

## Selection of waterlogging-tolerant and water purification herbaceous plants for the construction of a sponge city in Shenzhen, China

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### Abstract

In recent years, seeking solutions to urban waterlogging and water pollution has always been one of the topics of concern. The problem of urban water accumulation occurs frequently in most areas of China in July and August. The contradiction between supply and demand of urban ecological water is prominent. In order to solve the problem of urban water accumulation caused by rainfall concentration, and to achieve the overall goal of building a water-saving green ecological city, the Shenzhen City should be built into a sponge city. Under this background, the physiological response of different forages to waterlogging stress and the removal of pollutants in rainwater were studied. In this study, ten herbaceous plants commonly used in Shenzhen were used as experimental materials. After 0, 7, 14, 21, 28 days of waterlogging stress treatment, six physiological indexes, such as MDA, SP, and Pro contents and SOD, POD, and CAT activities, were comprehensively evaluated. Combined with the morphological changes of the plants after waterlogging, seven plants with strong waterlogging tolerance were determined, which were *O. bodinieri*, *H. coronarium*, *I. tectorum*, *D. ensifolia*, *R. brittoniana*, *C. indica*, and *A. zerumbet*. Then, according to their comprehensive evaluation of the removal capacity of pollutants in the rainwater, it is suggested to select *O. bodinieri*, *H. coronarium*, *I. tectorum* and *D. ensifolia* in areas with serious waterlogging. In areas with serious water pollution, *R. brittoniana*, *A. zerumbet*, *D. ensifolia* and *H. coronarium* are recommended. However, *H. coronarium* and *D. ensifolia* not only have a strong adaptability in the waterlogged environment, but also have a strong ability to remove pollutants in the rainwater, so they are suggested to be alternative herbaceous plants for sponge city in Shenzhen, China.

**Keywords:** comprehensive evaluation; purification capacity; Shenzhen City; sponge city; waterlogging resistance

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### Introduction

Due to the lack of foresight in the early stage of development, many cities in China are facing many challenges of environmental problems, especially the problems of urban waterlogging and water pollution. Given the frequent rainstorms in July and August in most areas of China, the contradiction between the supply and demand of urban ecological water is particularly prominent. China has proposed the concept of sponge

cities in 2013 to solve the problem of urban water accumulation, caused by concentrated rainfall and achieve the overall goal of building a water-saving green ecological city (Liu *et al.*, 2017; Thu Thuy *et al.*, 2020). The phrase “sponge city” vividly describes a city’s environment and the commitment to finding ecologically appropriate alternatives and transforming urban infrastructure into green infrastructure such that these facilities can capture, control, and reuse precipitation in a beneficial and ecologically benign way (McBean *et al.*, 2019).

Plants constitute the foundation of sponge cities (Li *et al.*, 2019; Ma *et al.*, 2019). The interaction of plant stems, leaves, and roots with soil can aid in rainwater infiltration, reduce the runoff of rainwater, slow down the flow rate of rainwater, and purify and retain pollutants from rainwater (Ma *et al.*, 2019). The roots of plants absorb rainwater and penetrate into the soil, and the nutrients in rainwater can promote the growth of plants (Li *et al.*, 2019). Plant transpiration can regulate the local microclimate, reduce the urban heat island effect (Jochner *et al.*, 2013), and promote water circulation in the ecosystem. At the same time, plants are one of the basic elements of landscape, and play an important role in the construction and configuration of landscape. The appropriate plant selection is related to whether sponge city and green rainwater infrastructure can effectively play and maintain its function. Therefore, studying the growth habits and characteristics of the submerged green land plants has practical significance. The landscape function of plants and their role in waterlogging tolerance and decontamination capacity should be considered to maximize their ecological role.

According to the requirements and characteristics of building sponge City, only the herbaceous plants with strong waterlogging resistance can survive in the long-term waterlogged environment and maintain the landscape effect that meets the requirements of urban greening. Therefore, waterlogging tolerance is the most important index of herbage selection in sponge city. In the construction of sponge city, herbaceous plants should not only have strong waterlogging resistance and better ornamental, but also play a certain ecological function (such as rainwater purification function), which is also one of the important reference standards for herbaceous plant selection. If there are herbaceous plants that can not only maintain a well living condition in the waterlogged environment, but also has the purification function of pollutants in the rainwater, it will be an excellent alternative plant to meet the development concept of sponge city. This study was based on the investigation of commonly used herbaceous ground cover plants in Shenzhen and selected 10 kinds of native herbaceous plants. The comprehensive analysis of the physiological effects and water purification capacity of the selected plants under waterlogging conditions provides a theoretical basis for the construction of “sponge city” planting level and has guided and promoting roles. The herbaceous plants with strong flood resistance and certain water purification capacity were selected as the alternative plants for the construction of sponge city in Shenzhen.

## Materials and Methods

### *Test materials*

The test materials were *Nephrolepis auriculata*, *Ophiopogon bodinieri*, *Syngonium podophyllum*, *Iris tectorum*, *Ruellia brittoniana*, *Aspidistra elatior*, *Hedychium coronarium*, *Alpinia zerumbet*, *Canna indica*, and *Dianella ensifolia*. These plants are common and widely available herbaceous plants in Shenzhen. Healthy plants with strong growth and uniformity were introduced from Zhongshan City and planted in the nursery field (in the greenhouse, open around, only shade and rain protection function) of Gaoxin Road, Guangming New District, Shenzhen in March 2017. This area belongs to subtropical marine climate, with mild climate, abundant rain-fall and long sunshine time. The annual average temperature is 22 °C, the maximum temperature is 38.7 °C, and the minimum temperature is 0.2 °C. It is rainy season from April to September every year, with annual precipitation of 1926 mm, annual sunshine hours of 2060 h and frost-free period of

355 d. The plant physiological- and biochemical-related indicators were determined in the biochemical laboratory of Shenzhen Vocational and Technical College.

#### *Experimental design*

The experiment was conceived using a complete randomized design. The plants under testing were planted in a flowerpot with a diameter of 25 cm and a height of 18 cm. The soil used was the native Shenzhen lateritic red soil. Each plant trial group was established with three replicates, which contained 10 pots per replicate. The plants under normal water management were used as control group (CK). In order to reduce the test error, all the plants grew in the same environment and began to be treated after three months of normal cultivation. The plants were placed in nonporous pots with diameters of about 28 cm and a height of about 20 cm after they were well grown. Except for the control, all plants had a waterlogging depth of more than 5 cm layer of soil. The treatment time interval was 7, 14, 21, and 28 days. Five random samples were collected on 22 May, 29 May, 5 June, 12 June, and 19 June, and the related physiological indices were determined. Select several complete leaves as samples each time, freeze them in liquid nitrogen, and store them in -80 °C ultra-low temperature refrigerator after returning to the laboratory. The state of each plant before and after treatment was photographed for morphological comparison before and after waterlogging.

The allocation of simulated rainwater pollutants is based on the quality and composition of rainwater in Shenzhen city (Zhu *et al.*, 2016). Simulated rainwater was formed by adding 0.08 g/L road dust, 0.0038 g/L ammonium chloride, 0.005 g/L sodium dehydration phosphate, 0.0072 g/L potassium nitrate and 0.094 g/L potassium phthalate to tap-water. Plants with good growth and uniform appearance were chosen. Each plant had 3 replicates, and 10 pots per replicate. In order to eliminate the influence of tap water on the experiment, three blank water samples (tap-water without simulated pollutants) were considered as CK1 and three initial water samples (water with simulated pollutants and clarified after adding into flowerpots containing planting soil) as CK2. waterlogging height of all treatments was 5 cm above the soil surface. After 5 days of rainwater treatment, carefully take (avoid extracting to the underlying soil) 10ml water sample with disposable syringe (volume 20 ml) and send it to the Shenzhen Puni Test Group for detection of six pollutants, suspended solids (SS), total phosphorus (TP), total nitrogen (TN), ammonia nitrogen ( $\text{NH}_4^{++}\text{-N}$ ), chemical oxygen demand ( $\text{COD}_{\text{Cr}}$ ) and biological oxygen demand ( $\text{BOD}_5$ ). Comparing water quality indexes of plants before and after rainwater treatment, the plants with strong ability of decontamination were selected by comprehensive evaluation.

#### *Indicator determination*

The determination of soluble protein (SP) was estimated on the basis of a previously reported protocol (Lowry *et al.*, 1951). The content of proline (Pro) was determined via the sulfonic salicylic acid-acid three calorimetry (Davydova *et al.*, 2005). The superoxide dismutase (SOD) activity was determined through the aorta-anisidine method (Durak *et al.*, 1993). The activity of catalase (CAT) was determined on the basis of ultraviolet absorption (Durak *et al.*, 1999). The activity of peroxidase (POD) was determined via the guaiacol method (Rufino *et al.*, 2008). The malondialdehyde (MDA) content was determined using the thiobarbituric acid method (Gomez *et al.*, 1998). The detection methods of  $\text{COD}_5$ , TN, TP in this paper refer to the methods of Xu *et al.* (2018). The detection methods of  $\text{BOD}_{\text{Cr}}$  refer to the methods of Hamdy A *et al.* (2018). According to the method of Guo *et al.* (2017), the content of SS in water sample was determined. The detection methods of  $\text{NH}_4^{++}\text{-N}$  in this paper refer to the methods of Van T *et al.* (2017).

#### *Data analysis*

The waterlogging resistance coefficient ( $\alpha$ ) was calculated on the basis of the measured values of individual physiological indices:  $\alpha = (\text{measured value}/\text{control value}) \times 100\%$ . The correlation coefficient of each waterlogging resistance coefficient was calculated.

The waterlogging tolerance coefficient was subjected to principal component analysis (PCA) and used to analyse the  $\alpha$  of each physiological index, and several related indices were reduced to a small number of unrelated comprehensive indices.

The weight of each comprehensive index was determined in accordance with the contribution rate of the comprehensive index as follows:

$$W_j = P_j / \sum_{j=1}^n P_j,$$

$j=1,2,\dots$   $W_j$  indicates the importance of the  $j$ th comprehensive index in all the comprehensive indices, and  $P_j$  is the Percentage of Variance of the  $j$ th comprehensive index of each variety.

The comprehensive waterlogging tolerance or purification ability of herbaceous plants was sorted on the basis of the  $D$  value. The specific formula is:

$$D = \sum_{j=1}^n [U_j \times W_j],$$

$j = 1, 2, \dots$   $D$  is the comprehensive evaluation value of the waterlogging tolerance or purification ability of each species evaluated by the comprehensive index.  $U_j$  is the score of waterlogging tolerance or water purification capacity of herbs in the  $j$ th comprehensive index.

Multiple comparative analysis using LSD method (least significant difference method). The data were processed using the SPSS 23 and graphed using the Origin 2019.

## Results

### *Comprehensive evaluation of the waterlogging tolerance of 10 species of plants*

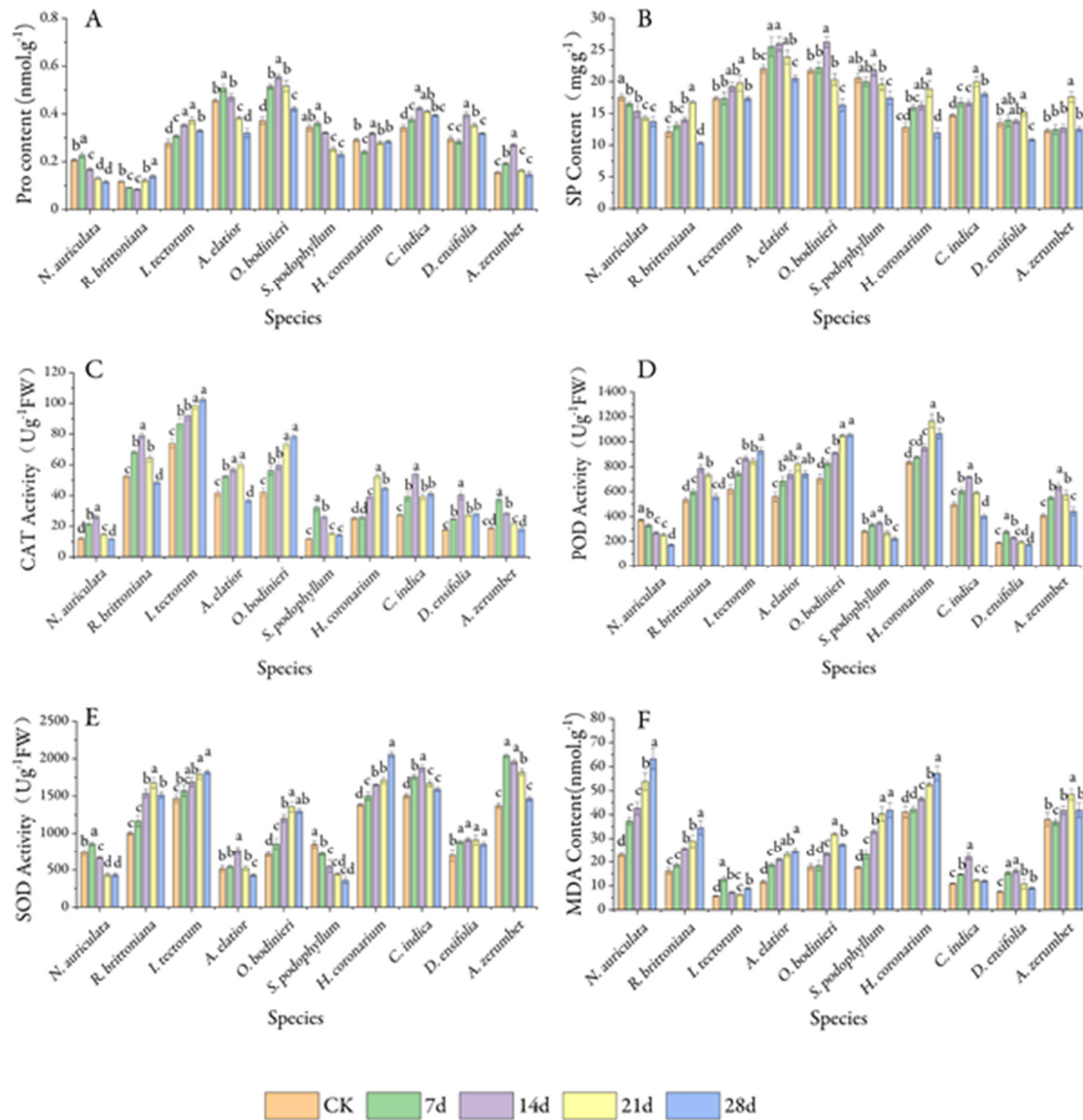
#### Effects of waterlogging stress on the Pro and SP content in leaves

The SP content of *N. auriculata* continued to decrease significantly ( $p < 0.05$ ) after waterlogging treatment, whereas the Pro (Figure 1A) and SP (Figure 1B) contents in the leaves of other plants increased at different time periods. The Pro and the SP content in the leaves of *R. brittoniana*, *I. tectorum*, *O. bodinieri*, *H. coronarium*, *C. indica*, *D. ensifolia*, and *A. zerumbet* can be maintained at high levels after 21 days of waterlogging treatment, and even some of the plants, such as *I. tectorum* and *C. indica*, maintained a high level on the day 28th. The Pro content of *N. auriculata*, *A. elatior*, and *S. podophyllum* leaves began to decrease significantly ( $p < 0.05$ ) after 14 days of waterlogging. The content of SP in the leaves of *S. podophyllum* decreased significantly ( $p < 0.05$ ) after 21 days of waterlogging. After 28 days of waterlogging, the Pro content of the leaves of *R. brittoniana*, *I. tectorum*, *O. bodinieri*, and *C. indica* were significantly higher than those of CK. At the same time, the SP content of the leaves of *C. indica* was significantly higher than that of CK. Results showed that *I. tectorum* and *C. indica* maintained a high level of Pro content of the leaves under waterlogging stress, which may be conducive to the balance of intracellular and extracellular osmotic potential, but the performances of *N. auriculata* were weaker than those of other plants.

#### Effects of waterlogging stress of the CAT, POD, and SOD activities in leaves

As shown in Figure 1C, the CAT activity of *I. tectorum* and *O. bodinieri* showed an upward trend during the test, reaching the maximum value on the 28th day. The other plants keep the trend of increasing first and then decreasing. The CAT activity of *S. podophyllum* and *A. zerumbet* reached the maximum on the 7th day, and then decreased significantly ( $p < 0.05$ ). On the 14th day, the activities of CAT in leaves of *N. auriculata*, *R. brittoniana*, *C. indica* and *D. ensifolia* reached the maximum, and then decreased significantly ( $p < 0.05$ ). On the 21st day, CAT activity of *A. elatior* and *H. coronarium* reached the maximum, and then decreased significantly ( $p < 0.05$ ). Only *R. brittoniana* and *A. elatior* decreased their CAT activity below CK treatment on the 28th day, and there was significant ( $p < 0.05$ ) difference between them. The results showed that *I.*

*tectorum* and *O. bodinieri* could keep high CAT activity in the process of waterlogging, which was good for them to resist the influence of adverse environment.



**Figure 1.** Effects of different waterlogging treatments on the 10 herbaceous plants. Effects on the (A) Pro content, (B) SP content, (C) CAT activity, (D) POD activity, (E) SOD activity, and (F) MDA content

As shown in Figure 1D, the POD activity in *N. auriculata* has been in a significant downward trend, reaching a minimum at 28 days. The POD activity of *I. tectorum* and *O. bodinieri* kept rising, and reached the maximum value on the 28th day. The POD activity of *R. brittoniana*, *S. podophyllum*, *C. indica* and *A. zerumbet* increased first and then decreased. On the 14th day, the activity of POD in vivo reached the highest level, and then decreased. The POD activity of *S. podophyllum* and *C. indica* decreased to below CK on the 28th day. The POD activity of *A. elatior* and *H. coronarium* increased significantly ( $p < 0.05$ ) before 21 days, and decreased significantly ( $p < 0.05$ ) at 28th day, but the POD activity was still significantly ( $p < 0.05$ ) higher than CK. The maximum POD activity of *D. ensifolia* appeared on the 7th day, and then decreased significantly ( $p < 0.05$ ),

which was significantly ( $p < 0.05$ ) lower than CK on the 28th day. The results showed that the POD activity in leaves of *I. tectorum* and *O. bodinieri* did not decrease after 28 days of waterlogging stress, and could maintain a high level of POD activity to cope with waterlogging environment.

As shown in Figure 1E, the SOD activity of *S. podophyllum* leaves continued to decline significantly ( $p < 0.05$ ), reaching a minimum at 28 days. The SOD activity of *D. auriculata* and *A. zerumbet* reached the maximum on the 7th day, and then decreased significantly ( $p < 0.05$ ). The SOD activity of *I. tectorum* and *H. coronarium* kept rising all the time in the experiment, and reached the maximum value on the 28th day. The SOD activity of *D. ensifolia* increased significantly ( $p < 0.05$ ) on the 7th day, and then remained at a high level, without significant ( $p < 0.05$ ) changes. The SOD activity of *R. brittoniana* and *O. bodinieri* reached the maximum at 21 days and decreased at 28 days. On the 28th day, the SOD activities of *N. auriculata*, *A. elatior* and *S. podophyllum* were significantly lower than CK. The results showed that *I. tectorum*, *H. coronarium* and *D. ensifolia* could keep the SOD activity in leaves at a high level without significant decrease under the influence of adverse environment.

#### Effects of waterlogging stress on the MDA content in the leaves

As seen from Figure 1F, the MDA content in the leaves of all plants was higher than that of the control group after 7 days of waterlogging. This result indicated that the cell membrane of plants had been damaged to some extent. However, different plants showed different trends with the intensification of waterlogging stress. The MDA content in the leaves of *N. auriculata*, *R. brittoniana*, *A. elatior*, *S. podophyllum*, and *H. coronarium* gradually increased after 28 days of waterlogging, and the MDA content in the leaves after 28 days of waterlogging was significantly higher than that under CK treatment ( $p < 0.05$ ). The MDA content of *I. tectorum*, *O. bodinieri*, *C. indica*, *D. ensifolia*, and *A. zerumbet* leaves first increased, reached the maximum value on the 7th day (*I. tectorum*), the 14th day (*O. bodinieri* and *C. indica*), and the 21st day (*D. ensifolia*, and *A. zerumbet*), and then decreased. The MDA content in the leaves of *C. indica*, *D. ensifolia*, and *A. zerumbet* increased, but with the extension of waterlogging time, the MDA content in the leaves returned to the level close to CK. These phenomena indicated that the plants of *C. indica*, *D. ensifolia*, and *A. zerumbet* had certain resistance to waterlogging stress and reduced the accumulation of MDA in the leaves.

#### Effect of waterlogging stress on plant morphology and appearance

*N. auriculata* (Figure 2J) and *S. podophyllum* (Figure 2I) exhibited a large number of yellow and dead leaves after 28 days of waterlogging treatment. These results indicated that these plants had poor waterlogging tolerance. Some leaves of *A. elatior* (Figure 2H), *D. ensifolia* (Figure 2D), *A. zerumbet* (Figure 2G), and *C. indica* (Figure 2F) were partially yellow, but no dead leaf appeared, and the plants continued to show strong activity. *I. tectorum* (Figure 2C), *O. bodinieri* (Figure 2A), *R. brittoniana* (Figure 2E), and *H. coronarium* (Figure 2B) were almost the same before and after treatment and in good condition, indicating strong waterlogging tolerance.

#### Comprehensive evaluation of waterlogging tolerance

As can be seen from Table 1, the waterlogging tolerance coefficient was different regardless of the different indicators of the same species or the same indicators of different species. Therefore, making a reasonable comparison of the waterlogging tolerance of the 10 plants and drawing a conclusion with high reliability is difficult. The results of evaluating waterlogging tolerance by using a single index were different, showing that the waterlogging tolerance of plants was not determined by a character index. Given that evaluating waterlogging tolerance with a certain index is one-sided, PCA was used to evaluate waterlogging tolerance.





**Figure 2.** Comparison of the 10 herbs before (left) and after (right) waterlogging treatment. (A) *O. bodinieri*, (B) *H. coronarium*, (C) *I. tectorum*, (D) *D. ensifolia*, (E) *R. brittoniana*, (F) *C. indica*, (G) *A. zerumbet*, (H) *A. elatior*, (I) *S. podophyllum*, and (J) *N. auriculata*

**Table 1.** Waterlogging tolerance coefficient ( $\alpha$ ) of each plant

Species	Waterlogging tolerance coefficient ( $\alpha$ )					
	Pro content	SOD activity	POD activity	CAT activity	SP content	MDA content
<i>N. auriculata</i>	0.558	0.583	0.521	0.961	0.633	2.751
<i>R. brittoniana</i>	1.188	1.502	1.049	0.924	0.861	2.137
<i>I. tectorum</i>	1.187	1.239	1.498	1.387	0.999	1.553
<i>A. elatior</i>	0.700	0.833	1.325	0.885	0.931	2.120
<i>O. bodinieri</i>	1.137	1.807	1.499	1.860	0.749	1.529
<i>S. podophyllum</i>	0.672	0.500	0.789	0.771	0.847	2.366
<i>H. coronarium</i>	0.979	1.484	1.270	1.764	0.959	1.388
<i>C. indica</i>	1.149	1.056	0.810	1.500	1.227	1.096
<i>D. ensifolia</i>	1.078	1.227	0.878	1.586	0.807	1.190
<i>A. zerumbet</i>	0.955	1.070	1.081	0.962	1.020	1.102

The  $\alpha$  values of the 10 herbs were subjected to PCA. Results are shown in Figure 3A. The comprehensive evaluation (D) of the waterlogging tolerance of each plant was calculated using PC1 and PC2 and used to rank the waterlogging tolerance of the 10 herbs (Table 2). The results showed that *O. bodinieri* had the highest flood tolerance, *H. coronarium*, *I. tectorum*, *D. ensifolia*, *R. brittoniana*, *C. indica* and *A. zerumbet* had the middle flood tolerance, and *A. elatior*, *S. podophyllum*, and *N. auriculata* had the worst flood tolerance. These results were similar to the comparison results of plant morphology and appearance before and after waterlogging (Figure 2).

#### *Comprehensive evaluation of the purification capacity of 7 herbs*

Because the waterlogging tolerance of *S. podophyllum*, *A. elatior* and *N. auriculata* is weak, the three kinds of plants are eliminated in the comprehensive evaluation of rainwater purification ability, and only the other 7 kinds of plants are evaluated and analyzed.

As shown in Table 3, among the 7 plants, *C. indica* and *D. ensifolia* have the highest removal rate of SS in rainwater, while *H. coronarium* has the lowest removal rate. However, after multiple comparisons, there was no significant difference in the removal rate of SS in rainwater between the 7 plants ( $P > 0.05$ ). The *A. zerumbet* has the highest removal rate of  $\text{NH}_4^{4+}\text{-N}$  in rainwater, but the removal rate of *I. tectorum* is the lowest. *H. coronarium* is the best for TP removal and *O. bodinieri* is the worst. The *R. brittoniana* has the best removal effect on TN in rainwater, *I. tectorum* has the worst effect on 7 kinds of plants. The removal effect of *R. brittoniana* on  $\text{COD}_\text{Cr}$  and  $\text{BOD}_5$  in rainwater is the best of 7 kinds of plants, but the effect of *O. bodinieri* is the worst.

The PCA analysis was carried out for 6 pollutant removal indexes of 7 kinds of plants, and the results are as shown in Figure 3B. The comprehensive evaluation (D) of the purification capacity of each plant was calculated using PC1 and PC2 and used to rank the purification capacity of the 7 herbs (Table 4). The results show that the order of water purification capacity from high to low is *R. brittoniana*, *A. zerumbet*, *D. ensifolia*, *H. coronarium*, *C. indica*, *O. bodinieri* and *I. tectorum*.



**Table 2.** Comprehensive evaluation of waterlogging resistance

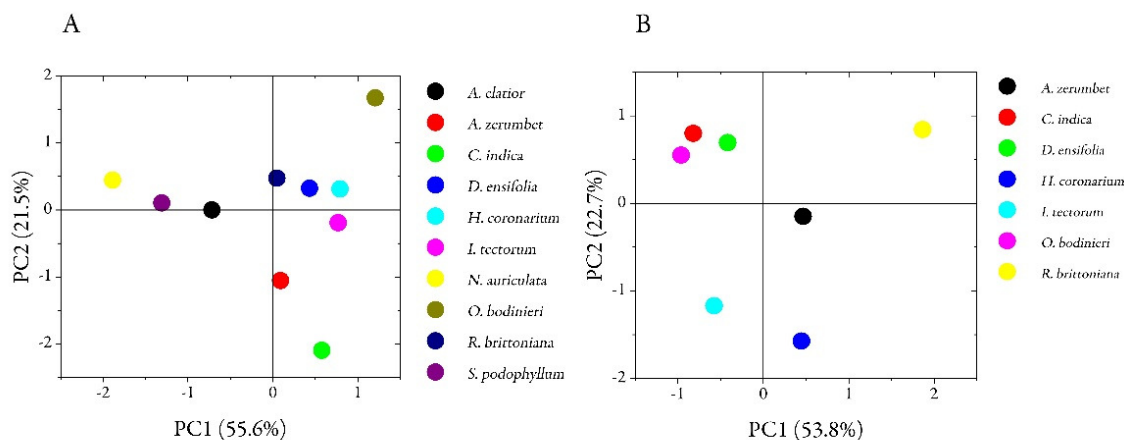
Species	PC1	PC2	D value	Ranking
<i>N. auriculata</i>	-1.888	0.446	-1.232	10
<i>R. brittoniana</i>	0.048	0.475	0.168	5
<i>I. tectorum</i>	0.770	-0.189	0.501	3
<i>A. elatior</i>	-0.718	0.000	-0.516	8
<i>O. bodinieri</i>	1.207	1.675	1.338	1
<i>S. podophyllum</i>	-1.309	0.106	-0.911	9
<i>H. coronarium</i>	0.791	0.315	0.657	2
<i>C. indica</i>	0.577	-2.099	-0.175	6
<i>D. ensifolia</i>	0.432	0.325	0.402	4
<i>A. zerumbet</i>	0.090	-1.055	-0.232	7
W	0.719	0.281		

**Table 3.** The influence of various herbaceous plants on the removal rate of pollutants in rainwater

Floristics	Removal rate (%)					
	SS	NH <sup>4+</sup> -N	TP	TN	COD <sub>Cr</sub>	BOD <sub>5</sub>
<i>N. auriculata</i>	26.37±2.73 a	57.06±1.70b	55.51±1.90c	34.35±1.27c	29.41±0.86cf	28.87±0.92 de
<i>R. brittoniana</i>	30.01±2.86a	55.49±1.00c	62.30±0.88ab	55.05±0.54a	55.46±1.38a	56.04±0.58a
<i>I. tectorum</i>	30.01± 3.15a	49.37±0.47f	63.19±0.69ab	18.81±0.35e	30.81±1.04de	30.56±0.81d
<i>A. elatior</i>	27.28 ±1.30a	54.96±0.62de	62.52±3.10ab	34.35±0.93c	30.53±1.28de	30.56±1.57d
<i>O. bodinieri</i>	30.92±2.17 a	51.34±0.17e	45.95±2.34d	34.11±1.08c	26.33±0.84g	25.33±1.19f
<i>S. podophyllum</i>	26.37± 2.43a	53.84±0.58d	57.07±2.88bc	35.52±0.54c	31.37±0.74cde	30.72±0.92d
<i>H. coronarium</i>	29.10±2.13 a	57.04±0.38b	67.63±2.19a	26.58±1.27d	35.29±1.17b	35.64±0.81b
<i>C. indica</i>	33.64±2.15a	49.83±0.12f	58.40±3.04bc	36.35±0.54c	28.01±1.26fg	28.02±1.14e
<i>D. ensifolia</i>	33.64±1.57a	50.60±0.16fg	61.41±1.96b	35.87±1.34c	33.05±0.54bcd	33.10±1.14c
<i>A. zerumbet</i>	30.92±2.33a	59.35±0.12a	61.85± ab	43.29±1.24b	33.61±1.58bc	33.41±0.62 c

**Table 4.** Comprehensive evaluation of the purification capacity

Species	PC1	PC2	D value	Ranking
<i>R. brittoniana</i>	1.865	0.843	1.562	1
<i>I. tectorum</i>	-0.577	-1.169	-0.753	7
<i>O. bodinieri</i>	-0.962	0.551	-0.512	6
<i>H. coronarium</i>	0.446	-1.572	-0.153	4
<i>C. indica</i>	-0.820	0.800	-0.339	5
<i>D. ensifolia</i>	-0.418	0.695	-0.087	3
<i>A. zerumbet</i>	0.465	-0.148	0.283	2
W	0.703	0.297		



**Figure 3.** Principal component analysis of the waterlogging tolerance and the purification capacity. (A) PCA of the waterlogging tolerance of 10 herbs, (B) PCA of the purification capacity of 7 herbs

## Discussion

MDA is the final decomposition product of membrane lipid peroxidation, and its formation is caused by excessive free radicals in cells (Qi *et al.*, 2017; Ullah *et al.*, 2017). The accumulation of free radicals can be used to measure the degree of damage caused by stress (Yadav and Hemantaranjan, 2017). In this study, the MDA content in leaves increased in the early stage of waterlogging and reached a significant level in some plants. The content of MDA in the leaves of *I. tectorum*, *A. elatior*, *H. coronarium*, and *C. indica* decreased with prolonged time, which may be because these plants adapt to the waterlogging environment, produce low amounts of free radicals, and decrease the MDA content in the leaves. These characteristics indicated that these plants may have good adaptability to waterlogging. In addition, the MDA content in the leaves of the six other plants increased with time, which may be because the adaptability to waterlogging was weak, the plant was continuously damaged, and free radicals were still accumulating. Thus, the MDA content in the leaves remained high.

Osmotic regulation is an important physiological mechanism of plant adaptation (Loreti *et al.*, 2016) and can promote cells to absorb external water by reducing the osmotic potential of the cell protoplasm (Tian *et al.*, 2019). SP can increase the bound water content of plant tissues, improve the water-holding capacity of cells, and reduce the damage caused by stress, dehydration to plant bodies by binding free water in cells (Zheng *et al.*, 2010; Pearson *et al.*, 2013). Pro is an organic solute involved in plant osmotic regulation (Anee *et al.*, 2019). Under stress, plants accumulate Pro to ensure osmotic balance between the protoplasm and the external environment and the normal physiological metabolism of cells (Loreti *et al.*, 2016). Under stress, the Pro content of most plants increase exponentially (Elansary *et al.*, 2019). Generally, a high Pro content is associated with the strong resistance of plants (Bandurska *et al.*, 2017; Han *et al.*, 2019). In this study, the SP content of *N. auriculata* decreased during waterlogging, and the Pro content of *N. auriculata*, *A. elatior* and *S. podophyllum* reached the maximum values after 7 days of waterlogging, indicating that the three plants had weak waterlogging tolerance. However, *I. tectorum* and *R. brittoniana* had the highest Pro and SP contents after 21 days of waterlogging. This result indicated that *I. tectorum* and *R. brittoniana* had strong waterlogging tolerance. *I. tectorum* and *R. brittoniana* showed their highest Pro contents on 21 and 28 days after waterlogging, respectively, which indicated that they had strong waterlogging tolerance.

Antioxidant enzymes, such as SOD and CAT, have been widely used as physiological indicators to measure the waterlogging tolerance of plants (Zhang *et al.*, 2014). Results showed that the increase in SOD, POD, and CAT activities can protect plants from ROS damage under long-term stress (Limon-Pacheco and Gonsebatt, 2009). In this experiment, the activities of the antioxidant enzymes of all plants increased by varying degrees after waterlogging. This phenomenon was the normal stress response of plants in the early stage of stress. With the extension of stress duration, the SOD, POD, and CAT activities of *N. auriculata* and *S. podophyllum* began to decrease significantly on the 14<sup>th</sup> day. The activities of the antioxidant enzymes of *I. tectorum* and *O. bodinieri* continuously increased, indicating that the activities of antioxidant enzymes were increasing until the end of the experiment and can effectively alleviate the accumulation of reactive oxygen species in cells and reduce their toxicity to plants. Moreover, these results showed that the two plants had strong waterlogging tolerance.

The rainfall pollution is an important environmental problem faced by cities. When choosing plants for sponge city, we should not only consider the waterlogging tolerance of plants, but also consider the purification and retention capacity of plants for rainwater pollutants, which will be a more comprehensive strategy. Plants are very important in the construction of sponge city. They can absorb N / P and other chemical elements in rainwater, not only provide nutrients for plant growth, but also play a role in purification. At the same time, the plant leaves also have a certain adsorption function for pollutants. Some scholars have studied the difference of removal rate of N, P and other pollutants between bare soil and planted soil, and found that planted soil has a higher removal rate of pollutants in rainwater. Fletcher and read (Lucas and Greenway, 2008; Read *et al.*, 2010) selected different kinds of plants to test the purification of N and P in rainwater. The results showed that the removal ability of different plants was significantly different, among which *Cyperaceae*, *Juncus* and *Crassulaceae* showed good decontamination ability, and they all had developed root system. Three waterlogged amphibious plants, *C. indica*, *I. pseudacorus* and *Typha angustifolia*, were selected for water purification. The results showed that the removal rates of COD<sub>Cr</sub>, TN, NO<sub>3</sub>-N and TP in the water were all over 80% (Zhu *et al.*, 2016). After comparing the growth and purification effect of 11 kinds of plants in the river sewage, it is recommended that *Thalia dealbata*, *C. generalis*, *H. coronarium*, *Cyperus alternifolius*, and *Arundo donax* can effectively purify the eutrophication of Guangzhou River water (Nie and He, 2012). These are similar to the results of this study.

## Conclusions

Ten herbaceous plants (*N. auriculata*, *O. bodinieri*, *S. podophyllum*, *I. tectorum*, *R. brittoniana*, *A. elatior*, *H. coronarium*, *A. zerumbet*, *C. indica*, and *D. ensifolia*) were selected as experimental materials to compare the effects of different durations of waterlogging stresses (0, 7, 14, 21, and 28 days) on the six physiological indices of MDA, SP, and Pro contents and SOD, POD, and CAT activities. The comprehensive evaluation results of the waterlogging tolerance of 10 herbages were ranked in decreasing order: *O. bodinieri*, *H. coronarium*, *I. tectorum*, *D. ensifolia*, *R. brittoniana*, *C. indica*, *A. zerumbet*, *A. elatior*, *S. podophyllum*, and *N. auriculata*. In addition, the purification capacity of 7 kinds of herbaceous plants with strong waterlogging tolerance was evaluated. The results were arranged in decreasing order: *R. brittoniana*, *A. zerumbet*, *D. ensifolia*, *H. coronarium*, *C. indica*, *O. bodinieri* and *I. tectorum*.

In conclusion, it is suggested that *O. bodinieri*, *H. coronarium*, *I. tectorum* and *D. ensifolia* should be selected as herbaceous plant alternatives in areas with serious waterlogging and less water pollution; *R. brittoniana*, *A. zerumbet*, *D. ensifolia* and *H. coronarium* are recommended to be selected as herbaceous alternative varieties in the areas with heavy water pollution and light waterlogging. However, *H. coronarium* and *D. ensifolia* not only

have a strong adaptability in the waterlogged environment, but also have a strong ability to remove pollutants in the rainwater, so they are suggested to be alternative herbaceous plants for sponge city in Shenzhen.

### Authors' Contributions

Bing Sun, the first author, is responsible for determination of some indexes and the writing of this manuscript, Xiao Pan is responsible for the analysis, mapping and typesetting, HAN Liebao is responsible for providing suggestions on experimental methods, and Yongjun Fei, the corresponding author, is responsible for the revision and quality control of the paper. All authors read and approved the final manuscript.

### Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 31270740); the Department of Science and Technology, Hubei Provincial People's Government, P. R. China (No. Q20181314); the Natural Science Foundation of Hubei Province, P. R. China (2017CFB390); the Natural Science Foundation of Hubei Province, P. R. China (No. 2013BBB24); and the Natural Science Foundation of Hubei Province, P. R. China (No. 2014CFB264).

### Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

### References

- Anee TI, Nahar K, Rahman A, Al Mahmud J, Bhuiyan TF, Ul Alam M, Fujita M, Hasanuzzaman M (2019). Oxidative damage and antioxidant defense in *Sesamum indicum* after different waterlogging durations. *Plants* 8:196.
- Bandurska H, Niedziela J, Pietrowska-Borek M, Nuc K, Chadzinikolau T, Radzikowska D (2017). Regulation of proline biosynthesis and resistance to drought stress in two barley (*Hordeum vulgare* L.) genotypes of different origin. *Plant Physiology and Biochemistry* 118:427-437.
- Davydova EG, Kotova DL, Krysanova TA, Selemenev VF (2005). Spectrophotometric determination of proline in aqueous solutions. *Zhurnal Analiticheskoi Khimii* 60:802-805.
- Durak I, Yalcin S, Burak Cimen MY, Buyukkocak S, Kacmaz M, Ozturk HS (1999). Effects of smoking on plasma and erythrocyte antioxidant defense systems. *Journal of Toxicology and Environmental Health Part A* 56:373-378.
- Durak I, Yurtarslanl Z, Canbolat O, Akyol O (1993). A methodological approach to superoxide dismutase (SOD) activity assay based on inhibition of nitroblue tetrazolium (NBT) reduction. *Clinica Chimica Acta: International Journal of Clinical Chemistry* 214:103-104.
- Elansary HO, El-Ansary DO, Al-Mana FA (2019). 5-Aminolevulinic acid and soil fertility enhance the resistance of rosemary to *Alternaria dauci* and *Rhizoctonia solani* and modulate plant biochemistry. *Plants* 8:585.
- Gomez E, Irvine DS, Aitken RJ (1998). Evaluation of a spectrophotometric assay for the measurement of malondialdehyde and 4-hydroxyalkenals in human spermatozoa: relationships with semen quality and sperm function. *International Journal of Andrology* 21:81-94.
- Guo C, Cui Y, Dong B, Luo Y, Liu F, Zhao S, Wu H (2017). Test study of the optimal design for hydraulic performance and treatment performance of free water surface flow constructed wetland. *Bioresource Technology* 238:461-471.
- Hamdy A, Mostafa MK, Nasr M (2018). Zero-valent iron nanoparticles for methylene blue removal from aqueous solutions and textile wastewater treatment, with cost estimation. *Water Science and Technology* 78:367-378.

- Han Q, Guo Q, Korpelainen H, Niinemets U, Li C (2019). Rootstock determines the drought resistance of poplar grafting combinations. *Tree Physiology* 39:1855-1866.
- Jochner S, Alves-Eigenheer M, Menzel A, Morellato LPC (2013). Using phenology to assess urban heat islands in tropical and temperate regions. *International Journal of Climatology* 33:3141-3151.
- Li C, Huang M, Liu J, Ji S, Zhao R, Zhao D, Sun R (2019). Isotope-based water-use efficiency of major greening plants in a sponge city in northern China. *PLOS ONE* 14(7):e0220083.
- Limon-Pacheco J, Gensebatt ME (2009). The role of antioxidants and antioxidant-related enzymes in protective responses to environmentally induced oxidative stress. *Mutation Research-Genetic Toxicology and Environmental Mutagenesis* 674:137-147.
- Liu H, Jia Y, Niu C (2017). "Sponge city" concept helps solve China's urban water problems. *Environmental Earth Sciences* 76.
- Loreti E, van Veen H, Perata P (2016). Plant responses to flooding stress. *Current Opinion in Plant Biology* 33:64-71.
- Lowry OH, Rosebrough NJ, Farr AL, Randall RJ (1951). Protein measurement with the Folin phenol reagent. *The Journal of Biological Chemistry* 193:265-275.
- Lucas WC, Greenway M (2008). Nutrient retention in vegetated and nonvegetated bioretention mesocosms. *Journal of Irrigation and Drainage Engineering* 134:613-623.
- Ma W, Zhao B, Ma J (2019). Comparison of heavy metal accumulation ability in rainwater by 10 sponge city plant species. *Environmental Science and Pollution Research* 26:26733-26747.
- McBean E, Huang G, Yang A, Cheng H, Wu Y, Liu Z, ... Bhatti M (2019). The effectiveness of exfiltration technology to support sponge city objectives. *Water* 11(4):723.
- Nie L, He MM (2012). A study on growth and sewage purification of ornamental emerged plants under rivulet water pollution. *Acta Agriculturae Universitatis Jiangxiensis* 34:832-838.
- Pearson M, Saarinen M, Nummelin L, Heiskanen J, Roitto M, Sarjala T, Laine J (2013). Tolerance of peat-grown Scots pine seedlings to waterlogging and drought: Morphological, physiological, and metabolic responses to stress. *Forest Ecology and Management* 307:43-53.
- Qi X, Xu W, Zhang J, Guo R, Zhao M, Hu L, ... Li Y (2017). Physiological characteristics and metabolomics of transgenic wheat containing the maize C-4 phosphoenolpyruvate carboxylase (PEPC) gene under high temperature stress. *Protoplasma* 254:1017-1030.
- Read J, Fletcher TD, Wevill T, Deletic A (2010). Plant traits that enhance pollutant removal from stormwater in biofiltration systems. *International Journal of Phytoremediation* 12:34-53.
- Rufino JL, Pezza HR, Pezza L (2008). Flow-injection spectrophotometric determination of azithromycin in pharmaceutical formulations using p-chloranil in the presence of hydrogen peroxide. *Analytical Sciences: International Journal of the Japan Society for Analytical Chemistry* 24:871-876.
- Thu Thuy N, Huu Hao N, Guo W, Wang XC (2020). A new model framework for sponge city implementation: Emerging challenges and future developments. *Journal of Environmental Management* 253.
- Tian L, Bi W, Liu X, Sun L, Li J (2019). Effects of waterlogging stress on the physiological response and grain-filling characteristics of spring maize (*Zea mays* L.) under field conditions. *Acta Physiologiae Plantarum* 41:63.
- Ullah I, Waqas M, Khan MA, Lee I-J, Kim W-C (2017) Exogenous ascorbic acid mitigates flood stress damages of *Vigna angularis*. *Applied Biological Chemistry* 60:603-614.
- Van Tai T, Singh RP, Fu D (2017). Transformation impact of vertical revetment on the river water quality and its mechanism. *Desalination and Water Treatment* 84:111-122.
- Xu D-F, Pan Q-C, Li Y-X, Chen X-Y, Wang J-J, Zhou L (2018). Effect of biochar on root morphological characteristics of wetland plants and purification capacity of constructed wetland. *Huanjing kexue* 39:3187-3193.
- Yadav DK, Hemantaranjan A (2017). Mitigating effects of paclobutrazol on flooding stress damage by shifting biochemical and antioxidant defense mechanisms in mungbean (*Vigna radiata* L.) at pre-flowering stage. *Legume Research* 40:453-461.
- Zhang X, Yin H, Chen S, He J, Guo S (2014). Changes in antioxidant enzyme activity and transcript levels of related genes in *Limonium sinense* kuntze seedlings under NaCl stress. *Journal of Chemistry* 749047.
- Zheng YX, Wu JC, Cao FL, Zhang YP (2010). Effects of water stress on photosynthetic activity, dry mass partitioning and some associated metabolic changes in four provenances of neem (*Azadirachta indica* A. Juss). *Photosynthetica* 48:361-3699.

Zhu ML, Guo YP, Huang XM, Liao J, Gao PF (2016). Study on suitability of three amphibian plants for LID technical measures. Water Resources Protection 32(01):46-50.



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