

Long-term Evaluation of Constructed Wetland Efficiency for Domestic Wastewater Treatment under Temperate Climatic Conditions in Beijing, China

Zeyuan Liu¹, Le Hien¹, Le Duc Anh Tuan², Nguyen Thi Xuyen^{3*}

¹University of Chinese Academy of Sciences, No.1 Yanqihu East Rd, Huairou District, Beijing 101408, PR China

²Southern Bus Station Service and Management Center, Department of Construction of Quang Tri Province, Vietnam

³Faculty of Fundamental Sciences, Viet-Hung Industrial University, No. 88, 419 St., Tay Phuong, Hanoi, Vietnam

*Correspondence: nguyensexuyen90qn@hotmail.com

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ABSTRACT: This study evaluated the long-term performance of a constructed wetland (CW) system for domestic wastewater treatment under temperate climatic conditions in Beijing, China. The system, with a capacity of 400 m³/day serving approximately 3,500 people, was monitored over four years. The results showed stable treatment performance, with average effluent concentrations of COD 30.04 ± 8.49 mg/l, BOD₅ 10.53 ± 3.12 mg/l, TSS 8.87 ± 3.38 mg/l, TN 12.34 ± 2.88 mg/l, TP 0.54 ± 0.16 mg/l, and NH₄⁺ 4.85 ± 1.15 mg/l, all meeting the Chinese discharge standard GB 18918-2002 (Level IB). Removal efficiencies were higher for organic matter and TSS (up to 76.49% and 84.52% in summer) than for nutrients (TN 66.62%, TP 55.61%, NH₄⁺ 49.68%). Seasonal variation significantly affected performance, with winter efficiencies decreasing to 57.87% (COD) and 41.50% (NH₄⁺). Correlation analysis indicated that temperature was the dominant factor ($r = 0.637$ – 0.638 , $p < 0.01$), while influent characteristics had moderate effects ($r = 0.405$ – 0.479). These results demonstrate that CW systems provide a stable and effective solution for decentralized wastewater treatment, although optimization is required to improve performance under low-temperature conditions.

KEYWORDS: Constructed wetland; domestic wastewater; climatic conditions; wastewater treatment.

1. Introduction

Domestic wastewater has become one of the main sources of environmental pollution in rapidly urbanizing areas [1]. Although centralized wastewater treatment systems have been widely implemented in urban regions, a significant portion of suburban and rural areas still rely on decentralized or inadequate treatment systems [2]. As a result, untreated or insufficiently treated domestic wastewater can lead to serious environmental problems such as eutrophication, water quality degradation, and ecosystem deterioration.

In Beijing, domestic water consumption reaches approximately 1.5 billion m³ per year, generating a large volume of urban wastewater [3]. Meanwhile, monitoring data indicate that nitrogen and phosphorus remain the main pollutants in receiving water bodies, highlighting the need for effective treatment technologies [4]. In recent years, China has strengthened regulatory requirements for domestic wastewater through the implementation of stringent discharge standards. According to the national standard GB 18918-2002, wastewater treatment plants must meet different discharge limits (Level IA, IB, II, III), among which Level IA is the most stringent, requiring COD \leq 50 mg/L, BOD₅ \leq 10 mg/L, NH₄⁺-N \leq 5 mg/l, and TP \leq 0.5 mg/l, particularly for environmentally sensitive areas. For domestic wastewater, various technologies have been applied and shown distinct advantages. However, for applications in rural areas, in addition to treatment efficiency, cost-effectiveness and ease of operation should be prioritized. Constructed wetlands (CW) are considered a sustainable and low-cost wastewater treatment technology [5, 6]. These systems utilize natural interactions among plants, microorganisms, and substrate materials to remove pollutants [7–9]. CWs have been widely applied worldwide in urban wastewater treatment and are regarded as an effective solution for decentralized systems. The treatment mechanisms in CW systems rely on natural transformation processes, and therefore are significantly influenced by weather conditions [10, 11]. Climatic factors, especially temperature, solar radiation, and humidity, play important roles in controlling biological transformation processes in constructed wetlands. These processes include organic matter decomposition, nitrification–denitrification, plant uptake, and phosphorus adsorption–desorption, all of which are strongly affected by seasonal variations [12, 13].

Temperature is the most critical factor affecting microbial activity in CW systems [14]. Most biochemical reactions follow Arrhenius kinetics, where reaction rates increase exponentially with temperature. Higher temperatures in summer enhance microbial metabolic activity, thereby improving organic matter degradation and the removal efficiency of COD and BOD [15]. In contrast, lower temperatures in winter reduce enzyme activity, resulting in slower degradation rates and decreased treatment efficiency. This phenomenon is particularly evident in nitrification processes, as nitrifying bacteria (*Nitrosomonas*, *Nitrobacter*) are highly sensitive to temperature and exhibit poor activity below 10°C. The nitrification–denitrification process is strongly influenced by climatic conditions [16]. Nitrification is an aerobic process requiring oxygen and suitable temperatures, while denitrification is an anaerobic process dependent on carbon sources [9]. Under cold conditions, reduced nitrification rates limit the supply of nitrate (NO₃⁻) for denitrification, thereby lowering total nitrogen removal efficiency. Additionally, low temperatures can alter microbial community structure, affecting nitrogen transformation pathways. Solar radiation and photoperiod also influence CW performance through their effects on plant growth and oxygen supply [12]. Strong sunlight in summer promotes photosynthesis, increasing oxygen diffusion through plant roots (radial oxygen loss), which supports aerobic processes such as organic matter degradation and nitrification [12, 17]. Conversely, in winter, reduced light intensity limits plant activity and oxygen supply, leading to lower treatment efficiency. Humidity and hydrological conditions affect both biological processes and transport mechanisms in CW systems [18]. Heavy rainfall can dilute pollutant concentrations but may also impact hydraulic retention time and flow regimes [19]. Conversely, dry conditions can increase pollutant concentrations and place stress on microbial systems. In addition, plant growth dynamics play a crucial role in seasonal treatment

performance. During the growing season, plants actively absorb nutrients (especially nitrogen and phosphorus), provide habitats for microorganisms, and enhance filtration capacity. In contrast, during autumn and winter, reduced growth and biomass decomposition may decrease nutrient uptake and even release previously accumulated substances [15, 20]. Although constructed wetlands have been widely applied, long-term studies evaluating seasonal performance under temperate northern climate conditions remain limited. Most existing studies are short-term or laboratory-scale. This study aims to evaluate the long-term treatment performance of a constructed wetland system for domestic wastewater under temperate climatic conditions in Beijing, China. The study focuses on analyzing seasonal variations of key water quality parameters (COD, BOD₅, NH₄⁺-N, TN, and TP), clarifying the influence of climatic factors on treatment efficiency, and providing a scientific basis for optimizing the design and operation of CW systems in cold climate conditions.

2. Methodology

2.1. System description.

The wastewater treatment system was applied to a suburban residential area in Shunyi District, Beijing, China, serving a population of 3,500 people, with a design capacity of 400 m³/day. The system was constructed following an ecological approach and includes the main units: a pre-treatment tank, vertical flow constructed wetlands, and a free-floating plant pond (Figure 1).

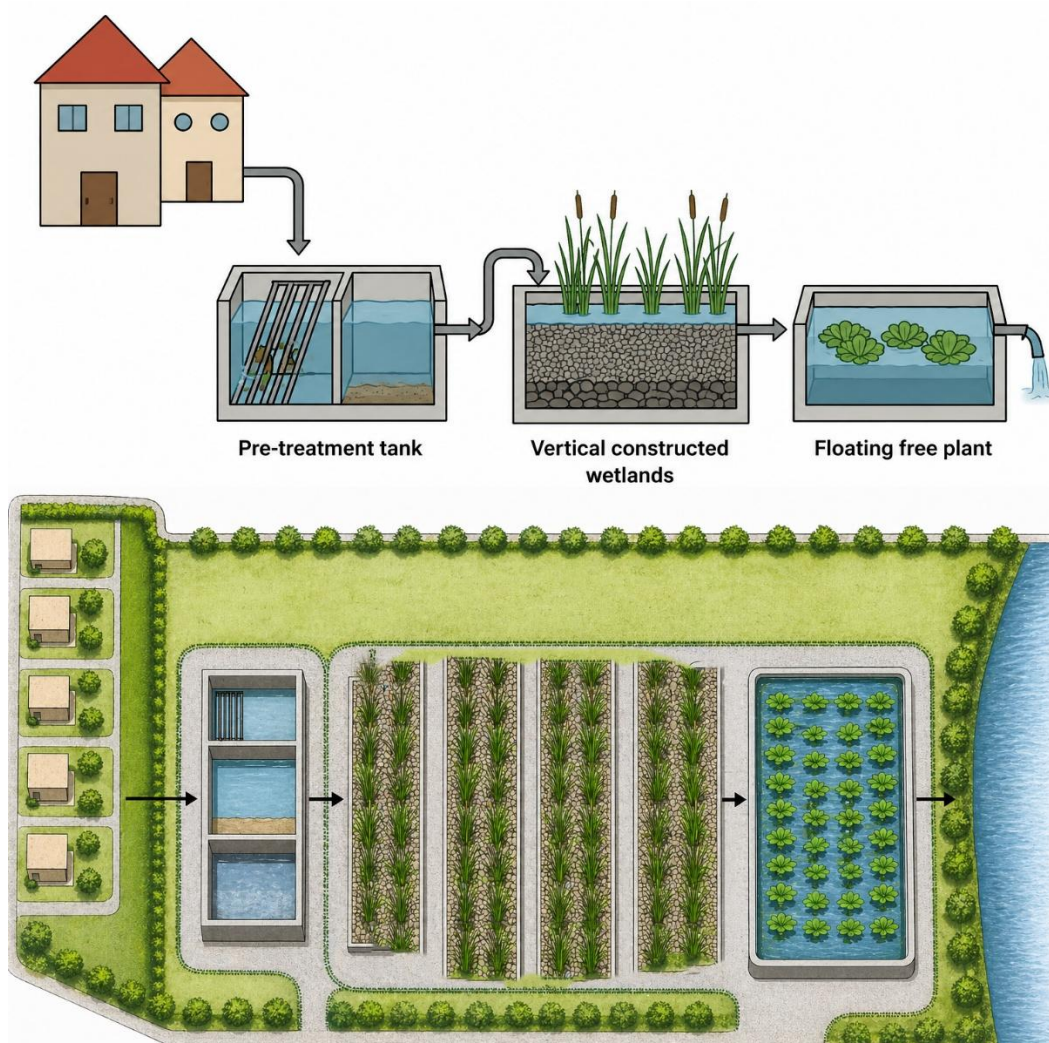


Figure 1. Layout of the domestic wastewater treatment system.

Collected wastewater is first conveyed to the pre-treatment tank, which consists of screening, grit removal, and grease separation compartments. The tank is designed with a volume of 96 m^3 and dimensions of $12 \text{ m} \times 4 \text{ m} \times 2 \text{ m}$, corresponding to a hydraulic retention time of approximately 6 hours. This ensures effective removal of coarse solids, settleable particles, and floating materials, while stabilizing flow and pollutant concentrations prior to biological treatment. After pre-treatment, wastewater is distributed onto vertical flow constructed wetlands. With a hydraulic loading rate of $0.10 \text{ m}^3/\text{m}^2/\text{day}$, the total wetland area is determined to be $4,000 \text{ m}^2$. The system is divided into four cells operating alternately, each with dimensions of $50 \text{ m} \times 20 \text{ m}$ and a filter media depth of 1.0 m . The wetland structure includes a distribution layer, sand–gravel layer, supporting stone layer, and a bottom drainage system, ensuring efficient filtration, adsorption, and biological degradation processes. The vertical flow constructed wetlands were planted with cattail (*Typha latifolia* L.), a robust emergent macrophyte widely used in CW systems because of its extensive root system, high tolerance to wastewater conditions, and ability to support microbial communities involved in organic matter degradation and nutrient removal. Effluent from the wetlands is then conveyed to a free-floating plant pond for polishing treatment. The pond is designed with a volume of $1,100 \text{ m}^3$ and dimensions of $45 \text{ m} \times 20 \text{ m} \times 1.2 \text{ m}$. Floating plant rafts are installed on the surface to enhance the removal of remaining nutrients, particularly nitrogen and phosphorus, and to further improve water quality before discharge or reuse. The floating rafts were

vegetated with umbrella sedge (*Cyperus alternifolius* L.), an ornamental aquatic plant characterized by rapid growth, high nutrient uptake capacity, and well-developed root systems that provide additional surfaces for biofilm development and pollutant removal.

2.2. Operation and sampling.

During operation, water samples were collected every 7 days at two locations: the influent of the CW system (i.e., wastewater after the pre-treatment tank before entering the constructed wetlands) and the effluent of the CW system (i.e., wastewater after passing through the vertical flow constructed wetlands). The influent wastewater exhibited relatively high concentrations of organic matter and suspended solids, with average COD, BOD₅, TSS, and TN levels of 94.32 ± 13.97 mg/l, 47.08 ± 8.39 mg/l, 41.06 ± 7.88 mg/l, and 32.35 ± 6.21 mg/l, respectively. Samples were collected at the same time of day, stored in clean bottles, preserved at 4°C, and transported to the laboratory for analysis within the prescribed holding time. In addition, weather conditions were monitored throughout the study period, including air temperature, humidity, and sunshine duration. The experiment was conducted under the climatic conditions of Beijing, China, where summers are typically hot and humid, with average temperatures of 25–27°C, relative humidity of 70–80%, and sunshine duration of 6–8 h day⁻¹, while winters are cold and dry, with average temperatures ranging from -3 to 2°C, relative humidity of 40–60%, and sunshine duration of 7–9 h day⁻¹.

2.3. Analytical methods.

Water quality parameters were analyzed following standard international methods. Biochemical oxygen demand (BOD₅) was determined using Method 5210B; chemical oxygen demand (COD) was analyzed using the closed reflux dichromate method (5220D); total suspended solids (TSS) were determined by the filtration and drying method (2540D). Ammonium (NH₄⁺-N) was measured using the phenate method (4500-NH₃ F), total nitrogen (TN) was analyzed using the persulfate digestion method combined with spectrophotometry (4500-N C), and total phosphorus (TP) was determined using the ascorbic acid method after digestion (4500-P E).

2.3. Data analysis.

One-way analysis of variance (one-way ANOVA) was applied to assess statistically significant differences in water quality parameters (BOD₅, COD, TSS, NH₄⁺-N, TN, and TP) among seasons. When ANOVA results indicated significant differences ($p < 0.05$), Tukey's HSD post hoc test was used to identify specific seasonal differences. Pearson correlation coefficients were used to evaluate linear relationships between water quality parameters and environmental factors such as air temperature, rainfall, and system operating conditions. The level of statistical significance was set at $p < 0.05$. Results are presented as mean \pm standard deviation, combined with graphical representations to illustrate temporal variations and relationships among variables.

3. Results

3.1. Water quality variation.

The system operated continuously for four years and showed promising results, with pollutant concentrations in the effluent significantly reduced compared to the influent (Figure 2). The average effluent concentrations were: COD 30.04 ± 8.49 mg/l, BOD₅ 10.53 ± 3.12 mg/l, TSS 8.87 ± 3.38 mg/l, TN 12.34 ± 2.88 mg/l, TP 0.54 ± 0.16 mg/l, and NH₄⁺ 4.85 ± 1.15 mg/l. Although influent water quality exhibited considerable fluctuations, the treatment performance of the CW system remained stable throughout the operational period. Compared with China's discharge standard (GB 18918-2002), all effluent parameters met the Level IB limits (COD ≤ 60 mg/l, BOD₅ ≤ 20 mg/l, SS ≤ 20 mg/l, TN ≤ 20 mg/l, NH₄⁺ ≤ 8 mg/l, TP ≤ 1 mg/l). These results indicate that the CW system is capable of effectively treating domestic wastewater and producing effluent that meets environmental discharge standards.

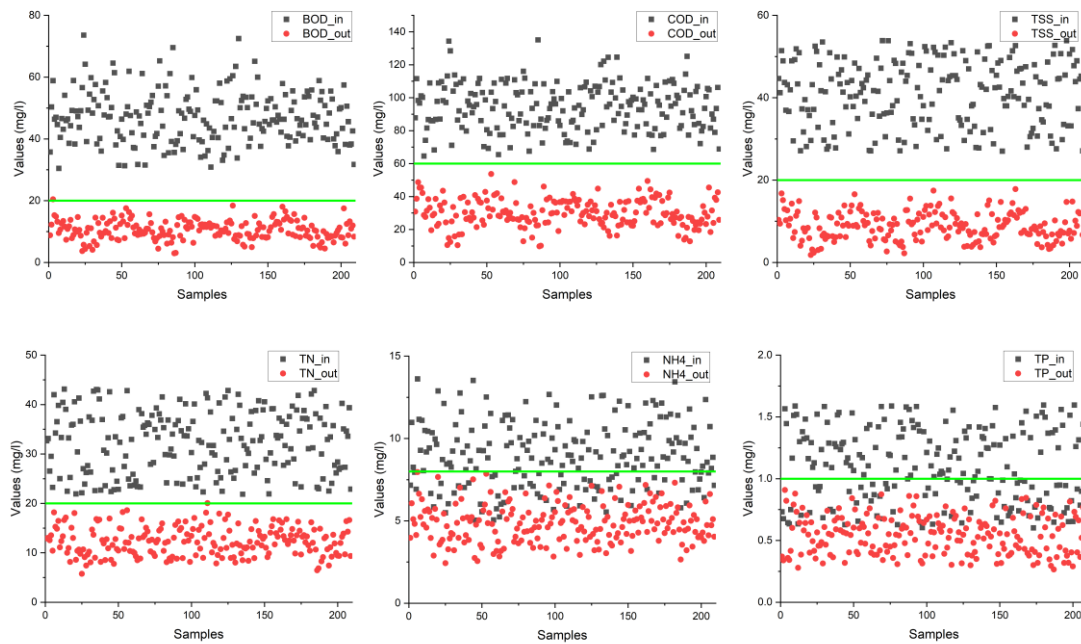


Figure 2. Variation of pollutant concentrations in influent and effluent of the CW system.

3.2. Seasonal variation in treatment efficiency.

The results indicate that the treatment efficiency of the constructed wetland system varied significantly across seasons and was strongly influenced by climatic conditions ($p < 0.05$, Table 1). The superior performance observed in summer was mainly associated with intensified microbial metabolism and plant-mediated pollutant removal, whereas reduced biological activity under low-temperature conditions limited treatment efficiency during winter. For COD, treatment efficiency increased significantly from $57.87 \pm 5.50\%$ in winter to $76.49 \pm 8.94\%$ in summer, while spring and autumn achieved $67.16 \pm 7.29\%$ and $68.31 \pm 7.20\%$, respectively, with no statistically significant difference between these two seasons ($p > 0.05$). A similar trend was observed for BOD, with removal efficiency increasing from $70.41 \pm 3.86\%$ in winter to $83.49 \pm 6.28\%$ in summer, while spring and autumn recorded $76.93 \pm 5.12\%$ and $77.74 \pm 5.06\%$, respectively. For TSS, treatment efficiency ranged from $72.26 \pm 3.62\%$ in winter to $84.52 \pm 5.89\%$ in summer, while spring and autumn reached $78.38 \pm 4.80\%$ and $79.13 \pm 4.74\%$, respectively. For nutrients, seasonal differences were even more pronounced. TN removal efficiency increased from $56.69 \pm 2.93\%$ in winter to $66.62 \pm 4.77\%$ in summer, while spring and autumn recorded $61.65 \pm 3.89\%$ and $62.26 \pm 3.84\%$, respectively. Similarly, NH₄⁺

removal efficiency was lowest in winter ($41.50 \pm 2.42\%$) and highest in summer ($49.68 \pm 3.92\%$), while spring and autumn achieved $45.58 \pm 3.20\%$ and $46.09 \pm 3.16\%$, respectively. For TP, removal efficiency increased from $45.81 \pm 2.89\%$ in winter to $55.61 \pm 4.70\%$ in summer, while spring and autumn recorded $50.69 \pm 3.85\%$ and $51.30 \pm 3.79\%$, respectively.

Table 1. Comparison of seasonal removal efficiencies for key pollutants in the constructed wetland system.

Parameter	Winter	Spring	Autumn	Summer
COD (%)	57.87 ± 5.50^c	67.16 ± 7.29^b	68.31 ± 7.20^b	76.49 ± 8.94^a
BOD (%)	70.41 ± 3.86^c	76.93 ± 5.12^b	77.74 ± 5.06^b	83.49 ± 6.28^a
TSS (%)	72.26 ± 3.62^c	78.38 ± 4.80^b	79.13 ± 4.74^b	84.52 ± 5.89^a
TN (%)	56.69 ± 2.93^c	61.65 ± 3.89^b	62.26 ± 3.84^b	66.62 ± 4.77^a
TP (%)	45.81 ± 2.89^c	50.69 ± 3.85^b	51.30 ± 3.79^b	55.61 ± 4.70^a
NH ₄ ⁺ (%)	41.50 ± 2.42^c	45.58 ± 3.20^b	46.09 ± 3.16^b	49.68 ± 3.92^a

3.3. Effects of weather factors on treatment efficiency.

The analysis results indicate that the treatment efficiencies of various parameters in the constructed wetland (CW) system are strongly correlated and significantly influenced by environmental conditions (SM Table 1). COD removal efficiency shows very strong correlations with BOD ($r = 1.000$), TSS ($r = 0.920$), and TN ($r = 0.821$), indicating that organic matter degradation, sedimentation–filtration, and nutrient transformation processes occur simultaneously within the system. Similarly, BOD removal efficiency is highly correlated with TP ($r = 0.751$) and NH₄⁺ ($r = 0.641$), reflecting the important role of microorganisms in the simultaneous removal of organic matter and nutrients. Climatic factors exhibit clear impacts on treatment performance. Temperature shows a significant positive correlation with all parameters ($r = 0.638$; $p < 0.01$), indicating that higher temperatures enhance biological activity. Humidity presents a moderate positive correlation ($r = 0.523$), while sunshine duration shows a negative correlation ($r = -0.267$), suggesting potentially unfavorable effects on treatment efficiency under certain conditions. Regarding influent wastewater, COD_{in} and BOD_{in} show moderate positive correlations with treatment efficiency ($r = 0.406$ – 0.478), indicating that the initial pollutant load influences system performance. In contrast, TN_{in}, TP_{in}, and NH₄_{in} do not exhibit statistically significant correlations, suggesting that the CW system maintains stable performance despite variations in influent nutrient concentrations. Overall, treatment efficiency is influenced by the combined effects of environmental factors and influent loading, with temperature identified as the most dominant controlling factor under temperate climatic conditions.

4. Discussion

The long-term operation of the CW system demonstrated stable and effective treatment performance for domestic wastewater under temperate climatic conditions. Over the four-year monitoring period, the system consistently achieved substantial reductions in organic matter, suspended solids, and nutrients, with effluent concentrations meeting the Chinese discharge standard GB 18918-2002 (Level IB). This confirms that CW systems can serve as a reliable and sustainable solution for decentralized wastewater treatment in suburban areas. The observed removal efficiencies indicate that organic matter (COD and BOD₅) and suspended solids (TSS) were more effectively removed than nutrients (TN, TP, and NH₄⁺). This pattern is commonly reported in CW systems and can be attributed to the relatively straightforward mechanisms of filtration, sedimentation, and microbial degradation involved in organic matter removal, compared to the more complex biological pathways required for nutrient

transformation. In particular, nitrogen removal depends on the coupled processes of nitrification and denitrification, which are highly sensitive to environmental conditions, while phosphorus removal relies on adsorption, precipitation, and plant uptake, which may become saturated over time.

Seasonal variation was identified as a key factor influencing treatment efficiency. Higher removal efficiencies observed in summer compared to winter highlight the strong dependence of CW performance on temperature. Elevated temperatures enhance microbial metabolic rates, enzyme activity, and plant growth, thereby improving both organic matter degradation and nutrient transformation [12, 21]. In contrast, low temperatures likely suppressed microbial activity, particularly nitrifying bacteria, resulting in reduced nitrogen removal efficiency [22]. The relatively similar performance observed in spring and autumn suggests transitional conditions where biological processes are moderately active but not optimal [23].

The findings of this study are consistent with previous reports indicating that seasonal variations in treatment performance are primarily driven by climatic conditions, although the magnitude of these differences varies across climate zones. In the present study, no significant seasonal variation was observed for TSS removal efficiency, suggesting that physical processes such as sedimentation and filtration remain relatively stable throughout the year. However, several studies have reported a decrease of 14–27.67% in TSS removal efficiency during winter compared to summer, mainly due to surface freezing and reduced hydraulic performance in colder climates [24, 25]. For other parameters, including COD, TN, NH_4^+ , and TP, the removal efficiencies in this study were higher in summer than in winter by 3.22%, 13.62%, 14.12%, and 9.29%, respectively. These differences are relatively moderate compared to those reported in colder regions. For instance, a CW system in Barcelona (Spain) exhibited substantial seasonal variation, where NH_4^+ removal efficiency reached approximately 99% in summer but dropped to below 0% (i.e., negative removal) in winter, indicating strong inhibition of nitrification under low-temperature conditions [24]. Similarly, studies conducted in China have reported that removal efficiencies of COD, TN, and TP in summer were 12–27% higher than in winter [26]. Li et al. (2024) further demonstrated that TN removal efficiency in winter could decrease by approximately 36% compared to summer, while COD removal differed by 15–40%, and TP removal showed a smaller reduction of 3.4–8.0% under cold conditions [27].

Seasonal variation differs across climatic zones. For example, in tropical monsoon climates, winter temperatures typically range from 14.5 to 26.9°C, which are not low enough to significantly inhibit microbial activity or plant growth [12]. As a result, biological processes such as organic matter degradation and nitrogen transformation can still proceed at moderate rates, leading to more stable treatment performance across seasons. This highlights the importance of regional climatic conditions in determining the extent of seasonal variability in CW systems and suggests that systems operating in temperate to subtropical climates may exhibit greater resilience to seasonal fluctuations than those in colder regions. In Beijing, winter conditions may pose additional operational challenges beyond the direct effect of low temperature. Air temperatures frequently fall below 0°C, and prolonged cold periods can result in partial or complete freezing of the wetland surface and the free-floating plant pond. Surface freezing may reduce hydraulic conductivity, limit oxygen diffusion, suppress microbial activity, and damage plant tissues, thereby impairing pollutant removal processes. These effects are particularly critical for nitrification, which requires both aerobic conditions and active microbial communities. Consequently, freezing events can substantially reduce

treatment efficiency and operational stability during winter. Although the system maintained acceptable performance throughout the monitoring period, winter freezing remains a major constraint for CW applications in cold-temperate regions such as northern China. The correlation analysis further supports the role of temperature as a dominant controlling factor. Significant positive correlations between temperature and all removal efficiencies indicate that biological processes govern system performance. The strong interrelationships among COD, BOD, TSS, and TN removal suggest that physical and biological processes are tightly coupled within the system. Additionally, the observed correlations between organic matter removal and nutrient removal parameters highlight the importance of carbon availability in supporting denitrification processes [19].

Environmental factors such as humidity and sunshine duration also influenced treatment performance, although to a lesser extent [18]. The positive correlation with humidity may reflect its role in maintaining favorable moisture conditions for microbial activity and plant function. Conversely, the negative correlation with sunshine duration suggests that excessive solar radiation could indirectly affect system performance, potentially through increased evapotranspiration, changes in hydraulic retention time, or stress on plant systems. Influent characteristics were found to have a moderate influence on treatment efficiency. Higher influent concentrations of COD and BOD were associated with increased removal efficiencies, likely due to enhanced substrate availability for microbial processes. However, the lack of significant correlations between influent nutrient concentrations and removal performance indicates that the CW system maintained relatively stable nutrient removal despite fluctuations in influent quality. This suggests a certain degree of resilience and buffering capacity inherent to the system. Overall, the results highlight that the performance of CW systems is governed by a complex interaction of biological processes, environmental conditions, and influent loading. Among these factors, temperature plays the most critical role in determining seasonal performance under temperate climates. These findings emphasize the need to consider seasonal variability in the design and operation of CW systems, particularly in cold regions. Optimization strategies, such as increasing hydraulic retention time, enhancing aeration, or integrating hybrid systems, may be necessary to improve winter performance and ensure consistent year-round treatment efficiency.

5. Conclusions

This study demonstrated that the CW system effectively treated domestic wastewater under temperate climatic conditions, maintaining stable performance over four years and meeting the Chinese discharge standard (GB 18918-2002, Level IB). Organic matter and suspended solids were removed more efficiently than nutrients. Seasonal variation significantly affected treatment performance, with higher efficiencies observed in summer due to enhanced microbial activity at elevated temperatures. However, the relatively moderate seasonal differences indicate good system resilience under temperate conditions. Correlation analysis confirmed temperature as the dominant controlling factor, while influent characteristics had a secondary influence. These findings highlight the importance of considering climatic conditions in CW design and suggest that optimization strategies are needed to improve winter performance.

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Author Contribution

Zeyuan Liu: Conceptualization, Methodology, Data Analysis, Writing; Le Hien: Data Collection, Writing; Le Duc Anh Tuan: Data Analysis, Methodology, Nguyen Thi Xuyen: Methodology, Data Collection, Data Analysis, Writing.

Competing Interest

The authors declare no competing interests.

Data Availability

The data supporting the findings of this study are available within the article and its Supplementary Materials.

Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.53623/tebt.v4i1.1192>.

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