EVALUATING THE IMPACT OF SUBSTRATE LAYER THICKNESS ON WET-ROOF (WR) MODELS WITH *PORTULACA GRANDIFLORA* FOR DOMESTIC WASTEWATER TREATMENT

ĐÁNH GIÁ ẢNH HƯỞNG ĐỘ DÀY CỦA LỚP GIÁ THỂ ĐẾN MÔ HÌNH WET-ROOF (WR) SỬ DỤNG CÂY HOA MƯỜI GIỜ *(PORTULACA GRANDIFLORA)* TRONG XỬ LÝ NƯỚC THẢI SINH HOẠT

Pham Ngoc Hoa*

Ho Chi Minh City University of Industry and Trade, Vietnam

*Corresponding author: hoapn@huit.edu.vn

(Received: March 03, 2026; Revised: April 15, 2026; Accepted: April 29, 2026)

DOI: 10.31130/ud-jst.2026.24(5A).117E

Abstract - This study evaluates the influence of substrate layer thickness in Wet-roof (WR) constructed wetlands using *Portulaca grandiflora* for decentralized domestic wastewater treatment. This approach offers a space-efficient, aesthetic, and simplified technological solution. Experimental results indicate that a substrate configuration of 20 mm soil and 100 mm sand optimizes plant growth and system stability. At an organic loading rate of 300 ± 10 kg COD.ha^{-1}.day^{-1}, the system achieved mean removal efficiencies of 85.37% (COD), 75.46% (TN), 68.01% (TP), and 98.2% (coliform). Corresponding effluent concentrations were 30.4 ± 2.0 mg/L, 12.0 ± 1.0 mg/L, 1.84 ± 0.11 mg/L, and 180 CFU/100 mL, respectively. These parameters demonstrate that the treated effluent meets the requirements for low-to-medium quality water reuse, highlighting the model's viability for sustainable urban water management.

Key words - Constructed wetlands; Wet-roof; *Portulaca grandiflora*; Domestic wastewater; Green-Roof structure.

Tóm tắt - Nghiên cứu này đánh giá ảnh hưởng của độ dày lớp giá thể trong hệ thống đất ngập nước kiến tạo Wet-roof (WR) trồng hoa mười giờ (*Portulaca grandiflora*) nhằm xử lý nước thải sinh hoạt phân tán. Các cấu hình giá thể khác nhau được khảo sát để xác định điều kiện tối ưu cho sinh trưởng thực vật và hiệu quả xử lý nước thải. Kết quả cho thấy cấu hình gồm lớp đất dày 20 mm kết hợp lớp cát dày 100 mm giúp hệ thống vận hành ổn định và đạt hiệu quả xử lý cao nhất. Ở tải trọng hữu cơ 300 ± 10 kg COD.ha^{-1}.ngày^{-1}, hiệu suất xử lý trung bình đạt 85,37% COD, 75,46% tổng nitơ (TN), 68,01% tổng photpho (TP) và 98,2% coliform. Nồng độ nước sau xử lý lần lượt đạt 30,4 ± 2,0 mg/L COD, 12,0 ± 1,0 mg/L TN, 1,84 ± 0,11 mg/L TP và 180 CFU/100 mL coliform, đáp ứng yêu cầu tái sử dụng nước chất lượng thấp đến trung bình và cho thấy tiềm năng ứng dụng trong quản lý nước đô thị bền vững.

Từ khóa - Đất ngập nước kiến tạo; Wet-roof; Hoa mười giờ (*Portulaca grandiflora*); Nước thải sinh hoạt, Cấu trúc mái xanh.

1. Introduction

In recent years, the process of urbanization in Vietnam has been progressing at a rapid pace. However, this accelerated development has significantly reduced the coverage of green spaces. If green spaces are developed adequately and in accordance with established standards, major cities could adopt an effective solution for climate change adaptation [1].

Constructed wetlands (CWs) have recently gained international attention as an environmentally friendly wastewater treatment technology that functions under natural conditions while offering high treatment efficiency, low cost, and system stability [1]. Additionally, CWs play an important role in enhancing biodiversity.

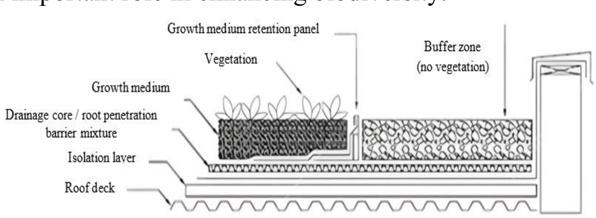


Figure 1. Structural composition of the WR System [2]

Green roofs (GRs) have also received increasing interest worldwide due to their multifunctional benefits. GRs not only contribute to wastewater treatment but also help reduce urban flood risks, save energy, enhance biodiversity [2, 3], increase urban green cover [4], and lower greenhouse gas emissions [5]. These systems are typically lightweight, consist of thin layers of substrate, and use low-height vegetation capable of withstanding varying weather conditions (Figure 1).

According to the Guideline for the Planning, Execution, and Upkeep of Green-Roof Sites, various plant groups used in GRs require different substrate thicknesses for optimal growth, and their pollutant treatment capacities are illustrated in Table 1.

***Table 1.** Standard depth requirements for selected baseline vegetation in WR systems [3]*

Plant type	Height (mm)	Plant type	Height (mm)
Moss and pioneer plants	40–80	Shrubs	300–500
Pioneer plants, moss, and herbs	60–100	Tall shrubs and small palms	400–700
Pioneer plants, herbs, and grass	100–150	Small trees and medium palms	600–1200
Grass, pioneer plants	150–200	Medium trees	1000–2000
Grass field	200–300	Large trees	1500–2000

Building on the GR concept, I. Blumberg [2] introduced the WR model have shown that WR systems using *Portulaca grandiflora* (commonly known as moss rose) exhibit promising efficiency in treating domestic wastewater. However, the substrate thickness in these systems has so far only been selected within acceptable limits, without optimization under the specific environmental and plant growth conditions in Vietnam.

To address this gap, the present study investigates the impact of substrate layer thickness on the performance of WR systems planted with *Portulaca grandiflora*. The objective is to optimize the substrate structure to enhance the treatment efficiency of WR models for domestic wastewater.

2. Materials and methods

2.1. Research Materials

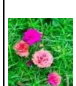
Wastewater: The wastewater was collected from the effluent tank of the wastewater treatment system at the Prosper Plaza residential complex, located in Tan Thoi Nhat Ward, District 12. The characteristics and composition of the wastewater are presented in Table 2.

Table 2. *Characteristics and Composition of Domestic Wastewater*

No.	Parameter	Unit	Value	QCVN 14:2025/BTNMT [7]	
				A	B
1	pH	–	7.6 ± 0.3	5–9	5–9
2	BOD_5	mg/L	145 ± 5	≤ 30	≤ 35
3	COD	mg/L	220 ± 20	≤ 80	≤ 90
4	TN	mg/L	48 ± 5	≤ 25	≤ 30
5	TP	mg/L	6 ± 2	≤ 4	≤ 6
6	Coliform	MPN/100 mL	$10^4 \pm 10^3$	≤ 3000	≤ 5000

Plants Used: According to the study [6], the *Portulaca grandiflora* model demonstrates high efficiency in treating domestic wastewater. Therefore, the plant used in this research is *Portulaca grandiflora*, with its characteristics and planting method shown in Table 3.

Table 3. *Characteristics and planting method of Portulaca grandiflora in the WR model*

Scientific Name	Family	Morphological Characteristics	Planting Density	Planting Method	Image
Portulaca grandiflora	Purslane (Portulaceae)	Herbaceous plant; succulent, small stem, many branches. Fast growth rate. Sun-loving species, easily propagated by stem cuttings.	35 plants.m^{-2}	Direct planting into the substrate layer	

2.2. Research methods

2.2.1. Research model

The research model was established in the laboratory, consisting of four experimental units, each with dimensions of L×W×H = 1.0×0.15×0.35 m.

The substrate of the WR system consisted of five layers: A – Stone layer (10–20 mm), B – Gravel layer (5–10 mm), C – Sand layer (0.5–2.0 mm), D – Clay layer (< 2.0 mm), and E – Substrate layer (0.1–2.0 mm) composed of sandy loam for plant growth, as shown in Figure 3. The stone, gravel, and sand were purchased from local construction material suppliers in Ho Chi Minh City and washed prior to use, while the soil materials were collected from local planting soil in the same area. The overall porosity of the substrate system was approximately 25%, representing the average porosity of the combined media.

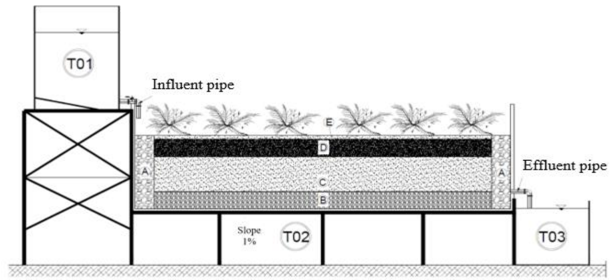


Figure 2. *Layout plan of the WR model for planting Portulaca grandiflora*

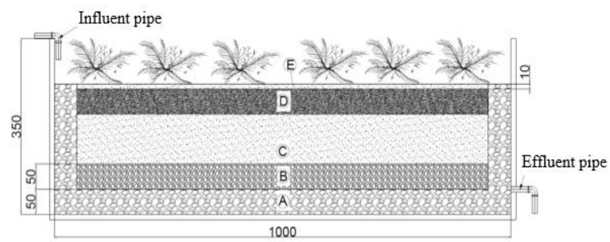


Figure 3. *Layer structure of materials used in the WR model*

E – Substrate layer; D – Clay layer; C – Sand layer; B – Gravel layer; A – Stone layer

The system operates under a Horizontal Subsurface Flow (HSF) configuration, as maintaining the water flow beneath the surface of the substrate minimizes the risks associated with odors and the proliferation of infectious organisms [6].

The system was operated under natural outdoor conditions in Ho Chi Minh City, Vietnam, characterized by a tropical climate with average temperatures of 27–32°C and relative humidity of 70–85%.

2.2.2. Model operation

The WR system was operated through three sequential experiments to evaluate the effects of substrate configuration and assess effluent reuse potential.

a. Experiment 1: Evaluating the effect of soil depth on treatment efficiency

After acclimation, the system was operated at 1 $L.h^{-1}$ with soil layer thicknesses of 0, 20, and 40 mm. The 0 mm case served as a control. This range represents typical substrate depths used in extensive green roof systems.

b. Experiment 2: Evaluating the effect of sand layer height on treatment efficiency

Based on the optimal soil thickness obtained from Experiment 1, the sand layer was varied at 80, 100, and 120 mm under identical conditions to evaluate the effect of filtration depth on treatment performance. These values were selected based on previous studies on CWs, where media depth influences hydraulic retention and microbial processes [11, 12]. The substrate configuration was designed to create a stratified system, in which the soil layer acts as a reactive zone, while the sand layer provides filtration and aerobic conditions. The operational parameters for this experiment are also summarized in Table 4.

***Table 4.** Operational parameters for experiments 1 and 2*

No.	Parameter	Unit	Experiment 1	Experiment 2
1	Soil layer height	mm	0 – 20 – 40	Results from exp. 1
2	Sand layer height	mm	100	80 – 100 – 120
3	Flow rate (Q)	$L.h^{-1}$	Adaptation: 0.45, Operating: 0.57	
4	HRT	Hours	14 – 15.3 – 16.6	11 – 12.1 – 13.1
5	Organic loading rate (Lorg)	kg COD. $ha^{-1}.day^{-1}$	Adaptation: 200, Operating: 250	
6	Domestic wastewater	-	Composition and properties are shown in Table 2	

c. Experiment 3: Preliminary evaluation of wastewater reuse potential after treatment

The optimal configuration obtained from Experiments 1 and 2 (soil and sand layer thicknesses) was further evaluated at an organic loading rate of 300 ± 20 kg $COD.ha^{-1}.day^{-1}$. The system was operated at a flow rate of 0.68 $L.h^{-1}$, corresponding to a hydraulic retention time (HRT) of approximately 10 h. Domestic wastewater characteristics were consistent with those presented in Table 2. This experiment aimed to assess system robustness and the potential for wastewater reuse under higher loading conditions.

The organic loading rates (OLRs) of 250 and 300 kg $COD.ha^{-1}.day^{-1}$ were selected based on typical ranges reported for CWs treating domestic wastewater (100–400 kg $COD.ha^{-1}.day^{-1}$) [1, 12]. In this study, 250 kg $COD.ha^{-1}.day^{-1}$ was applied in Experiments 1 and 2 to represent stable operating conditions, while 300 kg $COD\cdot ha^{-1}\cdot day^{-1}$ was used in Experiment 3 to evaluate system performance under higher loading conditions.

***Table 5.** Reuse Water applications based on the required quality of reuse water [8]*

No.	Required water quality	Reuse water applications	Treatment water quality requirements
1	Low	Irrigation for plants, parks; Cleaning of machinery and equipment; Cooling water for industry; Construction services	BOD_5 < 30 mg/L; Turbidity < 5 NTU; Cl_2 dư < 1 mg/L; pH = 5.8 – 8.6
2	Medium	Toilet flushing; Road watering; Firefighting; Recreational activities, landscape restoration	BOD_5 < 20 mg/; Turbidity < 2 NTU; Residual chlorine < 1 mg/L; pH = 5.8 – 8.6; Color < 20 Pt-Co; TN < 15 mg/L; TP < 4 mg/L.
3	High	Groundwater recharge; Washing and bathing water	BOD_5 < 10 mg/; Turbidity < 2 NTU; Residual chlorine < 0,5 mg/L; pH = 5.8 – 8.6; Color < 15 Pt-Co; TN < 10 mg/L; TP < 4 mg/L

Selected reuse water applications: The choice of potential reuse applications is based on the quality of the treated water. The quality of the treated water is categorized into three levels: low, medium, and high, as shown in Table 5.

2.3. Analytical Methods

The parameters were analyzed using methods outlined in the *Standard Methods for the Examination of Water and Wastewater* [9] for Experiments 1, 2, and 3. Samples were collected from the inlet and outlet of the system once per day for the analysis of COD, TN, and TP, while pH was measured in situ.

Statistical analysis was performed using one-way analysis of variance (ANOVA) to evaluate the significance of differences among experimental conditions. The level of significance was set at $p < 0.05$. All data are presented as mean ± standard deviation (SD) based on triplicate measurements.

3. Results and discussion

3.1. Influence of soil layer height on treatment efficiency

The effect of soil layer thickness on COD, TN, and TP removal is presented in Figures 4–6.

As shown in Figure 4, COD removal increased from 70.00 ± 2.50% (0 mm) to 85.18 ± 1.11% (20 mm) and 86.19 ± 1.36% (40 mm), corresponding to effluent concentrations of 33.55 ± 2.2 mg/L and 33.0 ± 3.6 mg/L, respectively. This substantial improvement indicates that the introduction of a soil layer significantly enhances organic matter removal.

This observation is consistent with previous studies reporting COD removal efficiencies of 70–85% in CWs using reactive substrates [10, 12]. The improvement can be attributed to enhanced filtration, adsorption onto soil particles, and increased microbial activity supported by biofilm development.

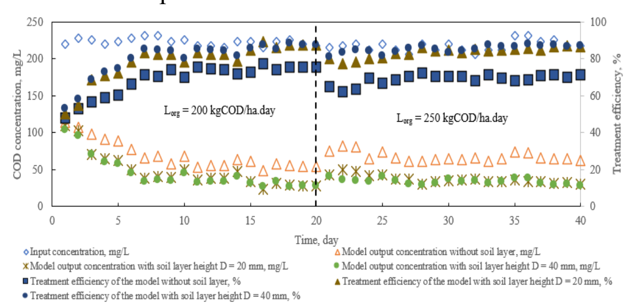


***Figure 4.** Variation in COD concentration and treatment efficiency in the WR model with different topsoil layer thicknesses*

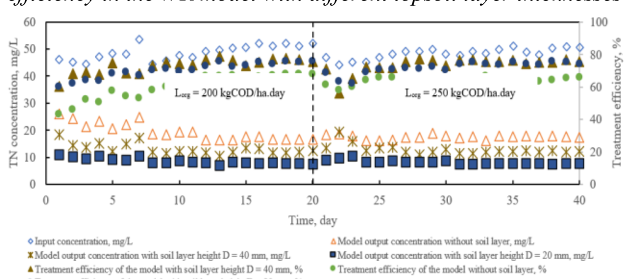


***Figure 5.** Variation in TN concentration and treatment efficiency in the WR model with different topsoil layer thicknesses*

As illustrated in Figure 5, TN removal increased from 64.24 ± 2.10% (0 mm) to 74.13 ± 1.27% (20 mm) and 75.42 ± 1.18% (40 mm), with effluent concentrations decreasing from approximately 18.5 ± 1.5 mg/L to 12.3 ± 1.1 mg/L and 11.8 ± 1.3 mg/L, respectively. These values are consistent with reported TN removal efficiencies of 60–75% in subsurface flow systems [11].

The enhancement in nitrogen removal can be explained by the role of the soil layer in supporting coupled nitrification–denitrification processes. The soil provides adsorption sites for ammonium and supplies organic carbon that facilitates denitrification. In addition, *Portulaca grandiflora* contributes to oxygen transfer in the rhizosphere, promoting nitrification and improving nitrogen transformation efficiency.

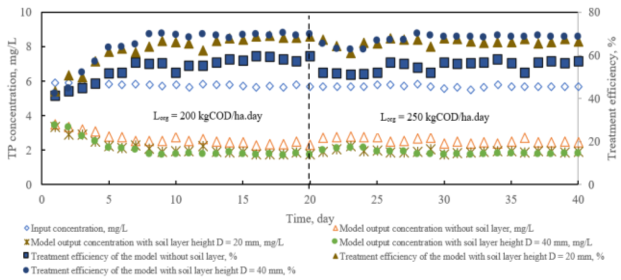


Figure 6. *Variation in TP concentration and treatment efficiency in the WR model with different topsoil layer thicknesses*

As shown in Figure 6, TP removal increased from 60.00 ± 2.00% (0 mm) to 65.69 ± 0.86% (20 mm) and 68.65 ± 1.12% (40 mm), corresponding to effluent concentrations of 3.2 ± 0.3 mg/L and 2.9 ± 0.4 mg/L, respectively. These values fall within the commonly reported range of 40–70% for phosphorus removal in CWs [11, 12], where adsorption and precipitation are the dominant mechanisms.

Although increasing soil thickness from 20 mm to 40 mm resulted in slight improvements, the increases in removal efficiency were minimal and not statistically significant ($p > 0.05$, ranging from 0.15 to 0.22). Specifically, COD removal increased from 85.18% to 86.19%, TN from 74.13% to 75.42%, and TP from 65.69% to 68.65%, indicating only marginal gains.

Similar diminishing returns have been reported in previous studies, where increasing substrate depth beyond an optimal level does not proportionally improve treatment efficiency [12]. Therefore, a soil thickness of 20 mm is considered optimal.

3.2. Influence of sand layer height on treatment efficiency

The experiment investigating the influence of the sand layer height was conducted using a model with a fixed soil layer height of 20 mm - selected based on previous experimental results evaluating the effect of soil layer height on treatment performance. In this study, the sand layer height was varied at 80 mm, 100 mm, and 120 mm, respectively. The system was first acclimated at a loading rate of 200 kgCOD.ha^{-1}.day^{-1} and subsequently operated at a loading rate of 250 kgCOD.ha^{-1}.day^{-1}.

As shown in Figure 7, COD removal increased from 79.9 ± 2.2% at 80 mm to 84.63 ± 1.53% at 100 mm and 86.47 ± 2.8% at 120 mm, indicating that increasing sand depth improves organic matter removal. This trend suggests that a thicker sand layer enhances physical filtration and prolongs the contact time between wastewater and microbial biofilms attached to the media surface.

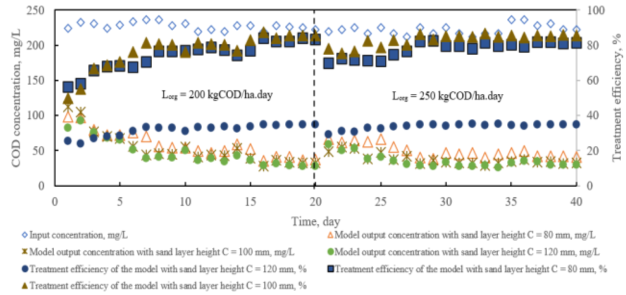


Figure 7. *Variation in COD Concentration and Removal Efficiency in the WR model with different sand layer heights*

The high removal of COD and coliforms further indicates the development of a well-established microbial community within the porous substrate. The sand layer acts as both a mechanical filter and a biofilm carrier, where coliform removal is mainly attributed to physical straining, adsorption onto sand particles, and inactivation within biofilms. This combination of filtration and biological processes contributes to improved pathogen removal efficiency.

A similar pattern was observed for nitrogen removal. As illustrated in Figure 8, TN removal increased from 67.5 ± 2.1% (80 mm) to 73.5 ± 1.7% (100 mm) and 75.31 ± 1.18% (120 mm), with effluent concentrations decreasing from approximately 14.8 mg/L to 12.1 mg/L and 11.5 mg/L, respectively. The improved nitrogen removal can be attributed to enhanced nitrification under improved oxygen transfer conditions within the sand layer. The porous structure of sand facilitates air diffusion and supports the development of aerobic microzones, which are essential for ammonium oxidation [13].

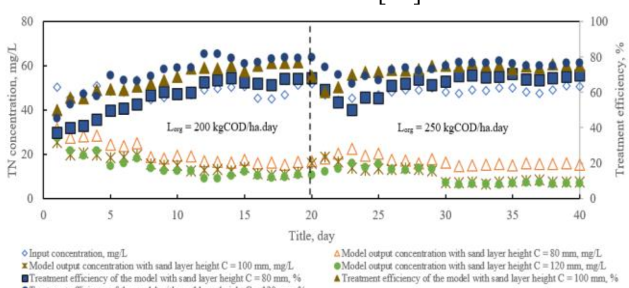


Figure 8. *Variation in TN concentration and removal efficiency in the WR model with different sand layer heights*

In contrast, phosphorus removal showed a more moderate increase. In the stabilized phase (day 25–40), under a loading rate of 250 kgCOD.ha^{-1}.day^{-1}, TP removal increased from 65.00 ± 2.10% (80 mm) to 67.35 ± 1.05% (100 mm) and 68.40 ± 1.12% (120 mm), corresponding to effluent concentrations of 3.4 ± 0.4 mg/L, 3.1 ± 0.3 mg/L, and 2.9 ± 0.4 mg/L, respectively (Figure 9).

This limited improvement indicates that phosphorus removal is less sensitive to changes in sand thickness, as it is primarily governed by physicochemical processes rather than biological activity. The observed variation can be explained by three main mechanisms: (1) increased adsorption capacity associated with longer hydraulic retention time in thicker sand layers; (2) enhanced contact between wastewater and media surfaces, promoting phosphorus retention; and (3) chemical precipitation with metal ions (e.g., Fe^{3+} and Al^{3+}) present in the substrate.

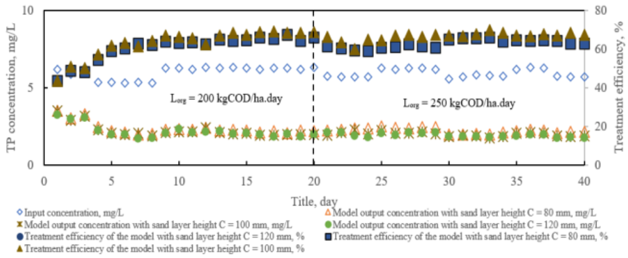


Figure 9. *Variation in TP concentration and removal efficiency in the WR model with different sand layer heights*

The observed trends are consistent with previous studies, which report that increasing media depth enhances treatment performance by improving hydraulic retention time and providing a larger surface area for microbial colonization [12]. Additionally, deeper media layers contribute to more stable flow distribution and reduce short-circuiting effects, thereby improving overall treatment efficiency. However, similar to findings reported by [14], the performance gain becomes less pronounced beyond a certain depth.

In this study, the differences between the 100 mm and 120 mm configurations were small for all parameters and not statistically significant ($p > 0.05$ across all parameters), indicating diminishing returns. Therefore, increasing sand thickness beyond 100 mm leads to higher material consumption and system weight without a proportional improvement in treatment efficiency.

From a design perspective, the sand layer plays a dual role in filtration and oxygen transfer. While increasing thickness improves treatment performance, excessive depth may reduce cost efficiency and complicate system construction. Therefore, a sand thickness of 100 mm is identified as the optimal configuration, providing a balance between treatment efficiency and practical feasibility.

3.3. Integrated performance, environmental considerations, and system sustainability

The overall performance of the optimized configuration is synthesized from the results presented in Figures 4–9.

The system with a 20 mm soil layer and a 100 mm sand layer achieved high removal efficiencies of 86.19 ± 1.36% for COD, 75.42 ± 1.18% for TN, and 68.65 ± 1.12% for TP, corresponding to effluent concentrations of 33.0 ± 3.6 mg/L COD, 12.3 ± 1.1 mg/L TN, and 3.0 ± 0.4 mg/L TP. These results demonstrate that substrate integration plays a key role in stabilizing treatment performance through complementary functions, where the soil layer provides adsorption and supports denitrification, while the sand layer enhances filtration and oxygen transfer. This vertical stratification promotes sequential aerobic and anoxic processes, consistent with established mechanisms in CWs [12].

In addition to substrate effects, *Portulaca grandiflora* contributes to system performance through nutrient uptake, root exudates, and oxygen transfer into the rhizosphere, supporting stable microbial activity. The system achieved 75.42% TN and 68.61% TP removal, highlighting effective plant–microbe interactions. Compared to conventional species such as *Phragmites australis* and *Typha latifolia* [12], *P. grandiflora* is better adapted to shallow WR conditions. Its dense root system and rapid growth enhance rhizosphere processes, thereby contributing to improved nutrient removal, consistent with previous findings [15].

WR systems differ from conventional horizontal or vertical flow wetlands by operating with much shallower substrates, resulting in shorter hydraulic retention time (HRT) but enhanced oxygen transfer due to direct atmospheric exposure. In contrast, traditional gravel-based systems rely on deeper media with more limited oxygen diffusion. This configuration aligns with recent green roof and nature-based solution (NBS) approaches, where optimized shallow substrates can achieve comparable treatment performance while reducing system footprint.

Environmental conditions also influenced system performance. The experiments were conducted under dry-season temperatures (27–32 °C), which favor plant and microbial activity, resulting in stable treatment efficiency. However, under wet-season conditions, increased hydraulic loading and reduced solar radiation may limit performance, particularly for *P. grandiflora*, which is adapted to high light conditions.

From a long-term perspective, the use of fine media may lead to clogging due to solids accumulation and biofilm growth, potentially reducing hydraulic performance. Therefore, periodic maintenance, such as surface cleaning or partial media replacement, is recommended to ensure long-term stability.

Overall, the results demonstrate that optimizing substrate configuration, together with plant–microbe interactions, is essential for achieving efficient and stable wastewater treatment in WR systems.

3.4. Reuse potential and economic considerations

Based on the optimal substrate configurations determined in Experiments 1 and 2 - specifically a 20 mm soil layer and a 100 mm sand layer - the WR model was operated under an organic loading rate of 300 $kgCOD.ha^{-1}.day^{-1}$. The system maintained stable performance, as summarized in Table 6.

Removal efficiencies reached 85.37% for COD, 75.46% for TN, and 68.01% for TP, corresponding to effluent concentrations of approximately 31–35 mg/L COD, 11–13 mg/L TN, and 2.8–3.2 mg/L TP.

These results demonstrate the robustness of the system under increased loading and highlight its suitability for non-potable reuse applications. As shown in Table 6, the effluent quality meets ISO 16075-2:2020 guidelines for restricted irrigation [16], particularly in terms of BOD_5 and coliform concentrations, supporting its application for uses such as irrigation and toilet flushing.

In addition to treatment performance, the economic feasibility of the WR system was evaluated under different substrate configurations. As shown in Table 7, reducing the soil layer from 40 mm to 20 mm and the sand layer from 120 mm to 100 mm decreased the substrate volume from 0.16 to 0.12 m^3/m^2, leading to a reduction in capital cost from 18.0 to 12.5 USD/m^2 (30.6%). This reduction is mainly attributed to lower material consumption, while maintaining comparable treatment efficiency.

Table 6. *Performance of the WR system and comparison with water reuse standards*

Parameter	pH	COD	BOD_5	TN	TP	Coliform
Unit	-	$mg.L^{-1}$	$mg.L^{-1}$	$mg.L^{-1}$	$mg.L^{-1}$	CFU/100 mL
Influent Concentration	7.6 ± 0.3	207.28 ± 6.48	145.87 ± 5.82	49.07 ± 2.64	5.72 ± 0.16	10,000 ± 200
Effluent Concentration	-	31.32 ± 3.92	18.79 ± 2.72	12.04 ± 0.96	1.83 ± 0.11	180 ± 20
Removal Efficiency (%)	-	85.37 ± 1.89	87.11 ± 1.59	75.46 ± 2.01	68.01 ± 1.91	98.2 ± 0.9
Low Standard	-	-	< 30			-
Medium Standard	-	-	< 20	< 15	< 4	-
High Standard	-	-	< 10	< 10	< 4	-
ISO 16075-2:2020 (restricted irrigation)	-	-	< 25	-	-	< 1000

Table 7. *Estimated capital cost of WR systems under different substrate configurations*

Configuration	Soil thickness (mm)	Sand thickness (mm)	Material volume (m^3/m^2)	Capital cost (USD/m^2)	Cost reduction (%)
Conventional	40	120	0.16	18.0	–
Optimized	20	100	0.12	12.5	30.6

The cost estimation was based on local construction conditions in Ho Chi Minh City and includes material, transportation, and installation costs. Since the stone and gravel layers were unchanged, the cost difference is primarily related to soil and sand thickness.

From an operational perspective, the system requires minimal energy input due to the absence of mechanical aeration and pumping, resulting in lower operating costs than conventional systems. Maintenance is limited to periodic management of clogging in fine media layers.

Overall, the WR system offers a cost-efficient and sustainable solution for decentralized wastewater treatment.

4. Conclusion

The findings of this study demonstrate that the WR system planted with Portulaca grandiflora is effective for treating domestic wastewater. Optimizing substrate configuration enhances treatment performance while improving economic feasibility for real-world applications. The optimal design, consisting of a 20 mm clay loam soil layer and a 100 mm coarse sand layer, provides stable treatment efficiency and cost-effectiveness. This configuration is well-suited for decentralized wastewater treatment, particularly in systems that prioritize sustainability and landscape integration.

At an organic loading rate of 300 ± 10 kg $COD.ha^{-1}.day^{-1}$, the system achieved removal efficiencies of 85.37 ± 1.20% (COD), 75.46 ± 1.10% (TN), and 68.01 ± 1.05% (TP), and 98.2% for coliforms. The corresponding effluent concentrations were 30.4 ± 2.0 mg/L (COD), 12.0 ± 1.0 mg/L (TN), 1.83 ± 0.11 mg/L (TP), and 180 CFU/100 mL (coliforms). These results indicate that the treated wastewater meets the requirements for low- to medium-quality reuse and complies with ISO 16075 guidelines for restricted irrigation, particularly in terms of BOD_5 and coliform concentrations. Therefore, the effluent is suitable for non-potable applications such as irrigation and toilet flushing.

In addition, substrate optimization reduced capital cost by 30.6% (12.5 USD/m^2). However, the system was evaluated under dry-season conditions, and its performance under wet-season conditions should be further evaluated.

REFERENCES

[1] V. T. D. Hien, *"Application of Wetland Roof for Domestic Wastewater Treatment"*, Master's thesis, Ho Chi Minh City University of Technology, Ho Chi Minh City, Vietnam, 2011.

[2] I. Blumberg, "Wetland roofs, a versatile and innovative type of green roof", *Blumberg Engineers*, [Online]. Available: https://www.blumberg-engineers.com/en/ecotechnologies/wetland-roofs/ [Accessed Jan. 01, 2026].

[3] J. C. Berndtsson, "Green roof performance towards management of runoff water quantity and quality: A review", *Ecological Engineering*, vol. 36, no. 4, pp. 351–360, 2010. https://doi.org/10.1016/j.ecoleng.2009.12.014

[4] J. C. Berndtsson, L. Bengtsson, and K. Jinno, "Runoff water quality from intensive and extensive vegetated roofs", *Ecological Engineering*, vol. 35, no. 3, pp. 369–380, 2009. https://doi.org/10.1016/j.ecoleng.2008.09.020

[5] J. F. Li *et al.*, "Effect of green roof on ambient CO_2 concentration", *Building and Environment*, vol. 45, no. 12, pp. 2644-2651, 2010. https://doi.org/10.1016/j.buildenv.2010.05.025

[6] P. N. Hoa, "Research on application of constructed wetland technology using green roof (GR) plants for recycling living waste water", *The University of Danang - Journal of Science and Technology*, vol. 5, no. 126.1, pp. 50-53, 2018. https://jst-ud.vn/jst-ud/article/view/429

[7] Ministry of Natural Resources and Environment (MONRE), *National technical regulation on domestic and municipal wastewater*, QCVN 14:2025/BTNMT, 2025.

[8] N. P. Dan *et al.*, *"Research on reuse of domestic wastewater for treatment in Ho Chi Minh city"*, research project report, Ho Chi Minh City Department of Science and Technology, Ho Chi Minh City, Vietnam, 2010.

[9] APHA, AWWA, and WPCF, *Standard methods for the examination of Water and Waste water*, 20th edition. American Public Health Association, 2012.

[10] S. Kumar, I. Takashi, K. Kato, H. Ietsugu, K. Tomita, and T. Nagasawa, "Seasonal efficiency of a hybrid sub-surface flow constructed wetland system in treating milking parlor wastewater at northern Hokkaido", *Ecological Engineering*, vol. 53, pp. 257-266, 2013. https://doi.org/10.1016/j.ecoleng.2012.12.054

[11] L. Zhang, K. B. S. N. Jinadasa, R. M. Gersberg, Y. Liu, S. K. Tan, and W. J. Ng, "Application of constructed wetlands for wastewater treatment in tropical and subtropical regions (2000-2013)", *Journal of Environmental Sciences*, vol. 30, pp. 30-46, 2015. https://doi.org/10.1016/j.jes.2014.10.013

[12] J. Vymazal, "Emergent plants used in free water surface constructed wetlands: A review", *Ecological Engineering*, vol. 61, pp. 582-592, 2013. https://doi.org/10.1016/j.ecoleng.2013.06.023

[13] Y. Zhang, Y. C. Gong, C. T. Chen, L. S. Zhou, and D. Fu, "Performance and influencing factors of vertical hybrid constructed wetland in treating domestic sewage", *Applied Ecology and Environmental Research*, vol. 22, no. 5, pp. 4525-4539, 2024. http://dx.doi.org/10.15666/aeer/2205_45254539

[14] S. Y. Wang, Y. F. Teng, F. K. Cheng, and X. W. Lu, "Application potential of constructed wetlands on different operation mode for biologically pre-treatment of rural domestic wastewater", *Sustainability*, vol. 15, no. 3, p. 1799, 2023. https://doi.org/10.3390/su15031799

[15] J. Li *et al.*, "The use of constructed wetland for mitigating nitrogen and phosphorus from agricultural runoff: A review", *Water*, vol. 13, no. 4, p. 476, 2021. https://doi.org/10.3390/w13040476

[16] International Organization for Standardization (ISO), "*ISO 16075-2:2020 – Guidelines for treated wastewater use for irrigation – Part 2: Development of the project*", Geneva, Switzerland, 2020.