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

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 (NH₄⁺-N), chemical oxygen demand (COD₅) and biological oxygen demand (BOD₅). 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 COD₅, TN, TP in this paper refer to the methods of Xu et al. (2018). The detection methods of BOD₅, 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 NH₄⁺-N in this paper refer to the methods of Van T et al. (2017).

**Data analysis**

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

\[ W_j = \frac{P_j}{\sum_{j=1}^{n} P_j}, \]

where \( W_j \) 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:

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

where \( D \) 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.

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. auriculate
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 |
|------------------|---------------------------------------------|-------------|--------------|--------------|--------------|------------|-------------|
| N. auriculata    |                                             | 0.558       | 0.583        | 0.521        | 0.961        | 0.633      | 2.751       |
| R. brittoniana   |                                             | 1.188       | 1.502        | 1.049        | 0.924        | 0.861      | 2.137       |
| I. tectorum      |                                             | 1.187       | 1.239        | 1.498        | 1.387        | 0.999      | 1.553       |
| A. elatior       |                                             | 0.700       | 0.833        | 1.325        | 0.885        | 0.931      | 2.120       |
| O. bodinieri     |                                             | 1.137       | 1.807        | 1.499        | 1.860        | 0.749      | 1.529       |
| S. podophyllum   |                                             | 0.672       | 0.500        | 0.789        | 0.771        | 0.847      | 2.366       |
| H. coronarium    |                                             | 0.979       | 1.484        | 1.270        | 1.764        | 0.959      | 1.388       |
| C. indica        |                                             | 1.149       | 1.056        | 0.810        | 1.500        | 1.227      | 1.096       |
| D. ensifolia     |                                             | 1.078       | 1.227        | 0.878        | 1.586        | 0.807      | 1.190       |
| A. zerumbet      |                                             | 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 NH$_4^+$-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 COD$_c$, and BOD$_s$ 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 |
|------------------|------|------|---------|---------|
| N. auriculata    | -1.888 | 0.446 | -1.232 | 10      |
| R. brittoniana   | 0.048 | 0.475 | 0.168   | 5       |
| I. tectorum      | 0.770 | -0.189 | 0.501  | 3       |
| A. elatior       | -0.718 | 0.000 | -0.516 | 8       |
| O. bodinieri     | 1.207 | 1.675 | 1.338   | 1       |
| S. podophyllum   | -1.309 | 0.106 | -0.911 | 9       |
| H. coronarium    | 0.791 | 0.315 | 0.657   | 2       |
| C. indica        | 0.577 | -2.099 | -0.175 | 6       |
| D. enisifolia    | 0.432 | 0.325 | 0.402   | 4       |
| A. zerumbet      | 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               | NH4-N | TP  | TN  | CODc5 | BOD5 |
| N. auriculata    | 26.37±2.73 a     | 57.06±1.70b | 55.51±1.90c | 34.35±1.27c | 29.41±0.86ef | 28.87±0.92de |
| R. brittoniana   | 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. tectorum      | 30.01±3.15a      | 49.37±0.47f | 63.19±0.69ab | 18.81±0.35c | 30.81±1.04de | 30.56±0.81d  |
| A. elatior       | 27.28±1.30a      | 54.96±0.62de | 62.52±3.10ab | 34.35±0.93c | 30.53±1.28de | 30.56±1.57d  |
| O. bodinieri     | 30.92±2.17a      | 51.34±0.17c | 45.95±2.34d | 34.11±1.08c | 26.33±0.84g  | 25.33±1.19f  |
| S. podophyllum   | 26.37±2.43a      | 53.84±0.58d | 57.07±2.88bc | 35.52±0.54c | 31.37±0.74cede | 30.72±0.92d  |
| H. coronarium    | 29.10±2.13a      | 57.04±0.38b | 67.63±2.19a | 26.58±1.27d | 35.29±1.17b  | 35.64±0.81b  |
| C. indica        | 33.64±2.15a      | 49.33±0.12f | 58.40±3.04bc | 36.35±0.54c | 28.01±1.266g | 28.02±1.14e  |
| D. enisifolia    | 33.64±1.57a      | 50.60±0.166g | 61.41±1.96b | 35.87±1.34c | 33.05±0.54bcd | 33.10±1.14c  |
| A. zerumbet      | 30.92±2.33a      | 59.35±0.12a | 61.85± ab  | 43.29±1.24b | 33.61±1.58be | 33.41±0.62 c  |

Table 4. Comprehensive evaluation of the purification capacity

| Species          | PC1  | PC2  | D value | Ranking |
|------------------|------|------|---------|---------|
| R. brittoniana   | 1.865 | 0.843 | 1.562   | 1       |
| I. tectorum      | -0.577 | -1.169 | -0.753 | 7       |
| O. bodinieri     | -0.962 | 0.551 | -0.512 | 6       |
| H. coronarium    | 0.446 | -1.572 | -0.153 | 4       |
| C. indica        | -0.820 | 0.800 | -0.339 | 5       |
| D. enisifolia    | -0.418 | 0.695 | -0.087 | 3       |
| A. zerumbet      | 0.465 | -0.148 | 0.283 | 2       |
| W                | 0.703 | 0.297 |         |         |
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 proplasm (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 proplasm 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 14th 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, TN, NO3-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.

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Conflict of Interests

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

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