University, Licheng District, Jinan City, Shandong Province, China. 12 plant species commonly used in extensive green roof are selected, P1: *Sedum lineare*, P2: *Sedum sarmentosum*, P3: *Sedum spectabile*, P4: *Hemerocallis fulva*, P5: *Hosta plantaginea*, P6: *Iris tectorum*, P7: *Dianthus chinensis*, P8: *Poa pratensis*, P9: *Kerria japonica*, P10: *Ligustrum vicaryi*, P11: *Buxus sinica* and P12: *Berberis thunbergii* var. *atropurpurea*. The formula substrates are divided into five categories: S1: 3 field soils + 2 river sands + 5 turfy soils, S2: 3 field soils + 2 river sands + 5 parts of perlites, S3: 3 field soils + 2 river sands + 5 vermiculites, S4: 3 field soils + 2 river sands + 5 decomposed sawdusts, S5: 3 field soils + 2 river sands + 5 parts of green composts. 12 plant species were planted on the above-mentioned 5 formula substrates, respectively. As a consequence, 60 planting combinations are formed; they are P1S1, P1S2, P1S3, P1S4, P1S5, P2S1, P2S2,

P2S3, P2S4, P2S5,……P12S1, P12S2, P12S3, P12S4, P12S5, respectively. In addition, the area of each combination is 0.5 m × 1 m [10], and the planting depth is 10 cm. In the process of construction, measured the basic foundation layer load, determined the weight of different formula substrates and the weight of the whole plant, and calculated the total load increase at the initial stage of planting. After 4 weeks of normal management, the transplant plants survived quickly. The whole phased experiment began in March 2019 and lasted until October. The construction of green roof, measurement of load data and plant growth mainly occurred from March to May in 2019. During this period, the weather average temperature was 14.5ºc, average precipitation was 45.0 mm and average sunshine duration was 236.2 h. The relative chlorophyll content (RCC) of each plant was measured in May 2019 by hand-held chlorophyll meter (RN-YL01). After collecting plant materials, other plant physiological indexes and data statistical analysis were carried out from June to October in 2019. The malondialdehyde content (MDA) was measured by Nanjing Jiancheng Kit (A003-1 TBA method), and the superoxide dismutase (SOD) activity was measured by Nanjing Jiancheng Kit (A001-1 hydroxylamine method), which was repeated three times per treatment.

Data Analysis

The physiological growth and total load increase of each combination were calculated by fuzzy mathematics subordinate function value method (SFV) or anti-subordinate function value method (ASFV) for comprehensive evaluation [33]. The subordinate function value is calculated as follows:

If there is a positive correlation between the index and the construction target, it shall be calculated by formula (1):

$$X(\mu) = \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$
$$\Delta = \sum X(\mu)/n \quad (1)$$

If there is a negative correlation between the index and the construction target, it shall be calculated by formula (2):

$$X(\mu) = 1 - \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$
$$\Delta = \sum X(\mu)/n \quad (2)$$

Where $X(\mu)$ is the subordinate function value, X is the average measured value of an indicator, X_{max} and X_{min} are the maximum and minimum values of an indicator, and n is the number of indicators.

The test data were statistically analyzed by Microsoft Excel 2007 and SPSS 23.0 software. The data were analyzed by one-way ANOVA and Duncan's multiple comparison. The analysis level was $P<0.05$.

Results and Discussion

Construction of the Planting Structure Layer of Green Roof

The construction of planting structure layer directly determines the success or failure of green roof. Based on the current mainstream construction mode of extensive green roof and taking into account the climate type of the research site, the planting structure layer used in this study is shown in Fig. 1. In the construction process, after leveling on the foundation of the original building, the structure layer from top to bottom is as follows: line 1 is the vegetation layer, line 2 is the substrate layer, line 3 is the filter layer, line 4 is the water storage and drainage layer, line 5 is the protective layer, and line 6 is the root penetration resistance and waterproof layer. The other layers are classified as the basic foundation layer for green roof except layers 1 and 2. Therefore, the structural layer can also be divided into three parts: foundation layer, planting substrate layer and vegetation cover layer. Because the structure of the foundation layer is the same in this study, the combination of planting substrate layer and vegetation cover layer is the main research part.

Green buildings greatly promote the development of urban green infrastructure. Urban green infrastructure is closely related to urban ecological environment. As an important part of green buildings, green roofs play a direct role in improving urban ecological environment and serve as a bridge between buildings and natural ecological environment [34-36]. The construction of green roof structure layer directly determines the success or failure of green roof. In the process of construction, in addition to considering the structural load limiting factors of planting roofs [37], the climatic conditions of the planting site are also important influencing factors [10, 38], these two factors are also the key factors restricting the current development of green roofs. Therefore, in order to promote the development of green buildings and improve the urban ecological environment, combined with the research site, extensive green roofs and plant species and planting substrates commonly used in warm temperate areas were selected in this study.

Physiological Indexes and Comprehensive Evaluation of 60 Planting Combinations

The physiological indexes and comprehensive evaluation of each plant in five formula substrates are shown in Table 1. P1 was suitable for growing in S2 and not in S1, P1S2 rank was the highest; P2 is suitable for growing in S5 and not in S1, P2S5 rank was the highest; P3 is suitable for growing in S2 but not in S3, P3S2 rank was the highest; P4 is suitable for growing in S1 and S3, but not in S2, therefore, P4S1 and P4S3 ranks was equal; P5 is suitable for growing in S1, S3 and S4, but not in S1 and S2, theses combinations needed to further

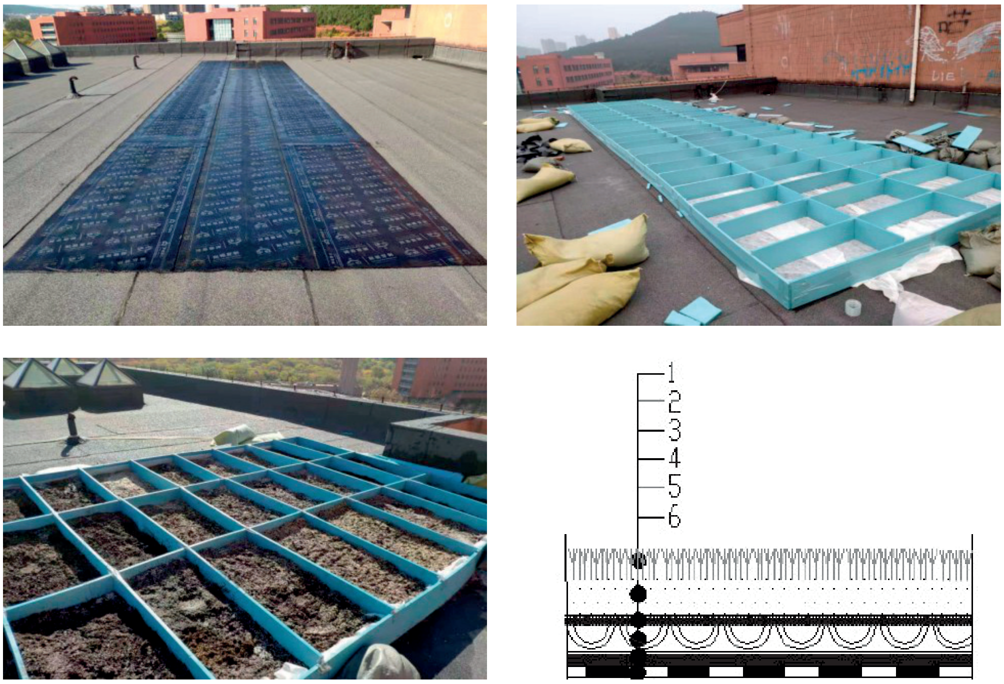

Fig. 1. The building process and the planting structure layer of green roof.

analyze; P6 is suitable for growing in S2 but not in S3, P6S2 rank was the highest; P7 is suitable for growing in S1 and not in S4, P7S1 rank was the highest; P8 is suitable for growing in S5 and not in S2, P8S5 rank was the highest; P9 is suitable for growing in S3 and S5, but not in S4; P10 is suitable for growing in S2 but not in S4, P10S2 rank was the highest; P11 is suitable for growing in S2, but not in S4 and S5, so P11S2 rank was the highest; P12 is suitable for growing in S5 and not in S1, P12S5 rank was the highest. From the plant physiological parameter indexes and comprehensive evaluation, S2 and S5 are more suitable for plant species.

Restricted by climatic conditions, plant species have obvious regional characteristics in the construction of green roofs; Vahdati et al. studied the growth status of nine plant varieties on the roof under dry and cold conditions in Iran [39]. It is concluded that succulent plants have the strongest ability to resist cold and drought, and ground cover plants grow better in cold season. 12 common plant species in warm temperate regions were selected in our study, including succulent plants and ground cover plants, with similar plant types. Farrell et al. applied plant physiological indexes to explore 12 species of green roof plants, and screened out 4 monocotyledons and 1 herb, which are suitable for the application of green roof [40]. Meetam et al. found that physiological parameters are helpful to evaluate the drought resistance of ground cover plants. Through the determination of physiological parameters, *S. portulacastrum* and *C. repens* are considered to be suitable for extensive green roof plants in tropical areas [41]. Combined with plant physiological parameters and comprehensive evaluation, the performance of each plant in five different planting substrate combinations was inconsistent. However, specific to a particular plant species, it has its corresponding substrate suitable for growth. It can be seen that plant species and planting substrates suitable for growth need specific analysis, and we can't only explore a single factor. In addition, the performance of plant physiological parameters under different substrate depths is also inconsistent. The study on the growth and physiological indexes of lavender planted on semi extensive green roof in Mediterranean climate with different substrate types and depths showed that lavender can survive successfully in 20 cm substrate; 30 cm substrate can better improve the growth and resistance in harsh summer environment [42]. Substrate depth and roof age are the dominant factors for the construction of green roof plant community. Shallow substrate and young roof are suitable for Sedum and bryophytes, while deep substrate and older roof are suitable for meadow plants [10]. *Sedum sediforme* was planted in two different substrate types with a depth of 7.5 cm and 10 cm. The deeper planting substrate increased the contents of chlorophyll and carotenoid, and the plant growth and physiological characteristics were also improved in the second year. Although the planting substrate of 7.5 cm is different, it can be successfully applied to the extensive green roof system under the semi-arid climate of the Mediterranean [43]. The physiological parameters of this study were obtained under different substrate types with a thickness of 10 cm. Whether the plant physiological parameter indexes and comprehensive evaluation under different thickness are similar or consistent with the results of this study still needs to be further studied.

Table 1. Physiological indexes of each plant combined with five different substrates and their comprehensive evaluation based on fuzzy mathematics subordinate function value method, respectively.

Groups	SOD (U·g^{-1} FW)	RCC (SPAD)	MDA(nmol·g^{-1})	SOD-SFV	RCC-SFV	MDA-ASFV	Mean SFV	Rank
P1S1	631.80±14.03a	31.20±0.72a	15.17±0.32b	0.41	0.48	0.48	0.46	3
P1S2	644.01±19.93a	11.03±0.15b	16.68±0.27a	0.59	0.47	0.58	0.55	1
P1S3	665.64±13.61a	8.23±0.54c	13.61±0.35c	0.48	0.57	0.54	0.53	2
P1S4	644.91±7.31a	12.00±0.12b	7.71±0.17d	0.50	0.50	0.60	0.53	2
P1S5	573.54±12.79b	5.63±0.20d	2.58±0.31e	0.55	0.48	0.55	0.53	2
P2S1	326.69±16.94c	21.03±0.48b	0.35±0.06b	0.50	0.36	0.47	0.44	4
P2S2	531.13±31.11a	33.30±0.62a	0.64±0.08b	0.54	0.43	0.43	0.47	3
P2S3	548.78±12.59a	8.97±0.24c	0.69±0.26b	0.41	0.58	0.58	0.52	2
P2S4	533.19±10.40a	6.20±0.23d	0.63±0.10b	0.57	0.50	0.50	0.52	2
P2S5	454.00±10.65b	21.47±0.32b	1.82±0.36a	0.64	0.52	0.51	0.56	1
P3S1	644.38±10.39a	5.67±0.20e	8.17±0.25b	0.46	0.52	0.41	0.46	3
P3S2	567.04±8.98c	15.23±0.43d	9.29±0.10a	0.63	0.49	0.49	0.54	1
P3S3	461.82±5.81d	27.23±0.50b	8.95±0.21a	0.49	0.43	0.37	0.43	5
P3S4	613.70±9.43b	23.10±0.21c	9.34±0.11a	0.48	0.43	0.60	0.50	2
P3S5	422.57±6.22e	30.23±0.72a	7.94±0.41b	0.47	0.49	0.40	0.45	4
P4S1	649.07±13.42ab	20.23±0.39c	9.24±0.31b	0.62	0.41	0.51	0.51	1
P4S2	553.84±11.18c	22.00±0.29c	8.97±0.26bc	0.39	0.50	0.41	0.43	4
P4S3	623.14±6.35b	33.03±0.48b	8.23±0.12cd	0.51	0.58	0.43	0.51	1
P4S4	667.40±13.02a	21.50±0.29c	18.62±0.19a	0.49	0.50	0.48	0.49	2
P4S5	555.84±9.04c	56.63±1.05a	8.01±0.24d	0.51	0.45	0.47	0.48	3
P5S1	256.02±21.07b	12.17±0.60a	9.47±0.50b	0.45	0.58	0.42	0.48	4
P5S2	238.17±8.93b	12.80±1.45a	10.36±0.6ab	0.44	0.52	0.48	0.48	4
P5S3	330.88±10.48a	5.37±0.56b	11.36±0.39a	0.41	0.56	0.52	0.50	3
P5S4	331.20±17.40a	2.43±0.49c	10.33±0.06ab	0.59	0.49	0.54	0.54	1
P5S5	337.29±5.42a	3.17±0.55bc	11.21±0.25a	0.61	0.51	0.41	0.51	2
P6S1	608.01±25.23b	7.70±0.15e	4.21±0.23a	0.53	0.4	0.44	0.46	2
P6S2	633.18±11.77ab	16.63±0.35c	4.27±0.40a	0.51	0.53	0.51	0.52	1
P6S3	600.2±11.97b	15.47±0.37d	2.94±0.16b	0.37	0.39	0.49	0.42	4
P6S4	426.95±13.52c	18.70±0.15b	4.13±0.08a	0.45	0.40	0.44	0.43	3
P6S5	659.78±5.12a	30.13±0.58a	3.13±0.41b	0.35	0.47	0.55	0.46	2
P7S1	594.52±20.87bc	34.40±0.87c	2.59±0.33a	0.62	0.47	0.58	0.56	1
P7S2	558.49±8.98c	11.60±0.70d	1.59±0.19b	0.53	0.36	0.51	0.47	3
P7S3	664.11±10.19a	38.23±0.67c	1.48±0.09b	0.54	0.45	0.41	0.47	3
P7S4	630.27±6.39ab	49.87±0.87b	1.79±0.22ab	0.36	0.52	0.49	0.46	4
P7S5	595.93±15.68bc	81.97±3.44a	1.94±0.46ab	0.50	0.50	0.57	0.52	2
P8S1	299.30±8.50a	8.50±1.32a	9.97±0.23c	0.61	0.44	0.37	0.47	3
P8S2	310.12±13.04a	5.93±0.41b	10.9±0.32ab	0.43	0.45	0.35	0.41	5
P8S3	287.12±24.59a	4.53±0.75bc	10.25±0.08bc	0.35	0.51	0.63	0.50	2
P8S4	280.80±35.68a	3.10±0.52c	10.58±0.08bc	0.34	0.50	0.50	0.45	4

Table 1. Continued.

P8S5	300.12±22.22a	2.87±0.49c	11.53±0.30a	0.48	0.51	0.53	0.51	1
P9S1	602.22±16.12a	12.27±0.15d	1.64±0.15a	0.61	0.53	0.43	0.52	2
P9S2	495.12±15.93b	33.70±0.15a	1.93±0.26a	0.47	0.40	0.62	0.50	3
P9S3	610.19±14.33a	23.63±0.68c	1.71±0.23a	0.58	0.35	0.65	0.53	1
P9S4	596.07±9.69a	29.00±0.64b	1.73±0.21a	0.41	0.45	0.6	0.49	4
P9S5	336.19±11.31c	22.07±0.81c	1.98±0.27a	0.50	0.49	0.59	0.53	1
P10S1	373.27±17.72c	5.73±0.18d	4.52±0.23d	0.53	0.56	0.49	0.53	3
P10S2	335.61±9.80c	23.90±0.98bc	5.71±0.21c	0.57	0.58	0.66	0.60	1
P10S3	337.44±10.78c	25.33±0.64b	13.74±0.32b	0.63	0.47	0.58	0.56	2
P10S4	446.51±7.98b	22.27±0.65c	24.53±0.43a	0.48	0.44	0.64	0.52	4
P10S5	549.42±9.54a	29.20±0.72a	5.15±0.26cd	0.58	0.48	0.53	0.53	3
P11S1	347.98±21.42b	31.53±0.81b	5.49±0.26b	0.51	0.48	0.46	0.48	3
P11S2	344.37±6.44b	43.10±0.61a	6.15±0.15b	0.54	0.52	0.57	0.54	1
P11S3	295.75±10.49c	24.13±0.24c	0.59±0.07c	0.55	0.42	0.58	0.52	2
P11S4	399.17±10.99a	31.00±0.36b	7.56±0.26a	0.41	0.42	0.57	0.47	4
P11S5	408.71±14.55a	41.93±0.92a	5.74±0.25b	0.53	0.51	0.38	0.47	4
P12S1	408.62±10.61c	12.07±0.12e	13.81±0.15a	0.47	0.42	0.47	0.45	5
P12S2	340.89±14.15d	14.33±0.68d	13±0.32ab	0.60	0.61	0.47	0.56	2
P12S3	351.23±5.54d	18.63±0.38c	11.73±0.33c	0.48	0.49	0.6	0.52	3
P12S4	472.59±7.62b	23.10±0.35b	12.57±0.3bc	0.47	0.50	0.53	0.50	4
P12S5	636.68±12.42a	25.27±0.64a	8.25±0.26d	0.56	0.63	0.51	0.57	1

Note: The values of number in the SOD, RCC and MDA columns are expressed as mean ± standard errors. The different lowercase letters in the same column indicate significant difference that the same species combined with five different substrates at the 0.05 level, respectively.

Weight of Substrate per Cubic Meter

The weight of the five formula substrates is shown in Fig. 2, which is generally divided into three categories. The formula substrates with the heaviest unit weight are S1 and S5, 533.47 kg·m^{-3} and 522.67 kg·m^{-3}, respectively. And there was no significant difference between them (P<0.05). The formula substrates with the lightest unit weight were S2 and S3, which were 377.52 kg·m^{-3} and 372.02 kg·m^{-3}, respectively. Moreover, there was also no significant difference between them (P<0.05). S4 was between the weight of the above two types of formula substrates, which was 494.01 kg·m^{-3}, but there were significant differences between S4 and (S1 and S5) as well as (S2 and S3) (P<0.05). On the whole, although there are significant differences between S4 and (S1 and S5), the weight difference is only about 28.66~39.46 kg·m^{-3}. However, the weight difference between S4 and (S2 and S3) is about 116.49~121.99 kg·m^{-3}, and the weight difference between (S1 and S5) and (S2 and S3) is greater. Only from the weight of formula substrates, S2 and S3 can meet the construction demand of extensive green roof. However, the roof conditions are relatively poor. In order to ensure the survival of plants, we also need to consider the ability of nutrition and water retention. Thus, S1, S4 and S5 were arranged, it will continue to be discussed later.

Planting substrate is indisputably the most important component of green roof, which provides water, nutrients and solid ground support for plant growth. Substrate composition should be fully considered in green roof design, and substrate composition needs to be tailored [44]. Among the five planting substrate combinations in this study, S1 containing turfy soil and S5 containing green composts are the heaviest, S2 containing perlite and S3 containing vermiculite are the lightest, and S4 containing decomposed sawdust is in the middle. From the perspective of building structure load, S1 and S5 cannot be used as the most ideal planting substrate. Nevertheless, due to the harsh growth environment of the roof, selection of the appropriate green roof planting substrate is one of the most important factors. The research on the organic matter doped in the commercial substrate of the green roof shows that the organic matter content of 10% is relatively appropriate, and the organic matter content required by different plant species is different, plant species in nitrogen rich habitats prefer high organic matter content [45]. Planting substrate design is very important for plant survival and storm retention. The use of organic waste materials can create a lightweight substrate with good air permeability and improve the available water of plants. Coarse coir, fine coir, composted green waste are the best choices [46]. Inorganic substrate is the main growth substrate of green roof. The ratio of organic matter is beneficial to improve plant growth. Adding green waste compost with a volume ratio of 30% can significantly improve the physical properties of the substrate, reduce the dry bulk density and enhance the water holding capacity. However, the composting effect of green waste with different inorganic substrate ratios is different [47]. During the construction of extensive green roof, although S2 and S3 have strong water retention and air permeability and are also good lightweight planting substrate; under the same ratio, S1, S5 and S4 substrate combinations are added with turfy, green composts and decomposed sawdust, and the organic matter content is higher. Therefore, the problem can't be considered only from a single point of view of load. The balance between the load increase caused by the combination of different substrate types and the content of inorganic and organic matter needs to be considered comprehensively, so as to find the balance point between the two. However, Liu et al. reported that the external morphology and leaf stomatal resistance of grassland plants and Sedum plants planted with green roofs in the central continental United States were not affected by the type of planting substrate [14]. In order to ensure the normal development of roof plants in the future, a suitable artificial substrate should be designed for the green roof. In addition to the ratio of inorganic and organic matter, the microbial, biochemical and physicochemical properties of the substrate should also be considered. The substrate composition and compost dose affect the structure and function of microbial development [48]. After adding biochar to the green roof substrate, the yield of lettuce (*Lactuca sativa*) planted in tropical areas increased, and the physical and chemical properties and microbial properties of the final substrate changed [49]. In addition to the study on the changes of substrate characteristics and microbial characteristics, combined with substrate improvement, reducing the infiltration of nutrient elements in the substrate and preventing and controlling the eutrophication pollution of rainwater runoff have also been reported. Adding biochar into planting substrate applied on the existing green roof in southern Finland, some nutrient elements can be obviously retained in the green roof substrate to avoid the problem of eutrophication rainwater pollution [50]. Although the improved substrate with adding biochar will affect the quality and quantity of runoff, due to the great change of biochar characteristics, the large-scale application of biochar improvement in green roof substrate needs careful consideration to avoid unexpected results [51]. In view of the existing research results and under the premise of considering the load, many works will be needed to do in the future such as the lightweight substrate, the substrate ameliorant, and the content of organic matter and the changes of microbial characteristics in the substrate.

Weight of Each Plant Species per Square Meter and Increase in Load Bearing Capacity

The weight change trend of each plant species per square meter is similar to that of the five formula substrates, The weight of plants per square meter is also divided into three categories, and there are significant differences among the three categories (P<0.05) (as shown in Fig. 3). The heaviest groups are P1, P2, P3 and P5, which are 6.27 kg·m^{-2}, 6.33 kg·m^{-2}, 6.28 kg·m^{-2} and 6.27 kg·m^{-2}, respectively. However, there is no significant difference among the four plants (P<0.05). The weight per unit area of the second type P9, P10, P11 and P12 was in the middle, which was 3.29 kg·m^{-2}, 3.36 kg·m^{-2}, 3.36 kg·m^{-2} and 3.32 kg·m^{-2}, respectively. Accordingly, there was also no significant difference among the four plant weights (P<0.05). The lightest

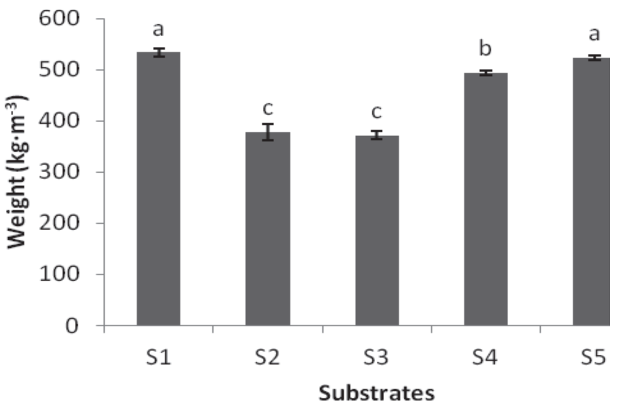

Fig. 2. Weight of five substrates per cubic meter. The different lowercase letters in the histogram indicate significant difference at the 0.05 level, respectively.

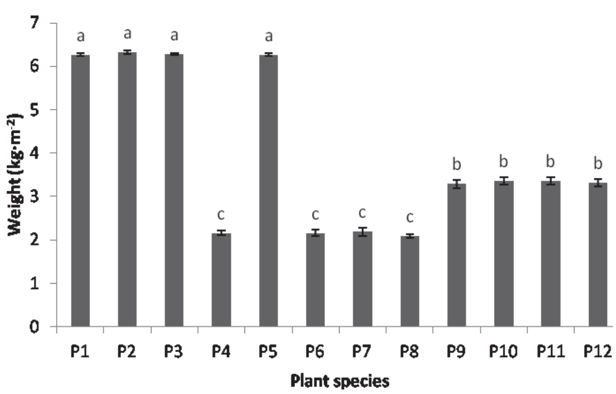

Fig. 3. Weight of each plant per square meter. The different lowercase letters in the histogram indicate significant difference at the 0.05 level, respectively.

types are P4, P6, P7 and P8, which are 2.16 kg·m^{-2}, 2.16 kg·m^{-2}, 2.19 kg·m^{-2} and 2.09 kg·m^{-2}, respectively. Nevertheless, there is also no significant difference in the weight of the four plants (P<0.05). From the results, the maximum difference in the weight of 12 plants per square meter is 4.24 kg·m^{-2}, with a difference of about 3 fold.

The load increase includes the sum of the weight of three parts, which are the same foundation layer, different formula substrate layer and different vegetation cover layer. The change trend of load increase is similar to that of unit formula substrate, and it is also divided into three categories (Fig. 2 and Fig. 4). Each plant shows that the load increase of S1 and S5 is the largest in five different formula substrates, but there is no significant difference between them (P<0.05). On the contrary, the load increase of S2 and S3 is the smallest, and there is no significant difference between them

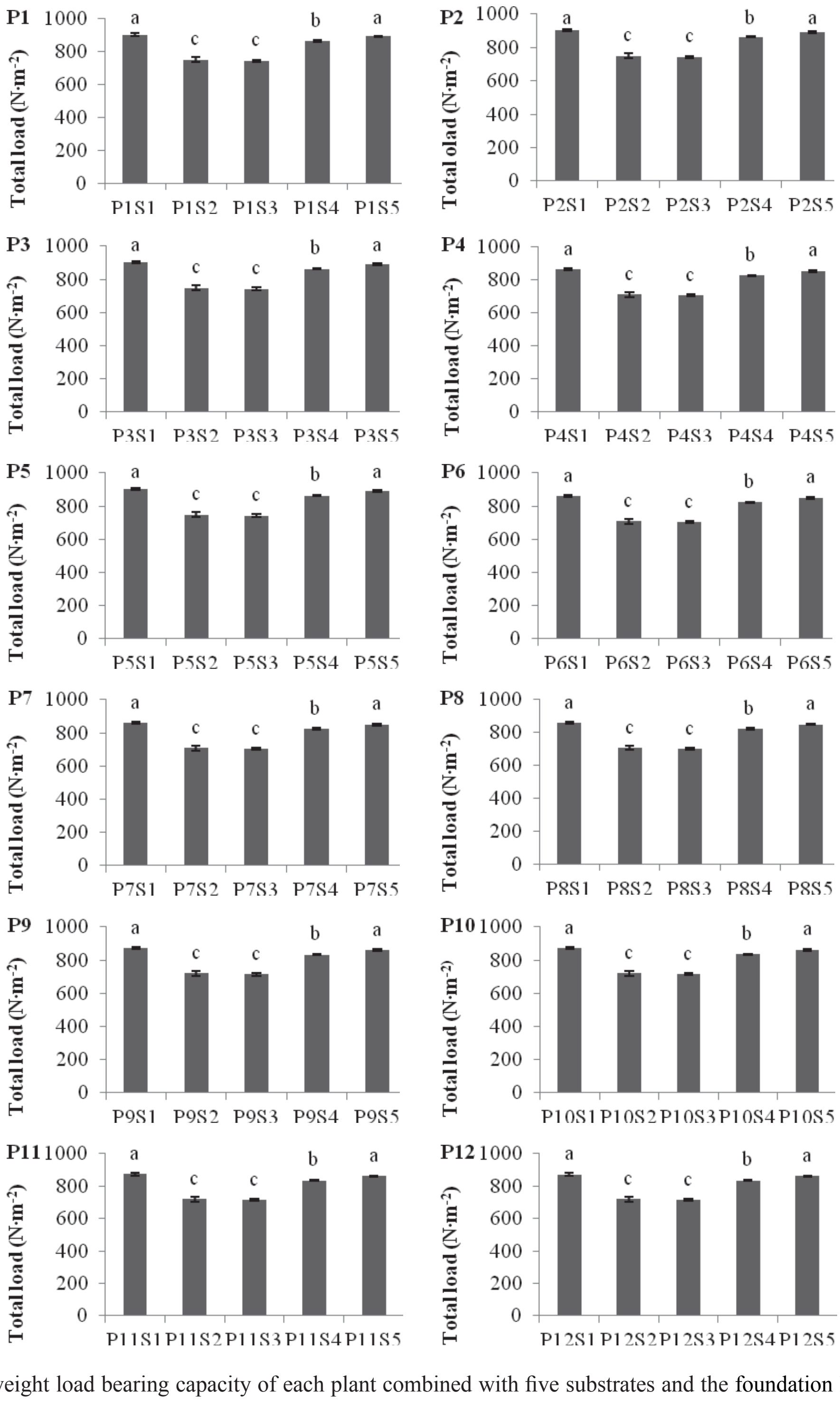

Fig. 4. Increase in weight load bearing capacity of each plant combined with five substrates and the foundation layer per square meter when the green roof is completed. The different lowercase letters in the histogram indicate significant difference at the 0.05 level, respectively.

(P<0.05). The load increase of S4 is between the load increases of (S1 and S5) and (S2 and S3), and there is a significant difference with them (P<0.05). The results show that on the basis of the same foundation layer, compared with the increase of vegetation load, the main determinant of the load increase of extensive green roof is the weight of different formula substrates.

At present, there are many studies on green roof plants, substrates and ecological functions. However, combined with these elements, there are few studies on the increase of green roof load bearing capacity caused by different planting combinations. In only a few studies, considering the load capacity of roofs and ecological protection, Hsieh et al. used fiber waste to make culture mediums as an extensive green roof, after which *Sedum makinoi* is then planted to evaluate the cooling effect of the waste fiber culture medium [52]. The experimental results show that waste fiber culture medium which is much lighter than that of the control group, and it also has a life-cycle, an energy-saving, ecological friendly merit, both of which qualify it for use of the culture medium as extensive green roof. Arkar et al. carried out a study of the thermal response of lightweight extensive green roofs with lightweight mineral wool growing media in wintertime in water-freezing conditions [53]. Although intensive green roof systems (>15 cm medium depths) are thought to be most suited for vegetable production, the greatest potential for sustained productivity is probably through extensive systems (<15 cm depths) due to weight load restrictions for most buildings [54]. However, these studies do not focus on the increase of roof load in depth. Comprehensive adaptability of the overall cover soil of saddle-shaped shell structures and energy efficiency are simulated and evaluated through Sap2000 software and Design Builder software. The findings are that cover soil greening can greatly save energy and the structures are highly adaptive to cover soil, and it is positively significant to combine large space "saddle-shaped" shell structures with cover soil greening [37]. Relevant simulation works were only carried out on software in this study. But regretfully, did not conduct practical operation. In this study, the weight of plant species with rhizosphere soil per square meter is divided into three categories. Although the maximum difference between the units weight of them is about 3 times, the difference is too insignificant compared with the unit weight of planting substrate. The difference between the weight

Table 2. Comprehensive evaluation of the combination of each plant with five different substrates and load capacity based on fuzzy mathematics subordinate function value method, respectively.

Groups	SOD-SFV	RCC-SFV	MDA-ASFV	Load-ASFV	Mean SFV	Rank
P1S1	0.41	0.48	0.48	0.53	0.48	4
P1S2	0.59	0.47	0.58	0.57	0.55	1
P1S3	0.48	0.57	0.54	0.43	0.51	3
P1S4	0.50	0.50	0.60	0.44	0.51	3
P1S5	0.55	0.48	0.55	0.52	0.53	2
P2S1	0.50	0.36	0.47	0.54	0.47	5
P2S2	0.54	0.43	0.43	0.56	0.49	4
P2S3	0.41	0.58	0.58	0.44	0.50	3
P2S4	0.57	0.50	0.50	0.45	0.51	2
P2S5	0.64	0.52	0.51	0.53	0.55	1
P3S1	0.46	0.52	0.41	0.53	0.48	3
P3S2	0.63	0.49	0.49	0.56	0.54	1
P3S3	0.49	0.43	0.37	0.44	0.43	5
P3S4	0.48	0.43	0.60	0.45	0.49	2
P3S5	0.47	0.49	0.40	0.53	0.47	4
P4S1	0.62	0.41	0.51	0.53	0.52	1
P4S2	0.39	0.50	0.41	0.55	0.46	3
P4S3	0.51	0.58	0.43	0.44	0.49	2
P4S4	0.49	0.5	0.48	0.48	0.49	2
P4S5	0.51	0.45	0.47	0.52	0.49	2

Table 2. Continued.

P5S1	0.45	0.58	0.42	0.54	0.50	3
P5S2	0.44	0.52	0.48	0.57	0.50	3
P5S3	0.41	0.56	0.52	0.44	0.48	4
P5S4	0.59	0.49	0.54	0.43	0.51	2
P5S5	0.61	0.51	0.41	0.53	0.52	1
P6S1	0.53	0.40	0.44	0.54	0.48	2
P6S2	0.51	0.53	0.51	0.55	0.53	1
P6S3	0.37	0.39	0.49	0.45	0.43	4
P6S4	0.45	0.40	0.44	0.48	0.44	3
P6S5	0.35	0.47	0.55	0.54	0.48	2
P7S1	0.62	0.47	0.58	0.55	0.56	1
P7S2	0.53	0.36	0.51	0.55	0.49	3
P7S3	0.54	0.45	0.41	0.46	0.47	4
P7S4	0.36	0.52	0.49	0.48	0.46	5
P7S5	0.50	0.50	0.57	0.55	0.53	2
P8S1	0.61	0.44	0.37	0.54	0.49	2
P8S2	0.43	0.45	0.35	0.56	0.45	4
P8S3	0.35	0.51	0.63	0.44	0.48	3
P8S4	0.34	0.50	0.50	0.45	0.45	4
P8S5	0.48	0.51	0.53	0.54	0.52	1
P9S1	0.61	0.53	0.43	0.55	0.53	1
P9S2	0.47	0.40	0.62	0.55	0.51	2
P9S3	0.58	0.35	0.65	0.46	0.51	2
P9S4	0.41	0.45	0.60	0.47	0.48	3
P9S5	0.50	0.49	0.59	0.55	0.53	1
P10S1	0.53	0.56	0.49	0.55	0.53	3
P10S2	0.57	0.58	0.66	0.55	0.59	1
P10S3	0.63	0.47	0.58	0.46	0.54	2
P10S4	0.48	0.44	0.64	0.48	0.51	4
P10S5	0.58	0.48	0.53	0.55	0.54	2
P11S1	0.51	0.48	0.46	0.54	0.50	2
P11S2	0.54	0.52	0.57	0.58	0.55	1
P11S3	0.55	0.42	0.58	0.43	0.50	2
P11S4	0.41	0.42	0.57	0.40	0.45	4
P11S5	0.53	0.51	0.38	0.53	0.49	3
P12S1	0.47	0.42	0.47	0.54	0.48	4
P12S2	0.60	0.61	0.47	0.58	0.57	1
P12S3	0.48	0.49	0.60	0.43	0.50	3
P12S4	0.47	0.50	0.53	0.39	0.47	5
P12S5	0.56	0.63	0.51	0.54	0.56	2

of the lightest planting substrate S3 and the heaviest plant weight used in this study is nearly 6 times, and there is a great difference between the weight of plant and planting substrate. From the perspective of the increase of total load after planting, the change trend of load increase of 12 plant species in 5 planting substrates is consistent, and the change trend is similar to that of 5 planting substrates. The plant weight has less effect on the increase of roof load bearing capacity than the substrate weight. Therefore, in the initial stage of extensive green roof construction, we should emphatically focus on the load increase of planting substrate. Under the condition of meeting the normal growth of plants, combined with the ecological function of green roof, we should choose lightweight planting substrate as far as possible. If a green roof needs to be amended to reduce weight but have improved plant-available water, coarse coir, fine coir and composted green waste would be the best choices [46]. Biochar addition makes green roof substrates lighter and improves plant water supply [55]. Biochar addition to green roof substrates may reduce green roof weight and improve storm water retention by increasing water holding capacity [56]. Our results have similarities with these studies in lightweight substrate. From the point of the load increase, only the best combination of 12 plant species in 5 different substrates at the initial stage of planting is discussed here. It should be noted that the pair-wise comparison and the best combination of different plant species in different substrates will be necessary to be carried out in the follow-up work.

Comprehensive Evaluation Based on SFV Method

The comprehensive evaluation of load bearing capacity and the combination of each plant and five formula substrates are shown in Table 2. For P1, P1S2 is the best combination. The ranking of the five combinations of P2 demonstrated that P2S5 was the most suitable combination for planting. The comprehensive evaluation of the five combinations of P3 is very obvious. Therefore, P3S2 is the best planting combination. As a result, P4S1 is the most suitable combination for application. In the comprehensive evaluation of P5 combination, it can be seen that P5S5 is the best combination. Interestingly, the comprehensive evaluation of the SFV method of P6 is consistent with the comprehensive evaluation trend of physiological indexes. P6S2 is a more suitable combination. However, for P7, P7S1 is considered as the best combination. Similarly, P8S5 can be recommended as the most suitable planting combination. Strangely, the comprehensive evaluation of the five combinations of P9 is quite different from the comprehensive evaluation of physiological indexes. P9S1 is considered as the best combination. Indisputably, P10S2 is the more suitable construction combination among the five combinations. Accordingly, it can be shown that P11S2 can be used as the recommended combination. Consequently, P12S2 is regarded as the best combination. From the results, the combination numbers of different plant species and planting substrate S2 are the most, indicating that substrate S2 can be used as a planting substrate which is more suitable for green roof. Of course, other different plant species have different planting substrate combinations, which also shows that the construction method of green roof can’t be generalized. On the basis of considering the increase of load capacity, the appropriate planting substrate must be selected for the appropriate plant species.

Conclusions

The increase of load was investigated when the extensive green roof construction was preliminarily completed, including the foundation layer of the construction structure, the planting substrate and the weight of the originally planted plants. According to the corresponding specifications, these belong to permanent load changes. In the early stage of planting, because plants need to regain the growth, after four weeks of recovery, plant species and substrate combinations that are relatively suitable for the application of extensive green roof can be screened out by determining the physiological indexes. Based on the change of permanent load, the internal physiological indexes of plant species and the comprehensive evaluation of formula substrate, 12 combinations of plant species and formula substrate suitable for the initial planting of extensive green roof in warm temperate zone were selected. Of course, the changes of permanent load and plant physiological indexes were surveyed when the construction was only completed in the initial stage. With the passage of time, the subsequent variable loads such as plant growth and the long-term performance of plant species under changeable climate need to be further explored in order to obtain more scientific data and support the development of green buildings in the future.

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Conflict of Interest

The authors declare no conflict of interest.

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