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Pollutant removal in an experimental bioretention cell situated in a northern Chinese sponge city

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ABSTRACT

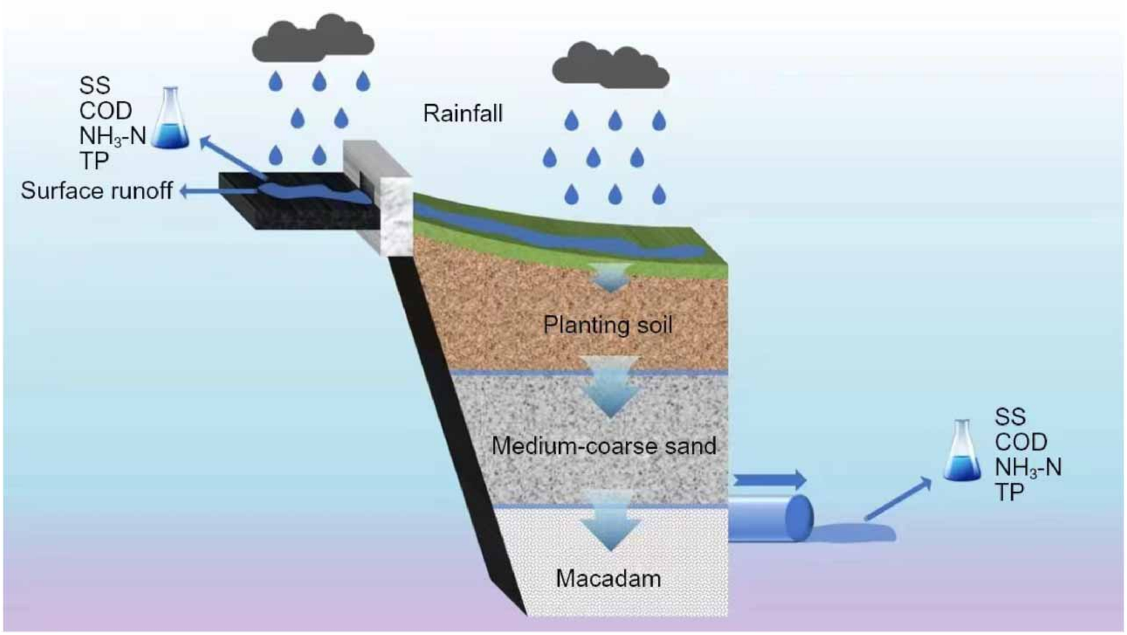
To assess the viability and effectiveness of bioretention cell in enhancing rainwater resource utilization within sponge cities, this study employs field monitoring, laboratory testing, and statistical analysis to evaluate the water purification capabilities of bioretention cell. Findings indicate a marked purification impact on surface runoff, with removal efficiencies of 59.81% for suspended solids (SS), 39.01% for chemical oxygen demand (COD), 37.53% for ammonia nitrogen (NH_3-N), and 30.49% for total phosphorus (TP). The treated water largely complies with rainwater reuse guidelines and tertiary sewage discharge standards. Notably, while previous research in China has emphasized water volume control in sponge city infrastructures, less attention has been given to the qualitative aspects and field-based evaluations. This research not only fills that gap but also offers valuable insights and practical implications for bioretention cell integration into sponge city development. Moreover, the methodology and outcomes of this study serve as a benchmark for future sponge city project assessments, offering guidance to relevant authorities.

Key words: bioretention cells, purification effect, rainwater reuse, sponge city, surface runoff

HIGHLIGHTS

- Explored the purification of bioretention cells on rainwater.
- Under the same conditions, the bioretention cell has the best purification effect on suspended solids.
- The bioretention cell's effluent quality complies with standards for urban recycled water, wastewater discharge, and sponge city assessments.

GRAPHICAL ABSTRACT



ABBREVIATIONS

NH_3-N	Ammonia nitrogen
COD	Chemical oxygen demand
EMC	Event mean concentration
SS	Suspended solids
TP	Total phosphorus
TN	Total nitrogen
PRE	Pollutant removal efficiency

1. INTRODUCTION

Urban rainwater causes surface runoff pollution to accumulate during dry periods and discharge abruptly on rainy or snowy days, exhibiting strong variability (Sui & van de Ven 2023). The increase in social activity and economic intensity leads to significant pollutant accumulation on urban surfaces, resulting in higher pollutant concentrations during runoff events. Pollution, produced in a dispersed manner, is linked to land use and urban non-point source pollution, necessitating integrated landscape planning and pollution control. Significant achievements in removing pollutants from roads and heavy metals highlight new measures in landscape ecological regulation for pollution control (Başar & Tosun 2021; Yu *et al.* 2023). Since the introduction of sponge city concepts in 2014, focusing on rainwater management through infiltration, retention, storage, purification, use, and discharge, these initiatives have seen wide application, particularly in transforming urban planning and design in many Chinese cities (Yin *et al.* 2021; Shi *et al.* 2023). However, the unique climatic conditions of the northern region influence the types of Low Impact Development facilities implemented, resulting in a reduced variety. The initial surface runoff produced during precipitation events is of poor quality, with significant exceedances in pollutants such as SS and COD. Research shows that the bioretention cell significantly reduces pollutant levels of COD, TN, NH_3-N, and TP from 52.21 to 78.93%, 59.20 to 66.64%, 48.98 to 71.86%, and 47.35 to 75.83%, respectively, with a notable 94.5% SS removal efficiency (Zhang *et al.* 2021; Fan *et al.* 2022; Fu *et al.* 2023). A bioretention cell is a sunken green space that temporarily stores and partially treats stormwater, thus reducing peak runoff rates and improving runoff quality. The plants used in the bioretention cell are typically dominated by native herbaceous species (Zhang & Li 2014; Cao *et al.* 2023). The bioretention cell, as a source control measure, shows great promise in northern China for their low-cost, effective runoff pollution reduction and public satisfaction, and is proving to be an economically viable sponge engineering solution that complements urban landscapes. This study explored the bioretention cell's effectiveness in purifying surface runoff and its applicability in northern China, offering insights for sponge city promotion and bioretention cell construction.

2. METHODS

2.1. The study area overview

Changchun, the capital of Jilin Province of China, has an annual average temperature of 5.5 °C. From November to March, the city experiences low temperatures and dry conditions with little rainfall. According to long-term data from the Changchun Meteorological Station, the average precipitation in the urban area is 585.2 mm. Furthermore, the average annual rainfall in Changchun city from 2006 to 2015 was 556 mm, according to the statistics of annual rainfall data.

The main urban area of Changchun covers an area of 458 km^2, encompassing 18 drainage basins. Within this central urban district, water bodies account for 1.63% of the area, impervious surfaces make up 27.32%, bare soil comprises 14.84%, cultivated land represents 12.97%, vegetation covers 21.06%, asphalt roads constitute 6.64%, and buildings occupy 15.53%. The main urban area faces significant pollution in surface runoff water. The total pollution load in the central urban area for COD, NH_3-N, TN, TP, and SS are 44,008.8, 5,812.2, 9,640.5, 803.5, and 18,766.3 t/yr, respectively. Of the total COD pollution load, COD accounts for 35%, NH_3-N for 26%, TP for 15%, and TN for 18%. Out of 48 water function zones in Changchun, only four met the standards in 2015, resulting in a compliance rate of 8.33%. This indicates that non-point source pollution is a significant component of urban pollution and cannot be overlooked (Xu *et al.* 2023).

To explore the control effect of bioretention cells on runoff pollution in the urban construction of Northeast China, this study focused on the Changchun sponge city pilot area. The bioretention cell experiment system was designed as illustrated in Figure 1. The bioretention cell area (Figure 2(a)) covers 105 m^2 with a concave depth of approximately 100 mm. The mix ratio of medium sand to planting soil is 1:1 (sand particle size according to the People's Republic of China National Standard GB/T 14684-2022 'sand for construction'), with a matrix layer thickness of 1,000 mm. The bioretention cell was covered with green grass. Runoff is directed into the bioretention cell via an opening curbstone (Figure 2(b)) and water samples from the bioretention cell are collected from the outlet of the perforated high-density polyethylene (HDPE) pipe (Figure 2(c)) at the bottom. A gravel layer, 200 mm thick, sits atop the perforated HDPE pipe to prevent clogging and to create a storage space for surface runoff. The perforated HDPE pipe has a diameter of 100 mm, with apertures ranging from 6–12 mm, and is wrapped in permeable geotextile. It features a longitudinal gradient of 1%. The gravel layer consists of clean gravel with a diameter of 20 mm, which is larger than the opening size of the perforated HDPE. A detailed dimensional profile is shown in Figure 2(d).

2.2. Monitoring of rainfall

In 2017, Changchun recorded an annual precipitation of 545.4 mm, with 377.5 mm occurring during the flood season (from June to August). The rainfall in the flood season was ranked 16th over the past six to seven years, 4th over the last decade, and 2nd in the last five years, making 2017 a year of notably high rainfall in recent times. Throughout the experiment, we monitored 19 precipitation events over the course of the year. In this study, we focused on rainfall events that were continuous and had a sufficient duration, generally lasting more than 3 h. Based on the rainfall intensity, we categorized the events into four different types of rainfall. Ultimately, we selected seven events for analysis (detailed in Table 1). Among these, the rainstorm event on July 13 was highlighted for further analysis because of its exceptional rainfall volume and duration, providing a diverse and abundant set of water samples. Rainfall intensity, defined as the amount of rainfall per unit of time and measured in mm/min or mm/h, varies among events, leading to different scouring intensities and, consequently, distinct rainfall events. To understand the water quality of natural rainwater, samples from each rainfall event were collected and analyzed during the experimental period (see Table 2). The testing parameters included SS, COD, NH_3-N, and TP.

2.3. Sampling and test methods

Sampling locations are illustrated in Figure 2, with Figure 2(b) depicting the site where stormwater runoff enters the bioretention cell and Figure 2(c) showing the sampling point at the outlet. Sampling commenced from the onset of surface runoff until cessation. Given the occurrence of the first flush effect – typically defined as the portion of runoff carrying the majority of pollutants during the initial runoff phase – we began collecting samples 3 min after initial runoff, with sampling intervals ranging from 90 to 120 min (Bertrand-Krajewski *et al.* 1998; Chaudhary *et al.* 2022; Gao *et al.* 2023). Specific intervals included 3, 5, 10, 15, 30, 60, 90, and 120 min after runoff began (Brattebo & Booth 2003).

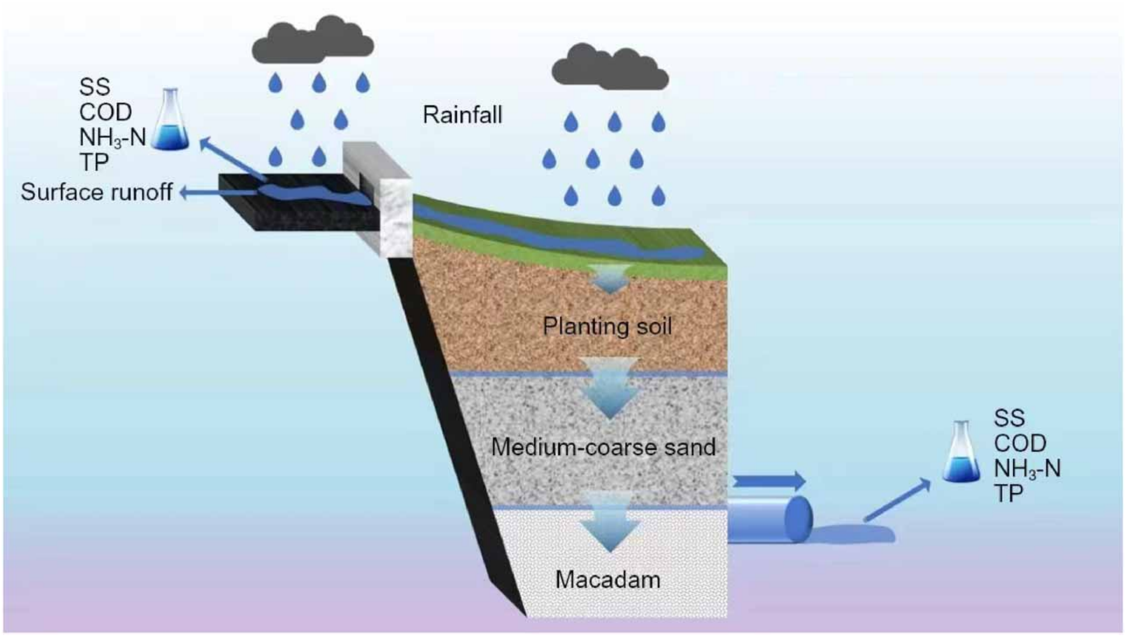


Figure 1 | The bioretention cell system diagram.

Collected samples were stored in polyethylene bottles at a low temperature (0.5 °C) to preserve their integrity, with all indicators being tested within 72 h. Throughout April to September 2017, 19 rainfall events were monitored, and effective, representative samples from seven events were selected for detailed analysis. This selection was based on their combined relevance to rainfall intensity. The methods for detecting these indices are detailed in Table 3.

2.4. Water quality evaluate method

Given the dynamic nature of pollutant concentrations throughout a rainfall event, the concept of event mean concentration (EMC) was utilized to encapsulate the water quality of runoff for a specific event. EMC is determined by calculating the concentration of pollutants averaged over the volume of runoff during a storm event, as shown in Equation (1). Subsequently, the pollutant removal efficiency (PRE) is assessed by measuring the reduction in EMC from the inflow to the outflow point, as shown in Equation (2) (O'Driscoll *et al.* 2010; Lucke & Nichols 2015; Nayeb Yazdi *et al.* 2021).

$$EMC = \frac{\mathrm{M}}{\mathrm{V}} = \frac{\int_0^{\mathrm{T}} C_t Q_t \mathrm{d}t}{\int_0^{\mathrm{T}} Q_t \mathrm{d}t} \tag{1}$$

where M is the total mass of a pollutant in runoff, g; V is total surface runoff volume, m^3; C_t is the instantaneous concentration of a contaminant at t, mg/L; Q_t is runoff displacement of surface runoff at t, m^3/s; T is the total duration of a rainfall event, s.

$$PRE = 1 - \frac{EMC_{\mathrm{outflow}}}{EMC_{\mathrm{inflow}}} \tag{2}$$

where $EMC_{outflow}$ and EMC_{inflow} represent the event mean concentration of pollutants at the inflow and outflow, respectively.

3. RESULTS AND DISCUSSION

This study employed field monitoring, laboratory testing, and mathematical statistics and analysis to evaluate the pollutant removal efficiency of the bioretention cell. The data presented in Table 4 encapsulates the results from seven rainfall events monitored between April and September 2017. Overall, the EMC values for SS, COD, NH_3-N, and TP exhibited

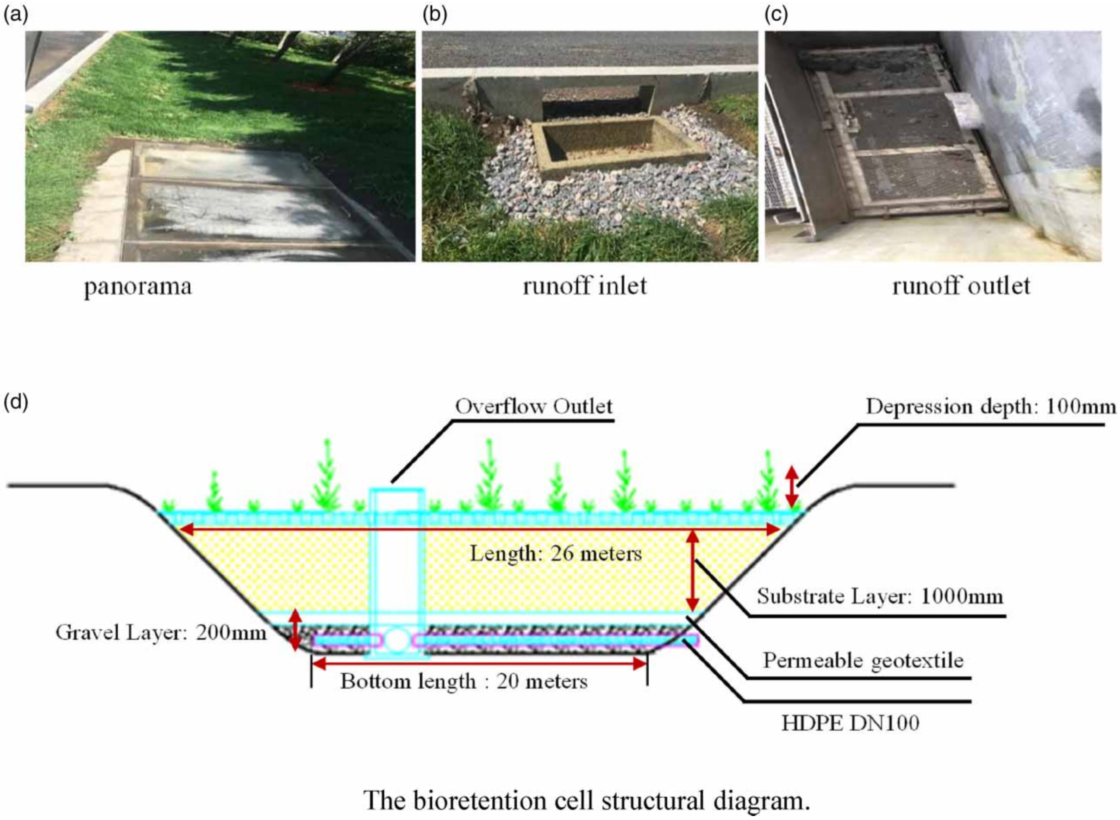


Figure 2 | The bioretention cell experimental site.

Table 1 | The basic characteristics of rainfall during the experiment

Date	Drying time before rain (d)	Start time of rainfall	End time of rainfall	Rainfall (mm)	Rainfall intensity (mm/h)	Rainfall patterns
2017.04.17	15	13:11	17:13	25	6.25	Heavy rain
2017.05.04	7	10:45	15:50	8	1.6	Light rain
2017.06.20	3	16:02	19:15	15.2	5	Light rain
2017.07.02	3	17:10	19:10	32.2	6.4	Heavy rain
2017.07.13	10	11:10	19:13	52	6.5	Storm
2017.08.03	8	8:10	16:20	24.5	3.5	Moderate rain
2017.09.22	3	13:20	18:30	9	1.8	Light rain

significant fluctuations. Specifically, EMC values for SS ranged from 38 to 584 mg/L, for COD from 111 to 539 mg/L, for NH_3-N from 2.2 to 6.33 mg/L, and for TP from 0.14 to 1.36 mg/L. Analysis of the data revealed that pollutant concentrations in surface runoff were notably higher during the early stages of rainfall compared to the later stages, with early-stage concentrations being more than twice as high as those in the late stage. All three rainfall events on June 20, July 2, and September 22 followed a three-day dry period. Despite higher rainfall intensity on July 2, lower pollutant EMC values were measured than for the other two events. This inconsistency across the seven monitored rainfall events suggests that higher rainfall intensity does not necessarily correlate with higher EMC values for pollutants. This phenomenon can be attributed to the dilution effect. Although high-intensity rainfall events have a strong scouring capability, the concurrently generated large volume of runoff can dilute the concentration of pollutants, potentially resulting in lower EMC values.

Table 2 | Test results of natural rainwater quality

Series number	Date	SS (mg/L)	COD (mg/L)	NH_3-N (mg/L)	TP (mg/L)
1	Urban greening limit	–	–	≤10	–
2	Landscape water	≤20	≤40	≤5	≤1
3	Class III water limits	–	≤20	≤1	≤0.2
4	2017.04.17	44	32.14	1.32	0.106
5	2017.05.04	23	26.22	1.23	0.112
6	2017.06.20	20	23.19	1.28	0.096
7	2017.07.02	16	19.67	1.36	0.115
8	2017.07.13	27	20.12	1.77	0.167
9	2017.08.03	24	16.55	1.41	0.134
10	2017.09.22	32	18.06	1.52	0.141

Table 3 | Index detection method

Detection indexes	Detection methods	
SS	Gravimetric method	GB/T 11901-1989
COD	Dichromate titration	GB/T 11914-1989
NH_3-N	Sodium reagent spectrophotometry	GB/T 7479-1987
TP	Potassium persulfate digestion	GB/T 11893-1989

Table 4 | The monitoring results of seven rainfall events

Time	Project	SS (mg/L)	COD (mg/L)	NH_3-N (mg/L)	TP (mg/L)
2017.4.17	Inflow EMC	584	539	6.33	0.96
	Outflow EMC	270	428	2.93	0.66
	PRE (%)	53.8	20.6	53.7	30.3
2017.5.4	Inflow EMC	360	371	5.2	0.68
	Outflow EMC	93	213	2.82	0.36
	PRE (%)	74.3	42.5	45.8	47.1
2017.6.20	Inflow EMC	354	276	4.29	0.24
	Outflow EMC	129	111	2.2	0.14
	PRE (%)	63.5	59.7	48.7	43.5
2017.7.2	Inflow EMC	188	247	4.53	0.58
	Outflow EMC	90	157	3.33	0.46
	PRE (%)	51.8	36.7	26.6	21.6
2017.7.13	Inflow EMC	550	440	6.18	1.36
	Outflow EMC	298	294	5.51	1
	PRE (%)	45.8	33.3	10.7	26.2
2017.8.3	Inflow EMC	260	347	4.32	0.64
	Outflow EMC	38	151	2.67	0.42
	PRE (%)	85.3	56.4	38.2	33.5
2017.9.22	Inflow EMC	232	261	4.35	0.46
	Outflow EMC	98	160	2.53	0.38
	PRE (%)	57.8	38.8	41.8	18.5

Concentrations of stormwater pollutants vary depending on rainfall depth, intensity, runoff volume, and season. Yan *et al.* (2023) examined the effects of rainfall characteristics on stormwater quality in the Auburn Bay and Cranston Watersheds and showed that antecedent dry days, rainfall intensity, and rainfall duration were the key rainfall characteristics affecting the EMC for SS, TN, and TP. Meanwhile, Hossain *et al.* (2005) emphasized the effects of road traffic volume, road maintenance practices, and adjacent land use on pollutant fluxes and concentrations entering wet ponds. Hydrologic patterns and hydraulic conditions are the key factors influencing the residence time of pollutants and play an important role in pollutant removal (Jia *et al.* 2019). In our study conducted exclusively in 2017, we observed a significant decrease in the EMC of SS, COD, NH_3-N, and TP from inlet to outlet, suggesting the bioretention cell's effectiveness in pollutant removal across varied rainfall and runoff scenarios within the examined period. It is important to note that this conclusion is based on data from a single year, and maintenance is critical for sustaining the bioretention cell's performance over time. Continuous monitoring and periodic maintenance are recommended to prevent potential efficiency decline and ensure long-term effectiveness in pollutant removal.

3.1. Analysis of runoff control effect

Despite noticeable fluctuations in the EMC of pollutants for both inflow and outflow across various rainfall events, a pronounced linear relationship and significant correlation have been observed between the effluent and inlet concentrations of SS, COD, NH_3-N, and TP within the initial hour. The experimental results from August 3, 2017, are displayed in Figure 3. Figure 3(a) shows the correlation coefficient for COD at the inlet and outlet to be 0.791, Figure 3(b) indicates a correlation

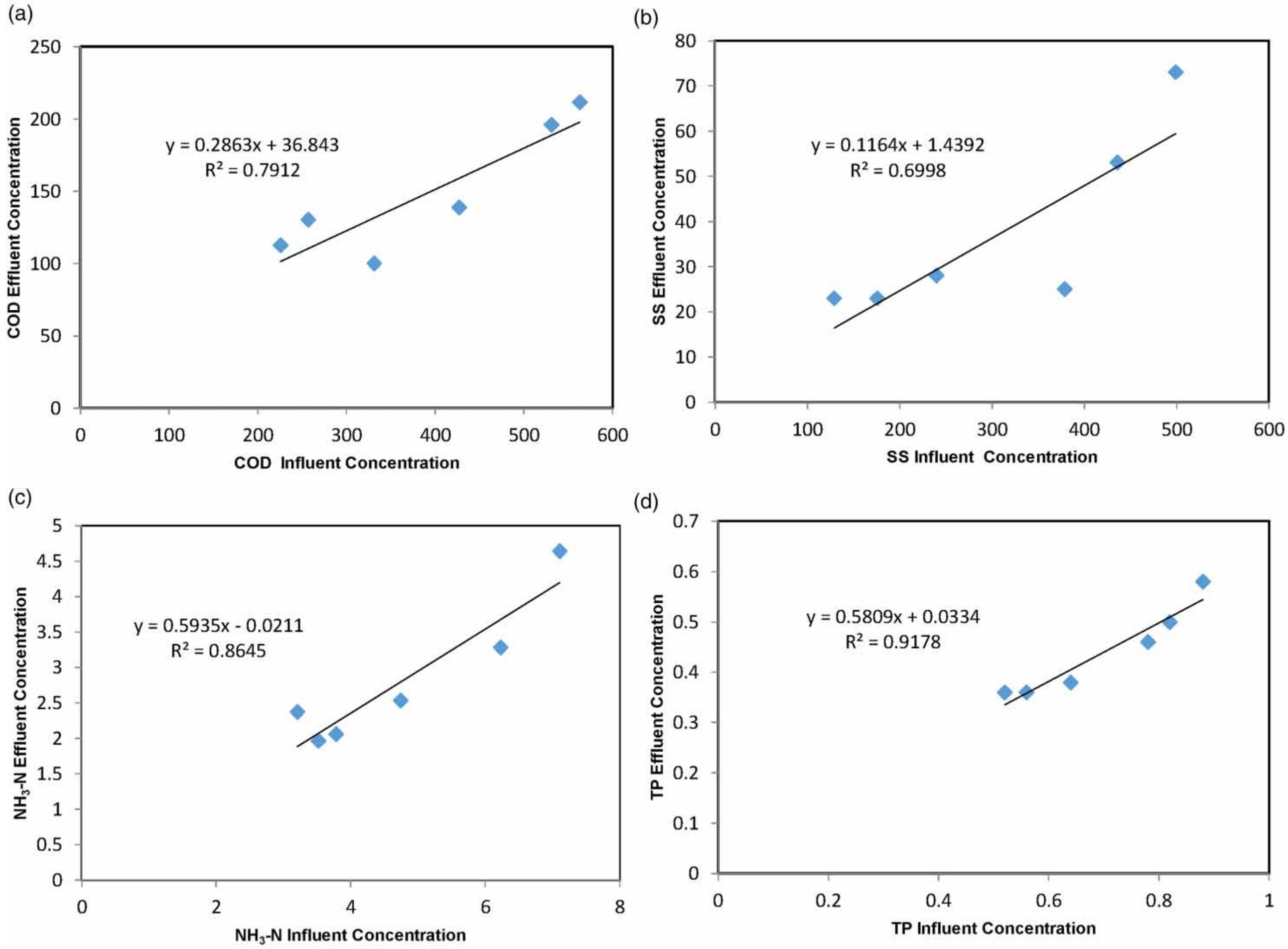


Figure 3 | The relationship between influent and effluent pollutants in the first hour of rainfall: (a) correlation coefficient for COD; (b) correlation coefficient for SS; (c) correlation coefficient for NH_3-N; and (d) correlation coefficient for TP.

coefficient for SS at the inlet and outlet of 0.700, Figure 3(c) presents the correlation coefficient for NH_3-N at the inlet and outlet as 0.865, and Figure 3(d) illustrates the correlation coefficient for TP at the inlet and outlet as 0.918. Among these, the linear relationship of TP concentration between inflow and outflow water was the strongest, whereas SS showed relatively lower correlation.

The variation in correlation coefficients for different pollutants can be attributed to the distinct mechanisms required for their removal. SS primarily require physical processes for effective removal, such as filtration and sedimentation, which might not always be uniformly efficient across different rain events, leading to a relatively lower correlation coefficient. On the other hand, the NH_3-N and TP is predominantly facilitated through chemical and biological processes within the bioretention system. These processes, including adsorption, ion exchange, and biological uptake by plants and microorganisms, tend to be more consistent in their effectiveness, resulting in higher correlation coefficients for NH_3-N and TP. This suggests that while physical mechanisms can vary in their removal efficiency due to factors such as inflow rate and particulate size, chemical and biological processes within the system offer a more stable and reliable means of pollutant removal, particularly for nutrients like nitrogen and phosphorus. When the hydraulic retention time is brief, the removal of SS, COD, NH_3-N, and TP by the bioretention cell primarily relies on the physical effects of medium filtration during the infiltration process, along with mechanical filtration and adsorption by the plant-covered soil (Xu *et al.* 2018; Kong *et al.* 2021).

3.2. Evaluation of removal effect

Figure 4 illustrates the pollutant removal efficiencies for all four pollutants across various storm events, plotted against their respective rainfall depths, rainfall intensity, and dry days. Analysis of different storm events reveals a broad range of pollutant removal efficiencies, attributed to the complex and stochastic variations in factors such as rainfall depth, intensity, and the duration of antecedent dry period (Soonthornnonda & Christensen 2008; Yan *et al.* 2023). The bioretention cell demonstrated an effective and notable purification effect on surface runoff. Specifically, the PRE for SS is 59.81%, while COD and NH_3-N have removal rates of 39.01 and 37.53%, respectively. The removal efficiency for TP is the lowest at 30.49%.

It is interesting to note that the removal efficiencies of COD and SS exhibit a similar temporal variation pattern, with the removal efficiency of SS notably higher than that of COD. This finding aligns with research indicating a linear relationship between SS and COD in surface water and sewage, suggesting significant reductions in COD values following SS removal (Al Bazedi & Abdel-Fatah 2020; Weiwei 2020). The interception of most SS in runoff is achieved through physical actions such as filtration and deposition by the stems and leaves of greenbelt plants. The soil and plants effectively act as a filtration device,

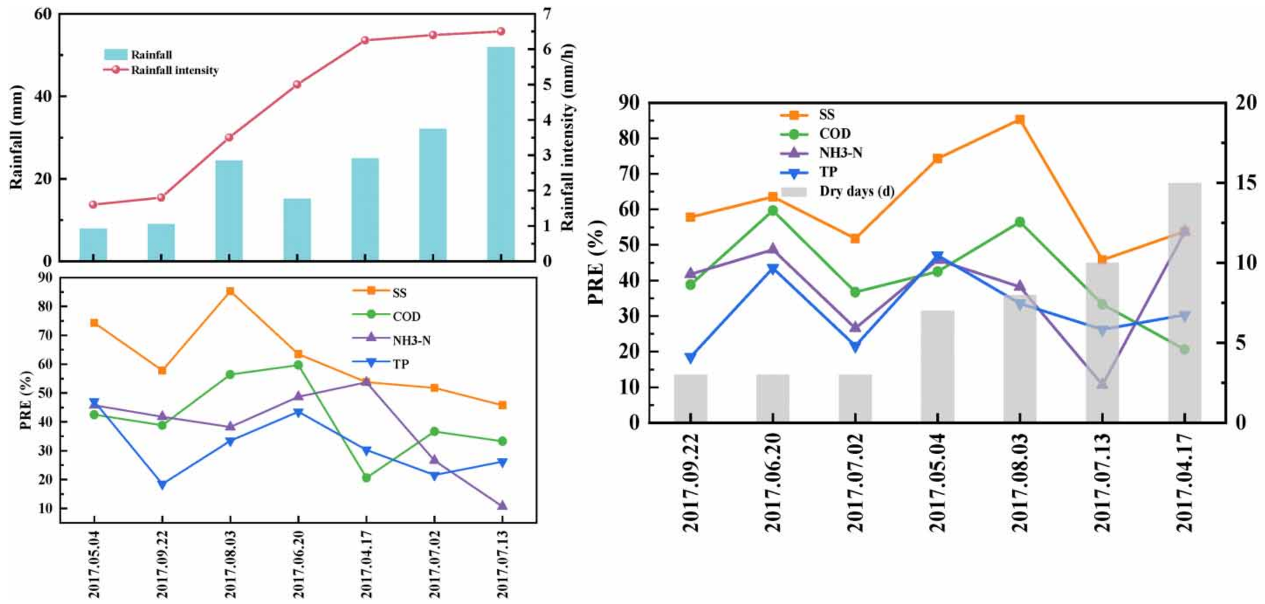


Figure 4 | The average removal efficiency for different pollutants.

with most SS being trapped and accumulated in the soil filler layer, facilitated by the soil matrix layer and plant root (Wei *et al.* 2021). The removal of COD in green spaces is primarily achieved through the interception by surface plants and soil, with the gravel layer playing a significant role in its removal. A study showed that the removal rate of COD by gravel is 81.99% (Hou *et al.* 2014).

The removal of nitrogen and phosphorus is also closely linked to the removal of SS, as a considerable portion of nitrogen and phosphorus in urban stormwater runoff is conveyed as sediment-bound pollutants (Vaze & Chiew 2004; Yang & Lusk 2018). Our results indicate that the removal efficiency of SS was significantly higher than that of NH_3-N and TP, corroborating findings from the International Stormwater Best Management Practices Database and other studies (Clary *et al.* 2011). Nitrogen and phosphorus generally exhibit lower and more variable removal efficiencies than SS, given that the dissolved components of TN and TP are not subject to sedimentation processes, unlike particulate components. Figure 5 showcases the transformation of nitrogen in soil, highlighting that major removal mechanisms for organic contaminants in the bioretention cell involve microbe-based bioremediation processes (e.g., nitrification/denitrification) rather than direct plant uptake. While green plants do absorb molecular pollutants for their growth, this is not the primary method for phosphorus removal (Liu *et al.* 2022). Phosphorus removal in green spaces is mainly achieved through medium particle adsorption, precipitation, and various chemical reactions, with phosphorus adsorption showing a strong correlation with calcium content. Calcium binds phosphorus more readily than other metals, and the redox potential of the matrix significantly impacts phosphorus adsorption (Zahed *et al.* 2022). Additionally, phosphorus adsorption on the soil surface is partly reversible, explaining the low phosphorus removal rate observed. Figure 6 depicts the transformation of phosphorus in soil.

The bioretention cell exhibited varying levels of pollutant reduction in surface runoff, influenced by rainfall. Optimal removal of SS and COD occurs with rainfall around 32 mm, whereas NH_3-N and TP are most effectively removed with rainfall between 9 and 15 mm. Under light rainfall conditions, the removal rate for SS is high, but COD and NH_3-N experience lower removal rates, and TP removal proves to be unstable. Moderate rainfall enhances the removal rates for SS and COD, but NH_3-N and TP reduced effectiveness. During heavy rainfall, SS removal outperforms other pollutants, though not as effectively as in moderate or light conditions. In such conditions, the removal efficiency for all pollutants is at its lowest, aligning with findings from the research by Hu *et al.* (2019). This pattern may be attributed to the following reasons: (a) Heavy rainfall leads to surface runoff exceeding the storage capacity of bioretention cell, resulting in part of the runoff being discharged into

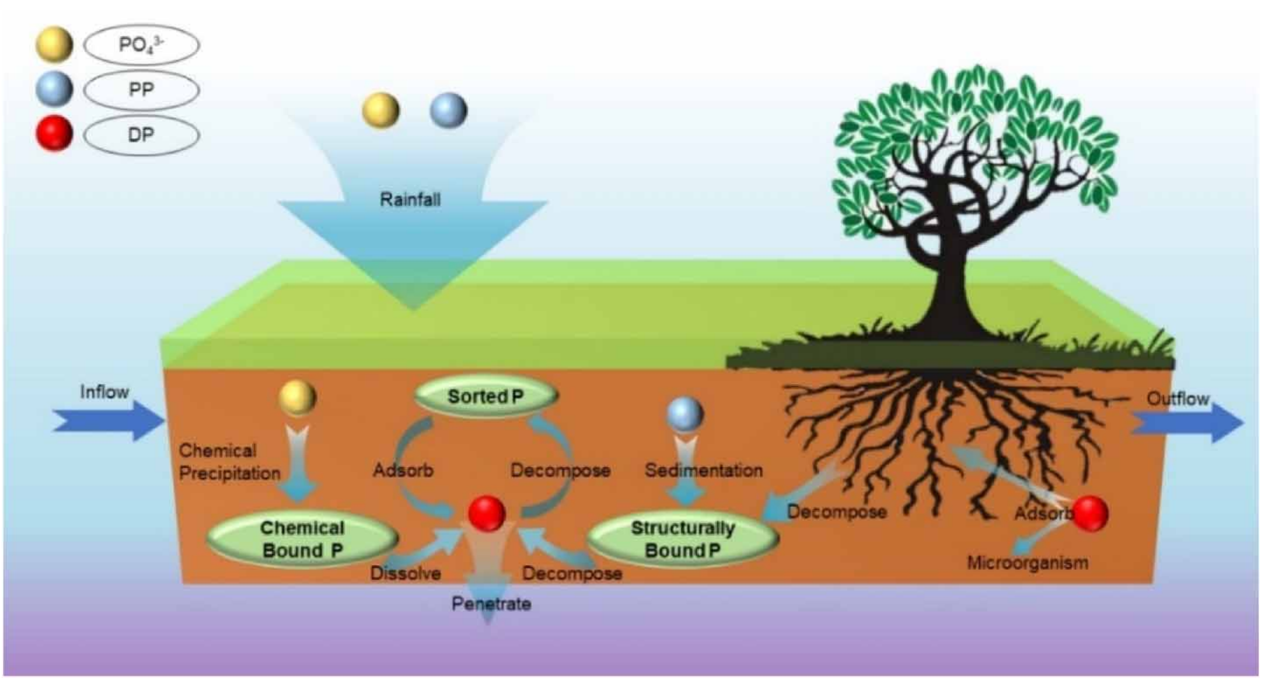


Figure 5 | Diagram of nitrogen conversion (Moser *et al.* 2018; Yang *et al.* 2023a).

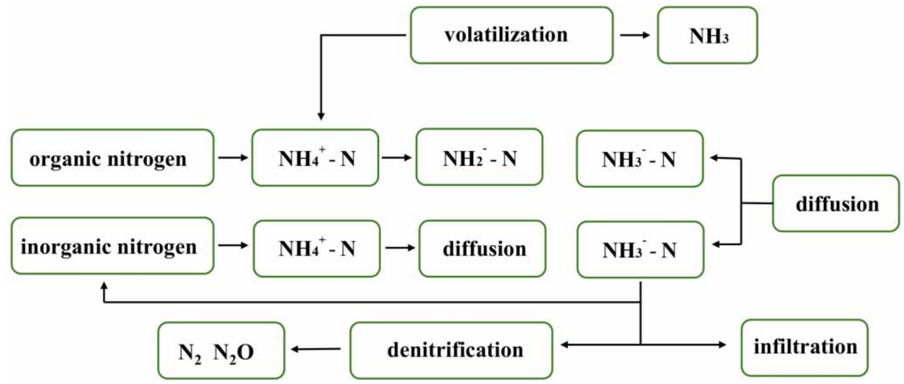


Figure 6 | Diagram of phosphorus conversion (Zhao *et al.* 2021, 2024).

the municipal pipeline network without treatment (Qiu *et al.* 2021). (b) Increased rainfall intensity accelerates water velocity and reduces the hydraulic retention time of runoff, significantly diminishing the pollutant removal rate (Chang *et al.* 2023; Fu *et al.* 2024). Under conditions where the antecedent dry period was consistently three days, pollutant removal rates exhibited fluctuations with increasing rainfall volume (and intensity). Specifically, TP showed a decreasing trend, while the PREs of COD and SS displayed similar patterns of temporal variation. In scenarios with antecedent dry periods exceeding ten days, under comparable rainfall intensities, the PREs of NH_3-N and TP exhibited a parallel pattern of temporal variation, both lower than that of SS. Overall, regardless of the antecedent dry period, rainfall amount, or intensity, the PRE for SS remained above 50%, indicating that the bioretention cell was highly efficient at trapping SS. The study confirmed that rainfall intensity and rainfall and dry period have an effect on pollutant migration, aligning with findings from researchers (Chua *et al.* 2009; Shen *et al.* 2016). However, our analysis of the correlation between rainfall characteristics and pollutant removal rates does not reveal a significant relationship for the four pollutants examined, diverging from Yang *et al.*'s (2023b) findings, which indicated a strong correlation between rainfall intensity and the removal efficiency of nitrogen, TP, and TSS. Similarly, the anticipated key role of antecedent dry periods in affecting pollutant concentrations did not yield significant correlations. We hypothesized that in traditional catchments, pollutant accumulation increases with longer antecedent dry periods. Conversely, in low impact development catchments, extended antecedent dry periods could enhance pollutant removal and rejuvenate the bioretention cell's capacity to absorb pollutants. These two processes counteract with each other and weaken the impact of the antecedent dry day.

3.3. Analysis on recycling with stormwater

Stormwater management plays a crucial role in the sponge city initiative, especially when the organic matter and nitrogen content in rainfall exceed the standards for reuse water. This study focuses on a bioretention cell, identified for its superior performance in rainwater treatment. The analysis of this effluent, in comparison to various domestic water reuse standards, reveals its potential applicability for rainwater reuse. The effluent of NH_3-N and TP conform to the reuse of urban recycling water (water quality standard for urban miscellaneous water consumption, GB/T18920-2002), while the measured COD in the effluent conforms to integrated wastewater discharge standard (GB8978-1996) level 3. As for SS, assessment standard for sponge city construction effect (GB/T 51345) clearly requires that the total reduction rate of SS of annual runoff pollutants should not be less than 40%, while the single removal rate of the bioretention cell reaches 59.81%.

Bioretention cells offer several benefits, including their affordability in terms of construction and maintenance, straightforward management, and contributions to both landscape aesthetics and the economy, as noted by Vijayaraghavan *et al.* (2021). Additionally, the specific system examined in this research has been shown to efficiently eliminate organic substances from rainwater, according to experimental findings. The treated water is suitable for various urban applications, including miscellaneous, landscaping, and industrial uses. Consequently, the insights gained from this study are of significant relevance and offer practical utility for the field of rainwater recycling.

4. CONCLUSIONS

This study evaluated a bioretention cell within Changchun's sponge city initiative, focusing on its effectiveness in improving runoff water quality in northern China's unique conditions. Results demonstrated significant pollutant removal efficiencies, with 59.81% for SS, 39.01% for COD, 37.53% for NH_3-N, and 30.49% for TP. A notable linear relationship and a significant correlation were observed between the concentrations of effluent and influent for COD, SS, NH_3-N, and TP within the first hour, with correlation coefficients of 0.791, 0.700, 0.865, and 0.918, respectively. Assessment of the bioretention cell's effluent quality against various water reuse standards indicates that it satisfies the criteria for urban recycled water, urban miscellaneous water uses, integrated wastewater discharge, and sponge city construction effect assessment standards. The treated water is suitable for reuse in urban applications such as miscellaneous and landscape water, as well as in industrial processes. This study presents a promising approach for sustainable urban water management in cold regions, contributing valuable insights to the sponge city initiative.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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