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EFFECTS OF DIFFERENT TYPES OF PLANTS ON RUNOFF REDUCTION AND SUSPENDED SOLIDS REMOVAL IN RAIN GARDENS

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Highlights

- Rain garden is more effective in reducing suspended solids.
- The runoff would be reduced in rain garden.
- *Ilex chinensis Sims* and *Cynodon dactylon* are the reference for the selection of rainwater garden vegetation in southern Jiangsu.

Abstract. This research conducted a series of experiments, determined that 40% is the optimal sand-soil ratio, built three rain gardens, and planted *Ilex chinensis Sims* and *Cynodon dactylon* as a key element in the rain gardens. Among them, rain garden A was planted with only *Cynodon dactylon* for a one-year observation period. Rain gardens B and C, designed as three-year rain gardens, were planted with *Ilex chinensis Sims* or *Cynodon dactylon*, respectively. The method of simulating rainwater runoff was used to monitor the rain gardens continuously. The results showed that the total runoff reduction rates of rain gardens A, B, and C were 43%, 53%, and 55%, respectively. The average removal rates of pollutant suspended solids in rain gardens A, B, and C were 94%, 88%, and 87%, respectively, and the suspended solids pollution load reduction rate reached 96%, 94%, and 95%, respectively. This would be significant for future work and as a reference for the selection of plants for rain gardens in China.

Keywords: *Ilex chinensis Sims*, *Cynodon dactylon*, rain gardens, suspended solids removal, water cleaning technologies, biotechnologies in environmental engineering.

Introduction

At present, lack of water resources affects many regions of the world, raising decision making about the best use of existing water resources a top priority for all countries. Rainwater and rainwater runoff offer great potential for the development and utilization of existing water resources. Increasing urban construction and housing density also make controlling rainwater runoff more challenging. The effective utilization of rainwater runoff also contributes to the urban water supply (Sharma & Gardner, 2020; Zhang et al., 2009). In the construction of Sponge City in China, the utilization and planning of rainwater resources is clearly articulated. According to the evaluation standard for Sponge City construction implemented on August 1, 2019, the total control rate of annual rainwater runoff and its runoff volume (sponge body) of new projects are required to be no less than the lower limit value specified for the region, and the total amount of annual runoff pollutants (calculated as suspended solids) of new projects should be reduced by not less than 70% (Cheng & Yan, 2019). To realize the sustainable management of rainwater resources, many facilities are required to utilize rainwater runoff, such as rain gardens, seepage channels, permeable surfaces and infiltration boxes (Godyń et al., 2020). Among them, rain gardens, as biological retention facilities combining filtration and infiltration, have become one of the most used rainwater management tools in the urbanization construction globally because they offer many advantages, such as a wide range of applications, small land use, and significant environmental and ecological benefits (Luo et al., 2008). Rain gardens facilities can greatly reduce runoff, remove pollutants, and replenish groundwater through filtration,

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substrate soil adsorption, biological treatment, and other mechanisms, with minimal time requirements. These attributes effectively meet the requirements of the "Sponge City Construction Evaluation Standard" (Hu et al., 2011; Machusick et al., 2010).

As the "absorbent sponge" of rain gardens, the substrate of planting soil plays a decisive role in the infiltration rate. Gardening soil can store rainwater runoff, as opposed to poorly permeable soil that allows water to flow along the surface and cause erosion (Chang & Zhang, 2011), or soils that accumulate water, which can have adverse effects on the ecological landscape environment. Therefore, the substrate soil of the planting soil layer should have the characteristics of a low runoff coefficient and high permeability. Past studies have shown that suspended solids play a decisive role in the properties and distribution patterns of other pollution indicators (Ding et al., 2014), and a variety of heavy metals can be attached to suspended solids and migrate into the soil with runoff (Turer et al., 2001). The plants in the vegetation layer of rain gardens play an important role in the process of filtering and reducing runoff pollutants and are a vital part of rain garden design (Li et al., 2021). Plants mainly reduce and filter impurities and pollutants in runoff rainwater through the absorption of their roots and simultaneously use the developed root system to strengthen soil penetration (Sharma & Malaviya, 2021). At present, many different types of shrubs and herbaceous plants have been used in rain gardens, which have good effects on filtering and removing pollutants (Zanin et al., 2018).

In this study, according to the characteristics of poor soil permeability in southern Jiangsu (Yuan et al., 2016), we explored the permeability of planting soil with different sand/soil ratios using practical applications aimed toward a more scientific approach. Through indoor rain garden simulation experiments, we developed an optimal sand: soil ratio and a model soil profile for rain garden planting soil. *Ilex chinensis Sims* and *Cynodon dactylon* were selected as the vegetation of the rain garden planting layer. They are the main species in the area and are well adapted to the soil, air, and other conditions (Xia et al., 2019). *Ilex chinensis Sims* is a shrub with a great adsorption ability, a well-developed root system, and space tolerance that may absorb and cleanse contaminants in rainwater. *Cynodon dactylon* is a herbaceous plant with an interwoven root system that forms more aggregates and large pores in the soil, effectively changing the structure of sand, improving the permeability of rainwater, and recycling it. The intent of this study was to compare the effects of rain gardens with different maturity and planting types in experiments assessing reductions in the rate of runoff, suspended solids removal, and pollution load. We analysed the capacity of rain gardens under long-term operating conditions for runoff reduction and the removal of suspended solids in runoff to provide a theoretical basis and technical reference for determining design parameters of rain gardens in similar areas.

1. Materials and methods

1.1. Overview of the study area

The study area of outdoor rain gardens is in the experimental base of Shanghai Tongsheng Environmental Protection Technology Co., Ltd., Jingkou District, Zhenjiang City, Jiangsu Province. It belongs to the north subtropical monsoon climate zone, with four distinct seasons, warmth, and humidity. The annual average temperature is 17.1 °C, and the average precipitation is 1,222.3 mm, with most precipitation concentrated in June and July.

1.2. Simulation soil column structure

The soil simulation column for the rain garden is a transparent PVC cylindrical pipe with a height of 120 cm and a diameter of 100 mm, which, from top to bottom, includes the water storage layer (20 cm), planting soil layer (40 cm), artificial filling layer (10 cm, fine sand) and gravel layer (30 cm). To prevent the gravel layer from being blocked by fine sand, geotextile is laid between the artificial filling layer and gravel layer. A tap is set at the bottom of the column to collect water. The ratios of sand to soil in columns #1to 4 were 30%, 40%, 50% and 60%, respectively.

1.3. Structure of rain garden

From top to bottom, the three rain gardens are the water storage layer (20 cm), planting soil layer (40 cm, sand: soil ratio 40%), artificial filling layer (10 cm, fine sand), and gravel layer (30 cm), and the water outlet is set at the bottom 3 cm. The same planting soil, fine sand and gravel are used for rain gardens A, B and C. Among them, rain garden A is a one-year rain garden covered with *Cynodon dactylon*. Rain gardens B and C are three-year rain gardens. The surface of Garden B is covered with *Ilex chinensis Sims*, and the surface of garden C is covered with *Cynodon dactylon*.

1.4. Data acquisition and analysis

The data collection adopts the method of artificial simulation of rainwater runoff. The rainwater runoff of the traffic road surface is collected on rainy days as the experimental water inflow. In the absence of a natural rainfall period, the pavement near the sampling point is washed with tap water to obtain semiartificial runoff. Before the semiartificial runoff enters the rain garden, the cleaned road area dust is added to obtain a high concentration of artificial runoff.

After runoff from the outlet of the rain garden occurred, samples were taken every 5 min, approximately 100 mL for each sample. Due to the limitation of outdoor operation, the water quality analysis index was mainly total suspended solids. The determination method was based on a suspended matter tester, model number: SS-1Z. From June to August 2020, the inlet and outlet water quality of rain gardens were monitored, and the date, temperature, storage depth, storage duration, and peak delay time of the outflow flood was recorded.

The runoff reduction effect was evaluated using the runoff reduction Equation (1). Field sampling is a discrete point that cannot correspond to the flow rate in all cases. The average concentration (EMC) is adopted for the concentration of pollutants in and out of the water. The calculation formula is shown in Equation (2). The purification effect of rain gardens on runoff quality is evaluated by the pollutant concentration reduction rate and pollutant load reduction rate. The calculation formula is shown in Equations (3) and (4).

$$R_V = \frac{V_{in} - V_{out}}{V_{in}} \times 100\% ; \quad (1)$$

$$EMC_{in/out} = \frac{M}{V} \approx \frac{\sum C_j \times V_j}{V_j} ; \quad (2)$$

$$R_C = \frac{EMC_{in} - EMC_{out}}{EMC_{in}} \times 100\% ; \quad (3)$$

$$R_L = \frac{EMC_{in} \times V_{in} - EMC_{out} \times V_{out}}{EMC_{in} \times V_{in}} \times 100\% , \quad (4)$$

where: R_V – runoff reduction rate, %; $V_{in}/_{out}$ – volume of inlet and outlet water, L; $EMC_{in}/_{out}$ – average concentration of inlet and outlet levels, mg/L; C_j – pollutant concentration in the sampling section, mg/L; V_j – inner diameter flow of sampling section, L; R_C – pollutant concentration reduction rate, %; R_L – pollutant load reduction rate, %.

2. Results

2.1. Simulate the penetration rate of the column

The simulation column adopts the alternate circulation, mode of water inflow, and drying. Tap water is slowly injected into the simulation column to test the seepage rate so that the water storage depth reaches 5 cm, 10 cm, 15 cm and 20 cm. The change in water storage depth is recorded every 10 min, and the change in seepage rate every 10 min in the first 100 min is calculated.

Figure 1 shows the comparative experiments of different water storage depths. The order of the soil stable infiltration rate of each simulation column at a storage depth of 10 cm is as follows: 60% sandy soil > 50% sandy soil > 40% sandy soil; the order of the stable infiltration rate of each simulation column at 15 cm and 20 cm water storage depths is 60% sandy soil > 50% sandy soil > 30% sandy soil > 40% sandy soil. The main reason is that the settlement of the 40% sand soil ratio soil layer is more obvious with the increase in water experiment times, which makes the soil structure more compact than other sand soil ratios, the total soil pore is smaller, and the permeability rate is also smaller and maintained at a relatively stable level (Li et al., 2009; Yang et al., 2008). In addition, the result shows that each simulation column had a water infiltration rate within 10 min, of which the largest was 60% sand, compared to the analogue column when the water depth was 20 cm at 24.6 cm/h. According to the classification standard of the soil infiltration level (Ding et al., 2014; Turer et al., 2001), when the infiltration rate was close to the level very quickly, the maximum penetration rate showed a declining trend as the percentage of planting soil and sand ratio decreased. 30% than the largest planting soil infiltration rate of sand is 9 cm/h, the soil infiltration degree was faster, and the planting soil infiltration rate fell faster in 0–20 min, 50% and 60% than the sand planting soil decreased obviously. The main reason for this is that the higher the sandy soil ratio, the looser the planting soil, the larger the void space of loose soil, and the faster the infiltration rate (Zhu et al., 2008). The infiltration rates of planting soils with 30% and 40%

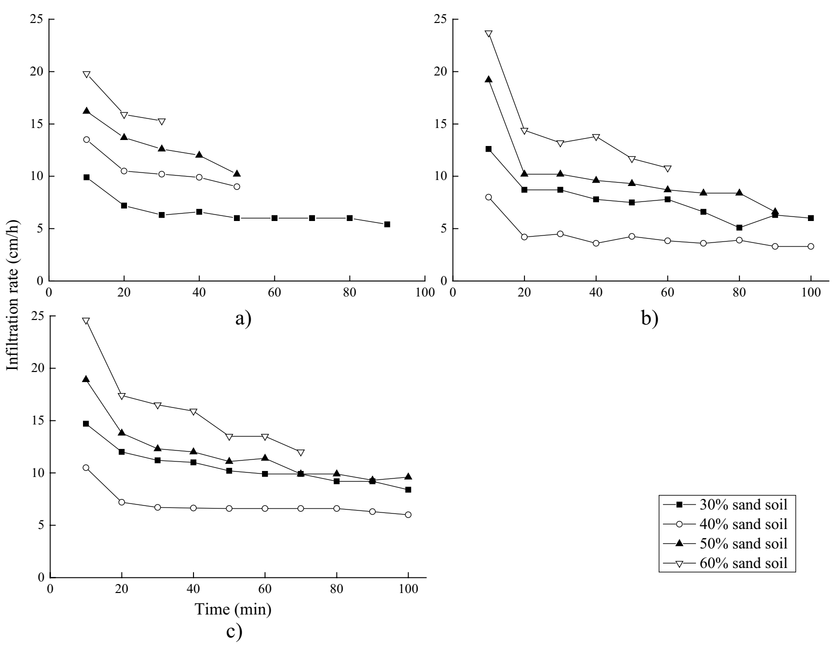

Figure 1. Comparative experiments of different water storage depths: a) 10 cm water storage depth; b) 15 cm water storage depth; c) 20 cm water storage depth

sand-soil ratios basically tend to be stable after 20 min of water supply, while those with 50% and 60% sand-soil ratios always show a downwards trend, indicating that the infiltration rates of planting soils with high sand-soil ratios are less stable.

The average soil infiltration rates of each simulation column at 20 cm water storage depth are as follows: V30% sand = 8.98 cm/h, V40% sand = 6.41 cm/h, V50% sand = 11.46 cm/h, and V60% sand = 14.22 cm/h, which is at the same level as the four kinds of rain gardens simulation columns designed by Yuan et al. (2016). Different countries have different requirements on the infiltration rate of ecological detention facilities. The U.S. The Environmental Protection Agency requires that the infiltration rate be at least 1.27 cm/h, that of Austria is 3.6–36 cm/h and that of Australia is 5–20 cm/h (Le Coustumer et al., 2009). It is recommended in the rain garden manual that the long-term infiltration rate of the system should be 1.25–5.0 cm/h. The short-term seepage rate of the rain garden simulation column in the laboratory is higher than this value, and the long-term stable permeability rate is expected to meet the application requirements (Deng et al., 2013). According to the experimental results, the soil infiltration grade of planting soil with a 40% sand: soil ratio ranks as medium, which meets the requirements of biological retention facilities in sponge city construction and is more suitable for the application of rain gardens.

2.2. Example application of rain gardens

2.2.1. Runoff reduction

The experiment of increasing water inflow and repeated experiment of 50 L water inflow were carried out in the three rain gardens. Then, 650 L water was added. The outdoor temperature was 24~33 °C. The total discharge of rain garden A is 368.65 L, and the total runoff reduction rate is 43.28%; the total outflow of rain garden B is 302.95 L, and the total runoff reduction rate is 53.39%; the total outflow of rain garden C is 294.03 L, and the total runoff reduction rate is 54.76%.

Figure 2 shows that the runoff reduction rate of the three rain gardens decreased with increasing water inflow. When the water inflow is 50 L, the runoff reduction effect of rain gardens is better, and the reduction rates of the three rain gardens are all higher than 60%. When the water inflow is 100 L, the runoff reduction rates of the three rain gardens are all below 40%.

The sig. values of rain garden A, rain garden B, and rain garden C were 0.029, 0.002 and 0.013, respectively, which indicated that there was a negative correlation between the inflow and the runoff reduction rate, a significant correlation between the runoff reduction rate of rain garden A and rain garden C, and a very significant correlation between the runoff reduction rate of rain garden B and A. Zhang et al. (2019) also found a similar situation, a negative correlation between rainfall and runoff reduction rate.

The runoff reduction rate of rain garden A showed a downwards trend, while that of rain gardens B and C showed a fluctuating state (Figure 3). When rain gardens receive runoff for a long time, the stomatal conductance of the soil matrix in the garden will gradually close and clog under the action of water pressure and natural soil deposition, the water conductivity and infiltration rate will be weakened, and the reduction effect of runoff will be gradually reduced.

With the same water inflow, rain garden A has more water outflow, and the water outflow is increasing all the time. Rain gardens B and C have little difference in water output and are unstable. The results show that the runoff reduction effect of the 1-year garden was better than that of the 3-year garden (Figure 3). The number of sunny days and hydrological and climatic factors have a certain influence on the reduction effect of the 3-year garden in the early stage. The longer the duration of sunny days in the early stage, the better the weather conditions, and the better the reduction effect of rain gardens on runoff. Compared with the rain garden planted only with *Cynodon dactylon*, the rain garden planted with *Ilex chinensis Sims* had a better effect on runoff reduction, indicating that the more developed the root system of plants, the stronger the

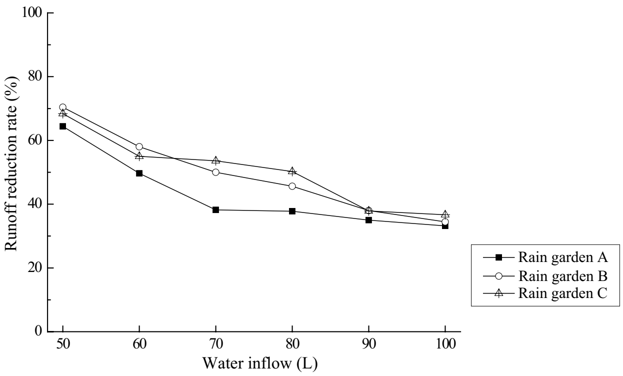

Figure 2. Runoff reduction effect of rain gardens with increasing inflow

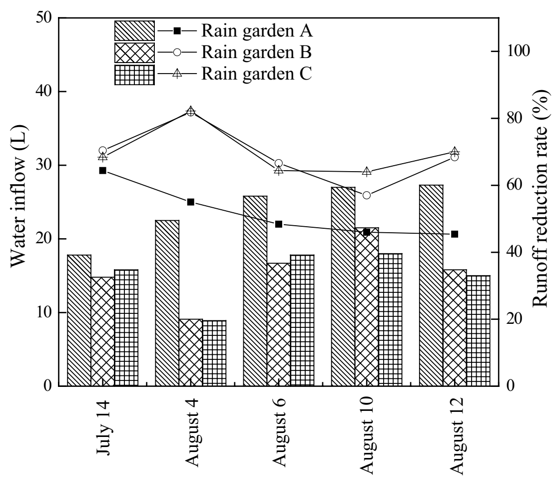

Figure 3. Runoff reduction effect of the 50 L repeated test in rain gardens

transpiration effect, and the better the runoff reduction effect (Davis et al., 2008; Hunt et al., 2012). Davis et al. (2009) similarly found that the moisture content of the filter filler was lower during a longer drying period, which could improve the processing capacity of the biological retention system. In addition, the presence of plants could increase the porosity of the filter filler and improve the processing capacity of the biological retention system.

2.2.2. Suspended solids concentration removal

The runoff with a high suspended solids concentration is prepared by scouring the road area dust and adding the cleaned accumulated dust. The suspended solids concentration in the influent was controlled to be more than 500 mg/L. Figure 4 depicts the rate of removal of suspended solids from rain gardens A, B, and C.

The results show that the removal rate of suspended solids by rain garden A reaches more than 90%, with an average removal rate of 93.79%, and the suspended solids removal rate keeps rising. With the operation of rain garden A, the structure layer tends to be stable, and the suspended solids concentration exhibits a downward trend. According to the concept of the "three-stage purification capacity" of rain gardens (Guo et al., 2018), rain garden A is in the first stage of rain gardens, and the purification capacity is generally high and growing.

The overall removal rate of suspended solids by rain garden B is between 75% and 95%, and the average removal rate is 87.72%. In the early stage, the suspended solids removal rate fluctuates. With the operation of the rain garden, the removal rate gradually decreases. Above this, it can be concluded that rain garden B is a "middle-aged rain garden" (Guo et al., 2018), and the removal effect generally shows a trend of rising first and then slowly decreasing. The reason may be the increase in runoff and the increase in storage time of rain gardens due to the sedimentation of water storage areas helping remove suspended solids from runoff. The reason for the slow decline in the later stage is that the addition of high concentration

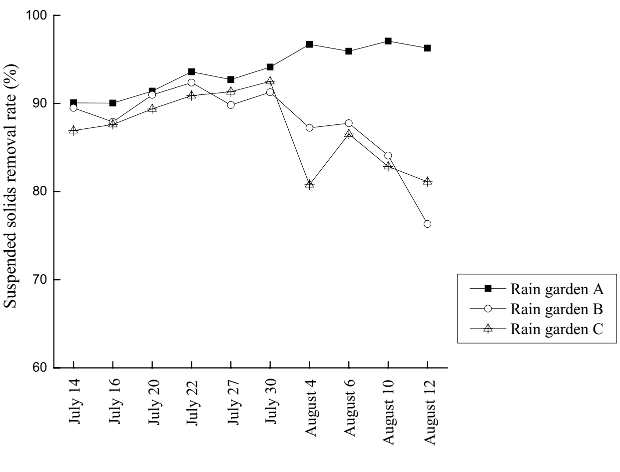

Figure 4. Removal effect of rain gardens on runoff suspended solids

runoff for a long time makes part of the suspended solids leach out from the B structure layer of the rain garden. On the other hand, the ability of the substrate to absorb pollutants and the ability of plants to absorb and degrade pollutants are in a state of high load adsorption, which requires a certain buffer period.

The removal rate of suspended solids by rain garden C is 80–95%, with an average removal rate of 86.99%, which is in the "middle-aged rain garden stage" (Guo et al., 2018). Compared with rain garden B, the influent suspended solids concentration has less impact on rain garden C, which may be due to the improper plant community collocation of rain garden B (Hang, 2017), which makes the shrub lush and inhibits the growth of herbaceous plants. Rain garden C has only *Cynodon dactylon*, and the luxuriant grass plants can better intercept the large particles in the runoff and reduce the runoff with high suspended solids concentrations. Fine particles are filtered and adsorbed by the surface soil of rain gardens (Davis et al., 2008; Tang et al., 2015).

The average removal rate of suspended solids concentration in the three rain gardens was higher than 85%. The removal effect of suspended solids in runoff was better, which was related to the higher suspended solids concentration in runoff. According to many studies, the suspended solids concentration in the influent water is lower than that in mines. Jiang et al. (2018) monitored that the average removal rate of suspended solids in the rain garden was 55.44%, and the total suspended solid concentration of its inflow was below 450 mg/L. Zhang et al. (2019) found that the suspended solids concentration of roof runoff was 80 below mg/L, the suspended solids concentration in effluent decreased, and the removal rate of suspended solids ranged from 23% to 40%.

2.2.3. Change rule of the suspended solids removal effect with time

Figure 5a shows that rain garden A has a good removal effect on suspended solids. The removal rate is higher than 85% when the effluent is discharged. Moreover, the removal rate of suspended solids in rain garden A was higher than 90% at 0 time of effluent in the suspended solids concentration monitored for 4 times. The removal rate of suspended solids by rain garden A increases with increasing effluent time and is basically stable from 10 min to 100%. The effluent time of rain garden A was 20–25 min, and the average water storage depth was 4.95 cm.

The rate of suspended solids removal in rain garden B increases linearly with the effluent duration, as shown in Figure 5b. The R2 values of the four monitoring tests are 0.9634, 0.9459, 0.9414 and 0.9587. With the increase in repeated experiments, the suspended solids removal rate at each time point decreased gradually. The suspended solids removal rate at time 0 of the first water supply experiment was 80.58%, and the fourth water supply experiment was 64.36%, which decreased by 16.22%. The reason was that the adsorption capacity of substrate B of rain garden B was

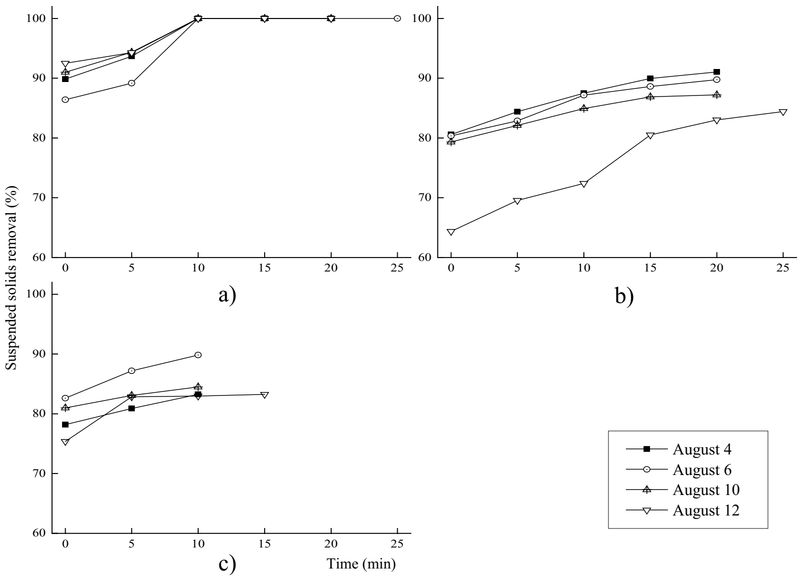

Figure 5. Change in suspended solids removal rate with time: a) Rainwater garden A; b) Rainwater garden B; c) Rainwater garden C

in the state of high load adsorption. The effluent time of rain garden B is between 22 and 30 min, and the suspended solids removal rate still tends to increase at the final effluent time. It is expected that the final removal rate will tend to a stable value when the effluent lasts for a long time.

According to Figure 5c, it shows the relationship between the suspended solids removal rate and effluent time of rain garden C. The removal rate of suspended solids is maintained above 75%, and the removal rate increases with increasing effluent time. However, the effluent time of rain garden C is shorter, which is 10–15 min. It is 50% less than that of rain garden B, which shows that the water holding capacity of rain gardens with *Ilex chinensis Sims* is better than that with *Cynodon dactylon*.

2.2.4. Suspended solids pollution load reduction rate

Table 1 shows the reduction rate of the suspended solids load of runoff pollutants in the single rain garden experiment. The reduction rate of the suspended solids load of runoff pollutants by the three rain gardens is significantly higher than that of the suspended solids concentration, which indicates that the rain garden has a more obvious effect on runoff reduction.

Calculating the total pollution load reduction rate of suspended solids in 10 water experiments showed that the total inflow and outflow of suspended solids in rain garden A were 492.48 g and 17.63 g; the total inflow and outflow of suspended solids in rain garden B were 504.24 g and 28.25 g; and the total inflow and outflow of suspended solids in rain garden C were 537.81 g and 27.2 g, respectively. The total pollution load reduction rates of rain gardens A, B and C to pollutant suspended solids were 96.42%, 94.4% and 94.94%, respectively. Rain garden A had the best pollution load reduction effect on suspended solids, and the average suspended solids load reduction rate of a single field was higher than that of rain gardens B and C. This indicates that the pollutant load reduction rate of rain gardens on suspended solids would decrease with increasing running time.

Table 1. Reduction effect of rain gardens on pollutant suspended solids load (units: %)

Date	Garden A	Garden B	Garden C
14 July	96.95	96.89	95.97
16 July	95.72	94.92	94.43
20 July	94.69	95.49	95.77
22 July	95.83	95.85	96.27
27 July	95.46	93.69	93.41
30 July	96.08	94.28	94.51
4 August	98.14	96.97	96.58
6 August	97.48	94.05	95.21
10 August	98.02	91.45	93.82
12 August	98.19	91.02	94.33

Conclusions

In this study, we planted *Cynodon dactylon* and *Ilex chinensis Sims* in three experimental rain gardens. During the observation of the three rain gardens, their purification effect was remarkable; the total runoff reduction rate reached 43%, 53%, and 55%, the removal rate of SS, on average was 94%, 88%, and 87%, and the suspended solids pollution load reduction rate reached 94%, 96%, and 95%. *Ilex chinensis Sims* is more effective in reducing pollutants due to its well-developed root system. The development and utilization of *Ilex chinensis Sims* and *Cynodon dactylon* in this study not only provides a reference for the selection of rainwater garden vegetation in southern Jiangsu but also promotes the development of efficient management and utilization of rainwater resources in China.

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Author contributions

Conceptualization, C. L.; investigation, H. L.; writing–original draft preparation, L. C. (Lingling Chen), H. L., and R. Y.; writing–review and editing, C. L., Z. M., and L. C. (Lei Chu); project administration, C. L., L. M., and H. Z.; funding acquisition, C. L. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare that they have no conflicts of interest to report regarding the present study.

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