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Original Research

Ecological Restoration of Construction and Demolition Waste Landfills by Plants: a Case Study in Suzhou, China

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Abstract

The restoration and reconstruction of ecosystems is the basis of the landscape reconstruction of construction and demolition waste (CDW) landfills, in which landscape plants play a prominent role. To screen appropriate landscape plants that could survive and grow in a mixture of CDW and soils, the Fenghuangshan CDW landfill in Suzhou, China, was taken as an example to study restoration technology by plants. The growth and physiological parameters of ten herbaceous species with high ornamental values, healthy growth and easy maintenance in the green space of Suzhou were measured under a mixture of CDW and soils. A comprehensive evaluation was conducted with the membership function method. The results showed that *Hemerocallis fulva*, *Panicum virgatum*, *Heliopsis helianthoides*, *Sedum aizoon* and *Carex oshimensis 'Evergold'* were well adapted to the mixed environment of CDW and soil in Suzhou. Among them, *Hemerocallis fulva* ranked first with a comprehensive evaluation index of 0.87. It could be the best herbaceous species for landscape reconstruction of CDW landfills. The study is instructive for vegetation restoration in surrounding areas and provides a method for plant selection and evaluation for vegetation restoration of CDW landfills.

Keywords: construction and demolition waste landfills, landscape plants, vegetation restoration, growth evaluation

Introduction

In recent years, with economic improvements and acceleration of urbanization, construction and renovation of urban traffic and buildings have been expanding rapidly [1]. However, the construction and demolition of infrastructure generate a large amount of construction and demolition waste (CDW), including waste concrete, bricks, glass, wall materials, etc. [2, 3], especially in developing countries. As the world's largest developing country, China produced over

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1 billion tons of CDW per year as early as 2013. After 2017, this number exceeded 1.4 billion tons, increasing by 1.55 billion to 2.4 billion tons annually [4].

However, CDW disposal in China is still in its infancy. According to relevant research, there are hundreds of small CDW disposal companies in China, while less than 70 disposal lines have an annual disposal capacity of more than 1 million tons. The total utilization of CDW resources is less than 100 million tons per year, and the overall utilization rate is less than 10%, which is far lower than that of developed countries such as South Korea, Japan and the European Union, whose utilization rates have reached 98%, 97% and 90%, respectively [5].

The main recycling methods of CDW are used for recycled aggregate, road base materials or sintered brick [6]. However, because of the lack of stable product quality and the low economic efficiency, the actual utilization is limited [7, 8]. Considering economic and technological constraints, approximately 95% of CDW is disposed of in landfills in China, causing soil and groundwater pollution and occupying the outer space of cities [9, 10]. Over time, CDW landfills have grown larger and become a serious problem to solve [11].

Compared with domestic waste, CDW has the characteristics of large particles, high hardness and slow degradation. It is an effective way to utilize CDW through the ecological development of CDW landfills, and this can make full use of CDW to reshape urban public space and create landscapes [12, 13]. Integrated management of pollutants and restoration and rehabilitation of ecosystems are prerequisites for the development and utilization of construction waste landfills [14]. Among them, the design and recovery of vegetation has irreplaceable ecological significance for the removal of pollutants from waste, improvement of soil and water quality, and the creation of plant and animal habitats. It is also an important basis for evaluating the effectiveness of ecological restoration and reconstruction. According to the successful cases, the complete process of vegetation restoration of construction waste landfills consists of three interrelated and independent development stages. During the first stage (0-5 years), kinds of wild herbs grew in the construction waste landfill soil and played positive roles in the structure and nutrition of the soil. During the second stage (6-10 years), herbs and shrubs with good adaptability to the thin soil layers and high resistance to undesirable environmental conditions could be planted. During the third stage (after 10 years), many species could be planted, and the habitats of animals and plants will be gradually restored. It is the ninth year since the closure of the Fenghuangshan CDW landfill. Sufficient settlement of soil and construction waste has been completed and more than 30 wild herbaceous species grow spontaneously at the top of the slope as well as on the slope surface. To evaluate the potential of landscape reconstruction and ecological restoration of CDW landfills, this paper tried to mix CDW and soil from the Fenghuangshan CDW landfill in a certain proportion as the space for plant growth. Four growth indexes and four physiology indexes were proposed to evaluate the growth and adaptation of the ten selected plants. According to planting experiments, the plants with the best growth and adaptation under the mixture of CDW and soil were selected for further vegetation restoration of the CDW landfill.

Materials and Methods

Experiment Materials and Design

CDW is mainly generated from the demolition and new construction of old buildings and road reconstruction and expansion construction near Fenghuangshan CDW landfill, Suzhou, China, as shown in Fig. 1. Among them, concrete blocks account for 43.2% of CDW, cement stabilized gravel blocks account for 33.7%, bricks account for 12.7%, gravel accounts for 6.1% and others account for 4.3%. Other materials include waste plastics, steel bars, wood, etc. Table 1 shows the physical and mechanical properties of CDW and soils, and Fig. 2 shows the grading curve of CDW. CDW with a particle size greater than or equal to 3 cm was manually selected for the following test considering the pot size and repeatability of the experiment. In the Fenghuangshan landfill, the proportion of CDW is about 70%. Considering the uneven distribution of CDW, the mass ratio of CDW to soil was 4: 1 to ensure better representativeness and applicability of the experimental results.

The tested plants were collected from the Xiaxi flower market in Changzhou, China. They were biennial container seedlings with robust growth, a complete root system and no diseases or pests. Each pot was filled with approximately 50 L of soil. Ten herbaceous species were selected based on the principles of high ornamental value, rapid growth rate and easy

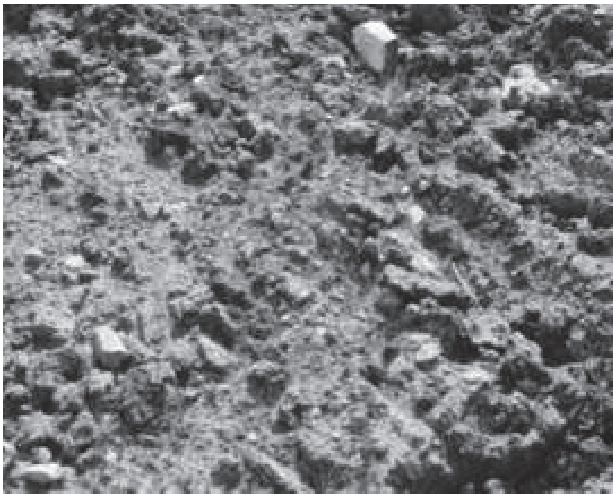

Fig. 1. Fenghuangshan CDW Landfills.

Table 1. Physical and mechanical properties of CDW and soil.

	Apparent density (g/cm^3)	Water content (%)	Water absorption (%)	Crushing value	Sulfur trioxide content (%)
CDW	2.65	2.35	6.43	0.19	0.35

	Natural density (g/cm^3)	Dry density (g/cm^3)	Water content (%)	Liquid limit	Plastic limit	Plasticity index
Soil	1.67	1.31	21.56	28.5	18.6	9.9

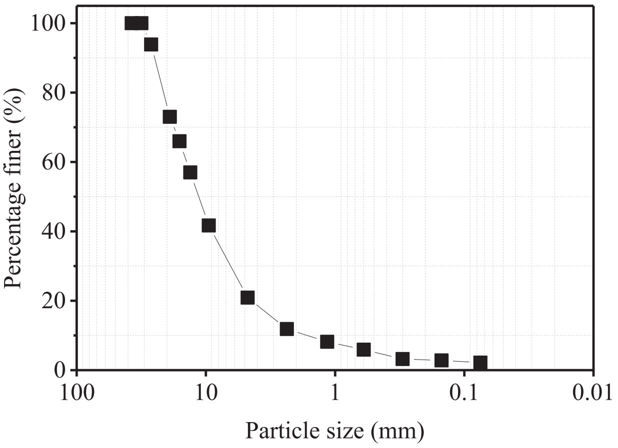

Fig. 2. Grading curve of CDW.

management in Suzhou's gardens and green spaces. 5 parallel groups were set up in the experiment. During the experiment, low-maintenance management was adopted, with no fertilization and pest control and only a small amount of water when it was necessary. The ornamental characteristics of the tested plants are shown in Table 2. The growth and development of the plants were observed and recorded.

Determination of the Index and Methods

Determination of Soil Indexes

The physical and chemical properties and main nutrient contents of garden soil and CDW landfill soil were determined before planting. The cutting ring method was used to measure the soil porosity, and the soil size void ratio was calculated according to Equation 1. pH, EC and the contents of organic matter, total nitrogen, available phosphorus and available potassium were determined by the potentiometric method, conductivity method, potassium dichromate method, Kjeldahl method, molybdenum-antimony resistance colorimetry and flame photometry, respectively. The content of available potassium was determined by flame photometry [15-20].

$$G = \frac{P_v}{P_w} \times 100\% \tag{1}$$

Table 2. Ornamental characteristics of ten herbaceous species.

Latin name	Family and genus	Main ornamental parts	Main ornamental seasons	Main ornamental color
Sedum aizoon	Crassulaceae, Sedum	Leaves, flowers	Spring, summer, autumn, and winter	Green and yellow
Physostegia virginiana	Labiatae, Physostegia	Flowers	Summer and autumn	Green and pink
Carex oshimensis 'Evergold'	Cyperaceae, Carex	Plant type, leaves	Spring, summer, autumn, and winter	Yellow
Acorus gramineus 'Ogan'	Araceae, Acorus	Plant type, leaves	Spring, summer, autumn, and winter	Yellow
Pennisetum alopecuroides	Gramineae, Pennisetum	Plant type, flowers	Spring, summer and autumn	Green and white
Panicum virgatum	Gramineae, Panicum	Plant type, flowers	Spring, summer and autumn	Green and pink
Lythrum salicaria	Lysimachiaceae, Lythrum	Flowers	Summer and autumn	Green and rose
Heliopsis helianthoides	Composite, Heliopsis	Flowers	Summer and autumn	Green and yellow
Hemerocallis fulva	Liliaceae, Hemerocallis	Plant type, flowers	Spring and summer	Green and orange
Tulbaghia violacea	Amaryllidaceae, Tulbaghia	Flowers	Spring, summer, autumn, and winter	Green and pink

where G represents the size void ratio of the soil, P_v represents the aeration porosity of the soil, and P_w represents the water holding porosity of the soil.

Determination of Plant Growth Indexes

The plant height, width, fresh biomass and coverage rate of the selected species in 2 kinds of soils were measured before and after planting for 1 year. Plant height refers to the distance from the ground to the highest point of the plant cluster, width refers to the diameter of the vertical projection plane of the plant cluster, fresh biomass is expressed by the sum of the fresh weight of the plant stem and leaf plus the fresh weight of the root, and the coverage rate is expressed by the ratio of the vertical projection area of the plant cluster to its corresponding planting area. Each index was repeated 5 times. According to Equations (2-5), the increase in the heights, widths and fresh biomass and coverage rates of the ten herbaceous species after planting for 1 year were calculated.

$$I_h = \frac{c_1}{c_0} \times 100\% \tag{2}$$

where I_h represents the height growth of a plant, C_1 represents the height of a plant after 1a planting, and C_0 represents the height of a plant before planting.

$$I_c = \frac{H_1}{H_0} \times 100\% \tag{3}$$

where I_c represents the width growth of a plant, H_1 represents the width of a plant after 1a planting, and H_0 represents the width of a plant before planting.

$$I_b = \frac{B_1}{B_0} \times 100\% \tag{4}$$

where I_b represents the fresh biomass growth of a plant, B_1 represents the fresh biomass of a plant after 1a of planting, and B_0 represents the fresh biomass of a plant before planting.

$$R_c = \frac{F_1}{F_0} \times 100\% \tag{5}$$

where Rc represents the increase in the coverage rate of a plant, F_1 represents the coverage rate of a plant after 1a of planting, and F_0 represents the coverage rate of a plant before planting.

Determination of Plant Physiological Indexes

Physiological indexes of the ten herbaceous species in 2 kinds of soils were measured after planting for 1 year. The chlorophyll content was determined by the anhydrous ethanol extraction method. The malondialdehyde (MDA) content was determined by the thiobarbituric acid colorimetric method, the proline content was measured by the ninhydrin reaction method, and the superoxide dismutase (SOD) activity was determined by the azoblue tetrazole method [21-23].

Comprehensive Evaluation of Plant Adaptability to CDW Landfill Soil

The growth index and physiological index of the ten herbaceous species in 2 kinds of soils were evaluated comprehensively by using the membership function method. For plants in CDW landfill soil, the subordinate function values of the growth index and physiological index were calculated according to Equation (6):

$$\mathrm{X}(\mu) = \frac{X - X_{\min}}{X_{\max} - \mathrm{X}_{\min}} \tag{6}$$

where $X(\mu)$ was the membership function value of an indicator, X was the measured value of this indicator, $X_{\max}$ was the maximum value of this indicator, and $X_{\min}$ was the minimum value of this indicator. The membership function values of all the indexes were accumulated and averaged, which was the comprehensive evaluation index of this plant. The larger the comprehensive evaluation index value, the stronger the comprehensive adaptability of this plant to the CDW landfill soil.

Results and Analyses

Soil Property Analysis

The physicochemical properties and main nutrient contents of the garden soil and the construction waste landfill soil are shown in Table 3. Due to the influence of large particles of construction waste, the capacity of construction waste landfill soil was larger than that of garden soil, and the proportion of large voids was larger than that of garden soil, while the proportion of small pores was lower than that of garden soil, indicating that the aeration of the construction waste landfill soil was stronger than that of the garden soil, while the water holding capacity was weaker than that of the garden soil. The pH of the construction waste landfill soil was higher than that of the garden soil and slightly acidic, and the EC was smaller than that of the garden soil, indicating that the content of soluble salts was lower than that of the garden soil. The organic matter content of the construction waste landfill soil was lower than that of the garden soil, the total nitrogen content, effective phosphorus content and fast-acting potassium content were 64.47%, 88.57% and 75.21% of that of

Table 3. Physical and chemical traits and major nutrient contents of different soils.

Soil species	Size porosity ratio	pH	EC (ms·cm$^{-1)}$	Organic matter Content (g·kg^{-1})	Total nitrogen content (g·kg^{-1})	Effective phosphorus content (mg·kg^{-1})	Fast-acting potassium content (mg·kg^{-1})
Soil (CK)	0.41±0.04	6.40±0.21	0.35±0.02	19.54±1.13	0.76±0.06	4.55±0.34	175.64±11.56
CDW Fill in the soil	0.61±0.05	6.98±0.21	0.25±0.02	11.84±0.94	0.49±0.03	4.03±0.37	132.10±9.93

garden soil, respectively, the overall nutrient content was lower than that of garden soil, and the nitrogen was especially insufficient.

Effect of Different Soils on the Growth Indicators

The heights of the ten herbaceous species grown in the garden soil and the construction waste landfill soil are shown in Fig. 3. The heights of all kinds of plants increased after the experiment, but the magnitude of growth varied. The height of *Heliopsis helianthoides* increased the most, at 163.83%, and the height of *Lythrum salicaria* increased the least, at 114.33%, under garden soil conditions. *Panicum virgatum* showed the largest height growth of 136.83%, and *Tulbaghia violacea* showed the smallest plant height growth of 104.32% under construction waste landfill soil conditions. Except for *Sedum aizoon* and *Carex oshimensis 'Evergold'*, the height growth of the remaining eight species under construction waste landfill soil conditions was relatively smaller than that under garden soil conditions.

After 1a of growth, the width growth of the ten herbaceous species is shown in Fig. 4. Different degrees of width growth could be observed. Under garden soil conditions, *Lythrum salicaria* showed the largest width growth of 136.83%, and *Acorus gramineus 'Ogan'* showed the smallest width growth of 106.20%. Under construction waste landfill soil conditions, *Heliopsis helianthoides* showed the greatest width growth of 140.32%, and *Tulbaghia violacea* showed the least width growth of 115.25%. Unlike the differences in height growth under the 2 kinds of soil conditions, the width growth of the eight species was relatively greater under construction waste landfill soil conditions than under garden soil conditions, except for *Lythrum salicaria* and *Tulbaghia violacea*.

As shown in Fig. 5, the fresh biomass of the the ten herbaceous species under different soil conditions also showed varying degrees of growth trends. *Heliopsis helianthoides* showed the highest biomass growth of 155.67% and *Lythrum salicaria* showed the least biomass growth of 106.53% under garden soil conditions. Under construction waste landfill soil conditions, *Heliopsis helianthoides* showed the greatest biomass growth of 144.50% and *Acorus gramineus 'Ogan'* showed the least biomass growth of 113.46%. The overall comparison revealed that the biomass of five herbaceous species, *Sedum aizoon*, *Carex oshimensis 'Evergold'*, *Panicum virgatum*, *Lythrum salicaria* and *Hemerocallis fulva*, in the construction waste condition was relatively greater than that under garden soil conditions. *Physostegia virginiana*, *Acorus*

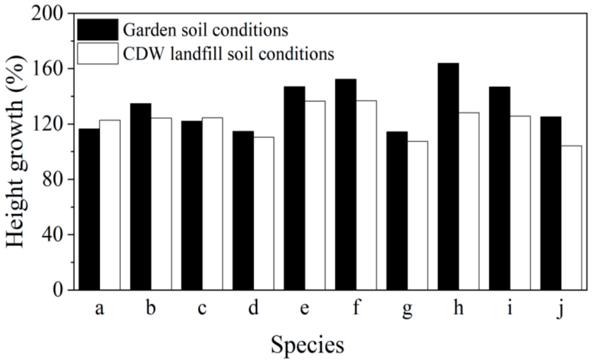

Fig. 3. Effect of different soil conditions on the height growth of ten herbaceous species.
Note: a is *Sedum aizoon*, b is *Physostegia virginiana*, c is *Carex oshimensis* 'Evergold', d is *Acorus gramineus* 'Ogan', e is *Pennisetum alopecuroides*, f is *Panicum virgatum*, g is *Lythrum salicaria*, h is *Heliopsis helianthoides*, i is *Hemerocallis fulva*, j is *Tulbaghia violacea.*

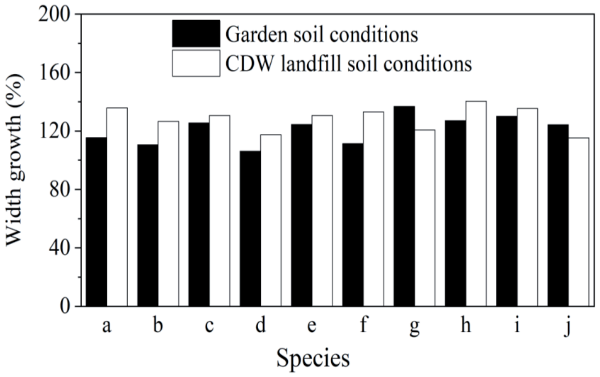

Fig. 4. Effect of different soil conditions on the widths growth of ten herbaceous species.
Note: a is *Sedum aizoon*, b is *Physostegia virginiana*, c is *Carex oshimensis* 'Evergold', d is *Acorus gramineus* 'Ogan', e is *Pennisetum alopecuroides*, f is *Panicum virgatum*, g is *Lythrum salicaria*, h is *Heliopsis helianthoides*, i is *Hemerocallis fulva*, j is *Tulbaghia violacea.*

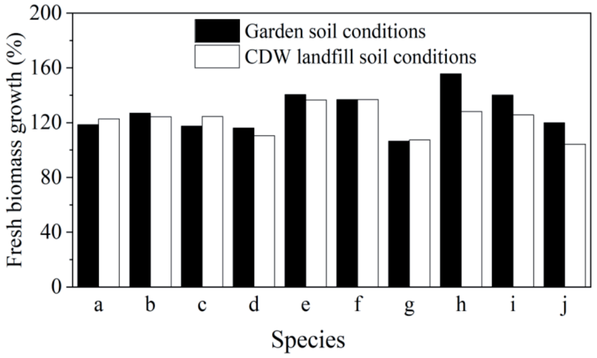

Fig. 5. Effect of different soil conditions on the fresh biomass growth of ten herbaceous species.
Note: a is *Sedum aizoon*, b is *Physostegia virginiana*, c is *Carex oshimensis* 'Evergold', d is *Acorus gramineus* 'Ogan', e is *Pennisetum alopecuroides*, f is *Panicum virgatum*, g is *Lythrum salicaria*, h is *Heliopsis helianthoides*, i is *Hemerocallis fulva*, j is *Tulbaghia violacea.*

gramineus 'Ogan', *Pennisetum alopecuroides*, *Heliopsis helianthoides, Heliopsis helianthoides* and *Tulbaghia violacea* showed relatively smaller biomass growth than that under garden soil conditions.

All the ten herbaceous species showed increasing trends in the coverage rate. Under garden soil conditions, *Hemerocallis fulva* showed the greatest increase in the coverage rate at 146.67%, and *Acorus gramineus 'Ogan'* showed the least increase at 109.53%. Under construction waste landfill soil conditions, *Carex oshimensis 'Evergold'* showed the greatest increase in the coverage rate at 148.20%, and the least increase in the coverage rate was 109.18% for *Acorus gramineus 'Ogan'*. The overall comparison showed that the increases in the coverage rate of *Lythrum salicaria* and *Tulbaghia violacea* under construction waste landfill soil conditions were relatively smaller than those of the same species under garden soil conditions, the increase in the coverage rate of *Acorus gramineus 'Ogan'* under construction waste landfill soil conditions was comparable to that under garden soil conditions, and the increases in the coverage rate of the remaining seven species in the construction waste landfill soil was relatively greater than those of the same species in the garden soil, as shown in Fig. 6.

Effect of Different Soils on the Physiological Indicators of ten Herbaceous Species

The construction waste landfill soil was not conducive to the synthesis of chlorophyll in the ten herbaceous species. After 1a planting, the chlorophyll contents of all the ten herbaceous plants showed decreasing trends compared with the same species in the garden soil, among which the chlorophyll content of Physostegia virginiana was 0.18 times lower than that in the garden soil, which was the largest decrease among the ten herbaceous species, and the visual manifestation was lighter leaf color. The chlorophyll content of Panicum virgatum was 0.02 times lower than that in the garden soil, which was the smallest decrease among the ten herbaceous species. The chlorophyll content of Carex oshimensis 'Evergold' and Acorus gramineus 'Ogan' decreased to different degrees, as shown in Fig. 7. No visible differences in leaf color were shown because both plants were horticultural species with golden leaves.

The activity of SOD, one of the antioxidant enzymes that responds rapidly to environmental factors, is also closely related to soil conditions. The SOD activities of the leaves of the ten herbaceous species under construction waste landfill soil conditions were all somewhat higher than those of the same species under garden soil conditions. As shown in Fig. 8, the effect of construction waste landfill soil on the SOD activity of Lythrum salicaria was the most pronounced, being

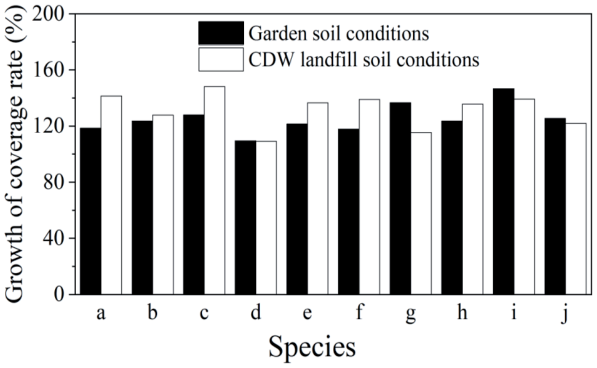

Fig. 6. Effect of different soil conditions on the growth of coverage rates of ten herbaceous species.
Note: a is *Sedum aizoon*, b is *Physostegia virginiana*, c is *Carex oshimensis* 'Evergold', d is *Acorus gramineus* 'Ogan', e is *Pennisetum alopecuroides*, f is *Panicum virgatum*, g is *Lythrum salicaria*, h is *Heliopsis helianthoides*, i is *Hemerocallis fulva*, j is *Tulbaghia violacea.*

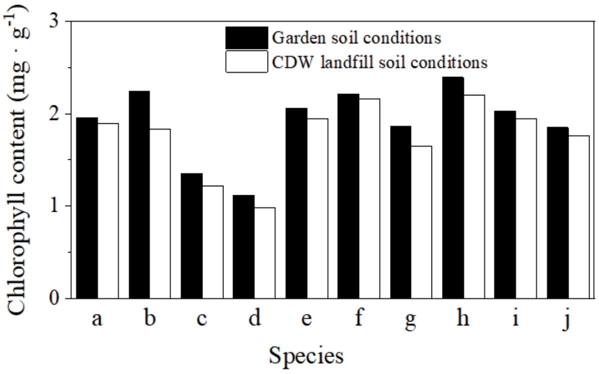

Fig. 7. Effect of different soil conditions on the chlorophyll contents of ten herbaceous species.
Note: a is *Sedum aizoon*, b is *Physostegia virginiana*, c is *Carex oshimensis* 'Evergold', d is *Acorus gramineus* 'Ogan', e is *Pennisetum alopecuroides*, f is *Panicum virgatum*, g is *Lythrum salicaria*, h is *Heliopsis helianthoides*, i is *Hemerocallis fulva*, j is *Tulbaghia violacea.*

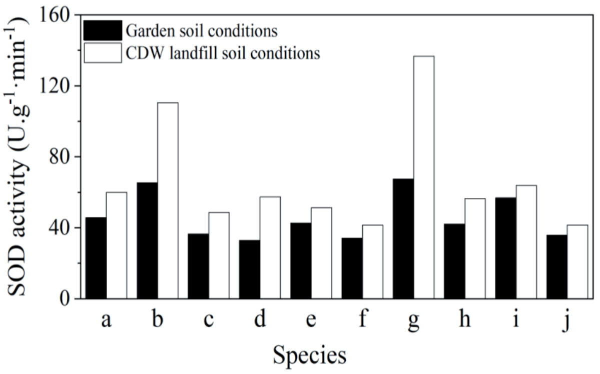

Fig. 8. Effect of different soil conditions on the SOD activities of ten herbaceous species.
Note: a is *Sedum aizoon*, b is *Physostegia virginiana*, c is *Carex oshimensis* ‘Evergold’, d is *Acorus gramineus* ‘Ogan’, e is *Pennisetum alopecuroides*, f is *Panicum virgatum*, g is *Lythrum salicaria*, h is *Heliopsis helianthoides*, i is *Hemerocallis fulva*, j is *Tulbaghia violacea.*

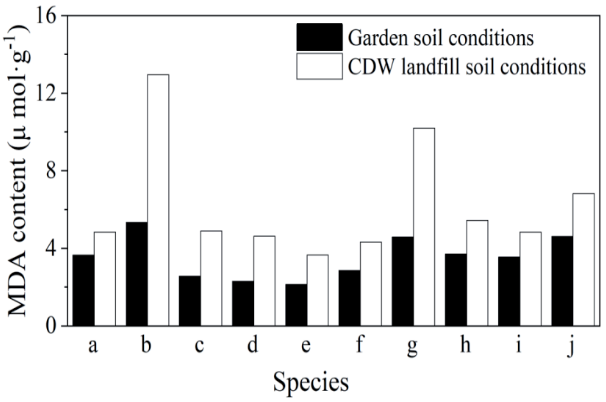

Fig. 9. Effect of different soil conditions on the MDA contents of ten herbaceous species.
Note: a is *Sedum aizoon*, b is *Physostegia virginiana*, c is *Carex oshimensis* ‘Evergold’, d is *Acorus gramineus* ‘Ogan’, e is *Pennisetum alopecuroides*, f is *Panicum virgatum*, g is *Lythrum salicaria*, h is *Heliopsis helianthoides*, i is *Hemerocallis fulva*, j is *Tulbaghia violacea.*

2.03 times higher than that in the garden soil, and the effect on the SOD activity of Hemerocallis fulva was the least, being 1.12 times higher than that in the garden soil.

The MDA contents of the leaves were also influenced by soil conditions. As shown in Fig. 9, the MDA contents of species grown in the construction waste landfill soil increased significantly compared with the same species grown in the garden soil. The MDA content of Physostegia virginiana increased the most, 2.43 times more than that in the garden soil, and the MDA content of Sedum aizoon increased the least, 1.33 times more than that in the garden soil.

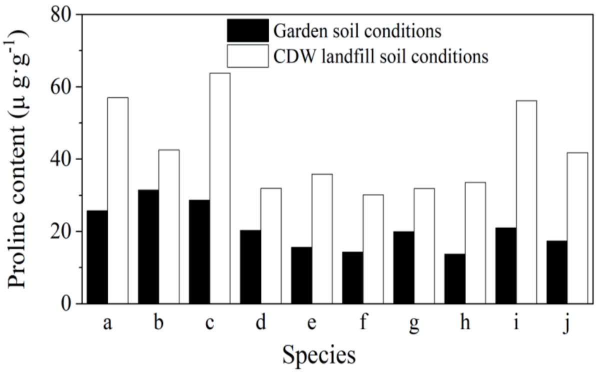

Fig. 10. Effect of different soil conditions on the proline contents of ten herbaceous species.
Note: a is *Sedum aizoon*, b is *Physostegia virginiana*, c is *Carex oshimensis* ‘Evergold’, d is *Acorus gramineus* ‘Ogan’, e is *Pennisetum alopecuroides*, f is *Panicum virgatum*, g is *Lythrum salicaria*, h is *Heliopsis helianthoides*, i is *Hemerocallis fulva*, j is *Tulbaghia violacea.*

Soil conditions also significantly affected the proline contents of the leaves of the ten herbaceous species. As shown in Fig. 10, the proline contents of plants grown in the construction waste landfill soil were higher than those of the same species grown in the garden soil. Among them, the proline content of Hemerocallis fulva was 2.68 times higher than that under garden soil conditions, which was the largest increase, and the proline content of Physostegia virginiana was 1.35 times higher than that under garden soil conditions, which was the smallest increase.

Comprehensive Evaluation

Table 4 shows the comprehensive evaluation results of the growth and physiological indexes of ten herbaceous species under construction waste landfill soil conditions. As seen from the comprehensive evaluation index, *Hemerocallis fulva* ranked first with a comprehensive evaluation index of 0.87, indicating its best adaptability to the construction waste landfill soil, followed by *Panicum virgatum*, *Heliopsis helianthoides*, *Sedum aizoon* and *Carex oshimensis* ‘Evergold’. Tulbaghia violacea grew normally under construction waste landfill conditions, without pests or diseases, but the relatively slow vertical and horizontal growth rates had adverse effects on the comprehensive evaluation index, which was 0.50. Vertical growth was the main growth pattern of *Physostegia virginiana* instead of horizontal growth. For poor physiological performance, especially low chlorophyll content, the overall evaluation index of *Physostegia virginiana* was 0.26.

During the experiment, a great degree of the leaf margins of Acorus gramineus ‘Ogan’ were scorched and the young leaves of Lythrum salicaria were damaged by beetles, which seriously affected both the growth rate and the physiological index. On the other hand, the ornamental values of these two species were the lowest. The overall evaluation indexes of A*corus gramineus* ‘Ogan’ and *Lythrum salicaria* were 0.21 and 0.15, respectively.

Table 4. Comprehensive evaluation of the adaptability of ten herbaceous species.

	a	b	c	d	e	f	g	h	i	j
Height	0.57	0.62	0.62	0.19	0.99	1.00	0.09	0.73	0.66	0.00
Width	0.82	0.45	0.61	0.09	0.61	0.71	0.21	1.00	0.80	0.00
Fresh biomass	0.58	0.19	0.23	0.00	0.63	0.87	0.22	1.00	0.88	0.20
Coverage rate	0.83	0.48	1.00	0.00	0.70	0.76	0.16	0.68	0.77	0.32
Chlorine content	0.92	0.00	0.60	0.36	0.81	1.00	0.13	0.65	0.86	0.84
SOD activity	0.79	0.37	0.77	0.31	0.91	0.90	0.00	0.76	1.00	0.96
MDA content	1.00	0.00	0.47	0.38	0.65	0.83	0.18	0.87	0.97	0.86
Proline content	0.65	0.00	0.66	0.35	0.71	0.57	0.18	0.82	1.00	0.80
Comprehensive evaluation index	0.77	0.26	0.62	0.21	0.75	0.83	0.15	0.81	0.87	0.50

Note: a is *Sedum aizoon*, b is *Physostegia virginiana*, c is *Carex oshimensis* ‘Evergold’, d is *Acorus gramineus* ‘Ogan’, e is *Pennisetum alopecuroides*, f is *Panicum virgatum*, g is *Lythrum salicaria*, h is *Heliopsis helianthoides*, i is *Hemerocallis fulva*, j is *Tulbaghia violacea.*

Discussion

The final thickness of the soil layer above the construction waste varies greatly according to the purpose of development and utilization of the landfills. Normally, the final thickness of the soil layer above the construction waste for herbaceous plant-based vegetation restoration should not be less than 30 cm, while the final thickness for woody plant-based vegetation restoration should not be less than 60 cm [24-25]. The thickness of the soil layer above the construction waste at the Fenghuangshan landfill in Suzhou was 10-60 cm, and the soil layer at the top of the slope was thicker than that on the slope surface. The thickness of construction waste landfill soil and the garden soil used in our experiments was 30 cm, which meets the soil requirements of herbaceous plants. Compared with garden soil, construction waste landfill soil was mixed with some part of the construction waste. Therefore, the bulk density of the construction waste landfill soil was larger than that of the garden soil and the water-holding capacity was poorer than that of the garden soil, which put forward high requirements for drought tolerance for plants. Meanwhile, the nutrient content, especially the nitrogen content of the construction waste landfill soil was low, thus, only plants with notable tolerance to low nutrients and a high nitrogen utilization rate could develop healthily.

Height, width, biomass and coverage rate are typical growth indicators of herbaceous plants and are often used to compare the performances of plants under different cultivation conditions [26-27]. The ten herbaceous species selected for this experiment could grew robustly under open-field conditions, with high drought resistance and very few pests and diseases. Under the experimental conditions, all of the survival rates of the ten species in the construction waste landfill soil were 100%, but the performances of the appearance level and the physiological level varied. Under our experimental conditions, the height of many herbaceous species grew more slowly than those in the garden soil, while the width grew more rapidly than those in the garden soil, which was related to the poor water-holding capacity of construction waste landfill soil. After 1a of growth, the biomass of *Sedum aizoon* and *Lythrum salicaria* was significantly greater than that of the same species grown in the garden soil, and the biomass of *Physostegia virginiana*, *Pennisetum alopecuroides*, and *Heliopsis helianthoides* biomass was significantly smaller than that of the same species grown in the garden soil, and the differences between the biomass of *Carex oshimensis* ‘Evergold’, *Acorus gramineus* ‘Ogan’, *Panicum virgatum*, *Hemerocallis fulva* and *Tulbaghia violacea* and the biomass of the same species grown in the garden soil was non significant. The coverage rate is an important indicator of the expansion capacity of plants and is particularly valued in greening projects that need to cover the ground rapidly, to prevent the growth of weeds. The coverage rate and the increase in the coverage rate were closely related to the morphology and the main growth direction of plants. Ordinarily, the coverage rates of plants with vertical structures were smaller than those of plants with mixed structures and horizontal structures. Furthermore, the increase in the coverage rates of plants with vertical structures was relatively slow. In our experiment, the pattern of the increase in the coverage rates and the changes in the width growth of the ten herbaceous species was consistent. The increases in the coverage rates of eight herbaceous species were relatively larger than those of the same species under garden soil conditions, among which the increases in the coverage rates of *Sedum aizoon*, *Carex oshimensis* ‘Evergold’, *Pennisetum alopecuroides*, *Panicum virgatum* and *Heliopsis helianthoides* were significant.

Chlorophyll is an important pigment for photosynthesis in plants. Changes in any of the environmental factors such as temperature, light, water, soil, or gas can affect the stability of leaf thylakoid membranes and chloroplast structure directly or indirectly, which in turn influence the activity of enzymes related to chlorophyll synthesis and ultimately lead to an increase or decrease in the rate of chlorophyll synthesis [28-32]. In this experiment, the chlorophyll contents of the leaves of the ten herbaceous species under construction waste landfill soil conditions were somewhat lower than those of the same species under garden soil conditions, which may be related to the physicochemical properties and the low nutrient levels of the construction waste landfill soil, especially the low nitrogen level, after all, the synthesis of chlorophyll was highly dependent on nitrogen nutrition. The leaf color of *Physostegia virginiana* and *Lythrum salicaria* was significantly lighter than that of plants grown in the garden soil, which means that they might be more sensitive than the other species. When the environment was suitable, the generation and elimination of reactive oxygen species were relatively balanced, but this balance could be broken easily when any kind of the environmental factor changed. At that time, the antioxidant enzyme system was rapidly activated to scavenge excess free radicals and alleviate the adverse effects caused by altered environmental factors, of which the changes in SOD activity were the most representative [33-34]. The SOD activities of all the ten herbaceous species under construction waste landfill soil conditions were somewhat higher than those of the same species under garden soil conditions, indicating that the construction waste landfill soil caused some degree of stress on the normal growth and metabolic activities of the plants compared to the garden soil, the increase of SOD activities of *Physostegia virginiana*, *Acorus gramineus* 'Ogan' and *Lythrum salicaria* were the most significant. The accumulation of free radicals in plant cells caused by construction waste landfill soil aggravated the membrane lipid peroxidation and led to an increase in the MDA contents of the ten herbaceous species under the landfill soil conditions, which was consistent with the results of Nie's study. We also found a certain correlation between MDA contents and SOD activities, and species with higher MDA contents usually had higher SOD activities. Proline is an important osmotic regulator in plants. The proline contents of the ten herbaceous species under construction waste landfill soil conditions were higher than those of the same species under garden soil conditions, indicating that plant cells respond to adverse conditions through the accumulation of osmoregulatory substances [35]. In this experiment, seven herbaceous species, including *Sedum aizoon*, *Carex oshimensis* 'Evergold', *Pennisetum alopecuroides*, *Panicum virgatum*, *Heliopsis helianthoides*, *Hemerocallis fulva* and *Tulbaghia violacea*, showed significantly greater increases in proline content than *Physostegia virginiana, Acorus gramineus* 'Ogan' and *Lythrum salicaria*, while the decrease in chlorophyll content was significantly smaller than that of the above three herbaceous species, and the correlation between the proline content and chlorophyll content was shown. There are several indicators for plant adaptability evaluation, and each indicator is meaningful, but usually a single indicator cannot accurately reflect the adaptability status of plants. In this paper, we used the affiliation function method to select four growth indicators and four physiological indicators in an attempt to jointly characterize the adaptability of the selected species to the construction waste landfill soil at the morphological level and metabolic level. The comprehensive evaluation results not only reflected the comprehensive performance of the ten herbaceous species under construction waste landfill soil conditions, but also visually reflected the growth rates, expansion modes and health levels of the ten herbaceous species. The results indicated that *Hemerocallis fulva, Panicum virgatum, Heliopsis helianthoides, Sedum aizoon* and *Carex oshimensis* 'Evergold' had higher comprehensive evaluation indexes and better adaptability to the construction waste landfill soil, the performance of *Tulbaghia violacea* was ordinary, and the comprehensive performances of *Physostegia virginiana, Acorus gramineus* 'Ogan' and *Lythrum salicaria* were poor.

Conclusion

Ecological restoration using landscape plants is an effective means of environmental management and value regeneration of construction waste landfills. In the middle stage of revegetation, herbaceous plants with high survival rates, rapid expansion rates and high resistance to undesirable environmental conditions are the most needed. The results of this study indicate:

(1) The density of CDW landfill soil is greater than that of garden soil, and the proportion of voids indicates that the aeration of CDW landfill soil is greater than that of garden soil, while the water holding capacity is lower. The pH value of CDW landfill soil is higher than that of garden soil, and the EC value is less than that of garden soil, indicating that the content of soluble salts is lower. The organic matter content of CDW landfill soil is lower than that of garden soil, and the total nitrogen content, effective phosphorus content and fast-acting potassium content are 64.47%, 88.57% and 75.21% of that of garden soil, respectively.

(2) The height growth under construction landfill soil conditions was relatively smaller than that under garden soil conditions, while the width growth of the 8 species was relatively greater. The overall comparison showed that five herbaceous species, *Sedum aizoon, Carex oshimensis 'Evergold'*, *Panicum virgatum, Lythrum salicaria* and *Hemerocallis fulva*, had relatively larger biomass under construction waste conditions than under garden soil conditions.

(3) The construction landfill soil was unfavorable for chlorophyll synthesis in these ten herbaceous species. the SOD activity of the leaves of all ten herbaceous species was somewhat higher in the construction landfill soil conditions than in the same species in the garden soil conditions. The MDA content of the species grown in construction waste landfill soil was significantly increased compared to the same species grown in garden soil. Proline content was higher in plants grown in construction landfill soil than in the same species grown in garden soil.

(4) The results of this study showed that five species of *Hemerocallis fulva, Panicum virgatum, Heliopsis helianthoides, Sedum aizoon* and *Carex oshimensis 'Evergold'* were well adapted to the construction waste landfill soil in Suzhou. On the other hand, they all had high ornamental values and rapid expansion rates, which made them excellent species for landscape reshaping at construction waste sites.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

References

1. HUANG Y.., CHEN J.., SHI S.., LI B.., MO J.., TANG Q. Mechanical properties of municipal solid waste incinerator (MSWI) bottom ash as alternatives of subgrade materials. Advances in Civil Engineering., **2020**.
2. TANG Q., GU F., CHEN H., LU C., ZHANG Y. Mechanical evaluation of bottom ash from municipal solid waste incineration used in roadbase. Advances in Civil Engineering., **2018**.
3. TANG Q., HEEJONG K., KAZUTO E., TAKESHI K., TORU I. Size effect on lysimeter test evaluating the properties of construction and demolition waste leachate. Soils and Foundations, **55** (4), 720, **2015**.
4. HUANG B., WANG X., KUA H., GENG Y., BLEISCHWITZ R., REN J. Construction and demolition waste management in China through the 3R principle. Resources., Conservation and Recycling., **129**, 36, **2018**.
5. WANG Z., ZHANG Z., JIN XA study on the spatial network characteristics and effects of CDW generation in China. Waste Management., **128**, 179, **2021**.
6. TANG Q., ZHANG Y., GAO YF., GU F., Use of Cement-Chelated Solidified MSWI Fly Ash for Pavement Material: Mechanical and Environmental Evaluations., Canadian Geotechnical Journal, **54** (11), 1553, **2017**.
7. TANG Q., LIU Y., GU F., ZHOU T., Solidification/stabilization of fly ash from a municipal solid waste incineration facility using Portland cement., Advances in Materials Science and Engineering, **10**, 7101243, **2016**.
8. TIAN A., CHEN J., FENG Z., XU Q., LUO X., TANG Q. Study on the Mechanical Properties of Fibre and Cement Reinforced Heavy Metal-Contaminated Soil. Polish Journal of Environmental Studies, **31** (3), 1, **2022**.
9. CHEN J., EUN J., FENG., Y., TINJUM J. Long-term Leaching Behavior of Chromite Ore Processing Residue as Backfill Material and the Propagation of Chromium in the Surrounding Soil., Journal of Hazardous., Toxic., and Radioactive Waste Management, **25** (3), 04021017, **2021**.
10. SUN J., TIAN A., FENG Z., ZHANG Y., JIANG F., TANG Q. Evaluation of zero-valent iron for Pb (II) contaminated soil remediation: from the analysis of experimental mechanism hybrid with carbon emission assessment. Sustainability, **13** (2), 452, **2021**.
11. ZHANG J., DING L., LI F., PENG J. Recycled aggregates from construction and demolition wastes as alternative filling materials for highway subgrades in China. Journal of Cleaner Production. **255**, 120223, **2020**.
12. YANG R., WANG H. Landscape Breakthrough: Ecological Regeneration and Landscape Reclamation of Urban Landfills. Urban Studies, **8**, 81, **2010**.
13. TANG Q., GU F., ZHANG Y., ZHANG YQ., MO JL. Impact of biological clogging on the barrier performance of landfill liners., Journal of Environmental Management, **222**, 44, **2018**.
14. EMANUIL N., AKRAM M S., ALI S., EL-ESAWI M. A., IQBAL M., ALYEMENI M. N. Peptone-Induced Physio-Biochemical Modulations Reduce Cadmium Toxicity and Accumulation in Spinach (*Spinacia oleracea* L.). Plants, **9** (12), 1806, **2020**
15. CUI J.Q., SUN H.B., SUN M.B., LIANG R.T., JIE W.G., CAI BY. Effects of Funneliformis mosseae on root metabolites and Rhizosphere soil properties to continuously cropped soybean in the potted-experiments. International journal of molecular sciences, **19** (8), 2160, **2018**.
16. REINA-BUENO M., ARGANDONA M., NIETO J J., HIDALGO-GARCÍA A., IGLESIAS-GUERRA F., DELGADO M. J., VARGAS C. Role of trehalose in heat and desiccation tolerance in the soil bacterium Rhizobium etli. BMC microbiology, **12** (1), 1, **2012**.
17. LUO Z., MA J., CHEN F., LI X., ZHANG Q., YANG Y. Adaptive development of soil bacterial communities to ecological processes caused by mining activities in the loess plateau., China. Microorganisms, **8** (4), 477, **2020**.
18. CREMADES A., DEL RIO-GARCIA J., LAMBERTOS A. Tissue-specific regulation of potassium homeostasis by high doses of cationic amino acids. Springer Plus, **5** (1), 1, **2016**.
19. CHEN J., SANGER M., RITCHEY R., GINDER-VOGOL M., EDIL TB. Neutralization of High pH and Alkalinity Effluent from Recycled Concrete Aggregate (RCA) by Common Subgrade Soil. Journal of Environmental Quality, **2020**.

20. ZHANG H., XU N., LI X. Arbuscular mycorrhizal fungi (Glomus mosseae) improves growth., photosynthesis and protects photosystem II in leaves of *Lolium perenne* L. in cadmium contaminated soil. Frontiers in plant science, **9**, 1156, **2018**.
21. ZHAO Q., QU R., TENG L., YIN C., YUAN Y. HO-1 protects the nerves of rats with cerebral hemorrhage by regulating the PI3K/AKT signaling pathway. Neuropsychiatric disease and treatment, **15**, 1459, **2019**.
22. WANG X., ZENG J., LI Y., RONG X., SUN J., SUN T., HE G. Expression of TaWRKY44, a wheat WRKY gene., in transgenic tobacco confers multiple abiotic stress tolerances. Frontiers in plant science, **6**, 615, **2015**.
23. LI X., JIA J., ZHAO P. LcMYB4., an unknown function transcription factor gene from sheepgrass, as a positive regulator of chilling and freezing tolerance in transgenic Arabidopsis. BMC Plant Biology, **20**, 1, **2020**.
24. ETTALA M.O. Short-rotation tree plantations at sanitary landfills. Waste Management and Research, **6**, 291, **1988**.
25. GILMAN E.F., FLOWER F.B., LEONE I.A. Standardized procedures for planting vegetation on completed sanitary landfills. Waste Management and Research, **3** (1), 65, **1985**.
26. HUSSNER A., HEIDBUCHEL P. Sediment-rooting affects growth and biomass allocation in Myriophyllum spicatum under varying growth conditions. Aquatic Botany, **170**, 103354, **2021**.
27. ALI S., CHATTHA M.U., HASSAN M.U. Growth., biomass production., and yield potential of quinoa (Chenopodium quinoa) as affected by planting techniques under irrigated conditions. International Journal of Plant Production, **14**, 427, **2020**.
28. ALLEN L.H., KIMBALL B.A., BUNCE J.A., et al. Fluctuations of CO_2 in free-air CO_2 Enrichment (FACE) depress plant photosynthesis, growth., and yield. Agricultural and Forest Meteorology, **284**, 107899, **2020**.
29. HOFFMANN A.M., NOGA G., HUNSCHE M. High blue light improves acclimation and photosynthetic recovery of pepper plants exposed to UV stress. Environmental and Experimental Botany, **109**, 254, **2015**.
30. SODA N., GUPTA B.K., ANWAR K., SHARAN A., SINGLA-PAREEK S.L., PAREEK A. Rice intermediate filament, OsIF, stabilizes photosynthetic machinery and yield under salinity and heat stress. Scientific Reports, **8**, 4072, **2018**.
31. GHOTBI-RAVANDI A.A., SHAHBAZI M., SHARIATI M., SHARIATI M., MULO P. Effects of mild and severe drought Stress on photosynthetic efficiency in tolerant and susceptible barley (*Hordeum vulgare* L.) genotypes. Journal of Agronomy and Crop Science, **200** (6), 403, **2014**.
32. ALSALEH A.E., ASTARAEI A.R., EMAMI H., EMAMI H., LAKZIAN A. The effect of mercuric toxicity in saline soil on growth., soluble sugars., photosynthetic pigments and some of enzymes in turnip. Indian Journal of Environmental Protection, **12**, 1125, **2019**.
33. ANSARI A., RAZMJOO J., M ZAREI M., KARIMMOJENI H. Salicylic acid affects mycorrhizal features., antioxidant enzyme activities and seed yield of linseed under water-deficit stress in open-field conditions. Biologia Futura, **72**, 211, **2021**.
34. AHMAD P., ALYMENIl M N., AHANGER M A., EGAMBERDIEVA D., WIJAYA L., ALAM P. Salicylic acid (SA) induced alterations in growth., biochemical attributes and antioxidant enzyme activity in faba bean (*Vicia faba* L.) seedlings under NaCl toxicity. Russian Journal of Plant Physiology, **65** (1), 104, **2018**.
35. SUN X.L., YUAN Z.B., WANG B., ZHENG L.P., TAN J.Z., CHEN F.D. Physiological and transcriptome changes induced by exogenous putrescine in anthurium under chilling stress Botanical Studies. **61**, 28, **2020**.