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Combining flowform cascade with constructed wetland to enhance domestic wastewater treatment

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A R T I C L E I N F O

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A B S T R A C T

This study reports the performance of a new combined flowform cascade (FC) and constructed wetland (CW) system to enhance nitrogen removal and biological degradation of urban wastewater. A series of 8 FC units at the flow rate of 200 L/h could markedly increase the dissolved oxygen level in the wastewater from the initial value of 0.2 mg/L to 5.6 mg/L, thus providing suitable aerobic condition in the front zone of the CW for nitrification and biodegradation of organic contaminants. The results demonstrate that the combined FC/CW system could achieve the sequence of aerobic and anoxic conditions for nitrification and denitrification, respectively. By using a series of FC units for aeration, the CW system could enhance the removal of total nitrogen from 49.4% to 71.2% and biochemical oxygen demand from 80.9% to 86.1% when the hydraulic loading rate was 31.25 $m^3/m^2 \cdot$day. On the other hand, the FC units exerted negligible effects on the phosphate and total suspended solid removals of the CW system. Thus, the combined FC/CW process exhibited phosphate and total suspended solid removals comparable to those of the CW alone.

1. Introduction

Direct discharge of domestic wastewater into natural water bodies is a major environmental and health issue in many parts of the world (Cao et al., 2022; Rout et al., 2021; Al-Ajalin et al., 2020). In developing countries, due to unplanned urban sprawling and lack of infrastructure, water bodies such as open canals, rivers, and lakes in the city have become part of the sewer network to convey domestic wastewater to centralized treatment facilities (Pham and kuyama, 2013). Thus, there is an urgent need to develop and optimize pollution abatement technologies that can be integrated to existing water bodies for deployment in densely populated areas.

Constructed wetland (CW) has been successfully applied for treatment of contaminated water in many locations around the world (Parde et al., 2021; Yang et al., 2021; Jizheng et al., 2019). Previous research has demonstrated CW as a robust, reliable, cost-effective, and environmentally friendly technology that can be integrated with natural water bodies for

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treating storm water and low strength domestic wastewater (Cao et al., 2022; Jehawi et al., 2020). CW can be used to remove a range of water contaminants including organic matter, suspended solids, pathogens, and nutrients via biological degradation, absorption to the root zone, and nutrient uptake by plants (Jehawi et al., 2020; Liu et al., 2019; Zhou et al., 2018; Huang et al., 2017). However, as a passive treatment technology, CW treatment performance is often low and highly variable (Zhou et al., 2018; Lu et al., 2020; Yu et al., 2019; Du et al., 2018). For example, the pilot-scale CW treatment of secondary effluents demonstrated in Thalla et al. (2019) exhibited removals of biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonia (NH_4^+-N), nitrate (NO_3^--N), and phosphate (PO_4^{3-}-P) in the ranges of 77%–83%, 60%–65%, 67%–85%, 67%–60%, and 85%–90%, respectively.

The biodegradation and hence the removal of contaminants of a CW is directly governed by aerobic condition of the wastewater within the system. For example, nitrification and denitrification can only achieved under aerobic and anoxic conditions, respectively. In other words, regulating the dissolved oxygen (DO) content of the wastewater is essential to achieve effective nitrogen removal by a CW system (Jizheng et al., 2019; Song et al., 2021; Nguyen et al., 2021). Before entering the CW, due to biological degradation, domestic wastewater is already depleted of oxygen. Therefore, current CW process for domestic wastewater treatment is dominated by the anaerobic condition, and hence exhibits limited nitrogen removal (Rout et al., 2021; Jehawi et al., 2020; Lu et al., 2020; Nguyen et al., 2021; Al-Zreiqat et al., 2018).

Recent studies on the CW treatment of domestic wastewater have centred on improving design/configuration and operation strategies for enhanced removal of nitrogen and other contaminants. Most notably, Vega De Lille et al. (2021) investigated the effect of recirculation strategies on nitrogen removal of a hybrid horizontal flow/vertical flow CW process during the treatment of a raw domestic wastewater. The hybrid CW process when operating under single-pass mode could remove >92% of organic matter, 88% total suspended solid, and 99% of pathogens, but exhibited a limited total nitrogen removal of only 66% (Vega De Lille et al., 2021). When operating under recirculation strategies to exploit the enhanced nitrification, the CW process achieved a markedly higher total nitrogen removal (i.e., up to 97%) (Vega De Lille et al., 2021). Jehawi et al. (2020) proposed a novel tidal constructed CW wastewater treatment process for enhanced nitrogen removal. The tidal constructed CW system allowed for alternating wet and dry operations and incorporated porous zeolite and pyrite into the substrates to facilitate the nitrification and denitrification processes, hence eventually enhancing the total nitrogen removal (up to 78%) (Jehawi et al., 2020). In another study, Li et al. (2014) proved that the combination of artificial aeration and step-feeding helped maintain adequate DO levels for nitrification and the anoxic condition required for denitrification during the CW process, thus greatly improving the nitrogen removal. Many other studies have also highlighted the importance of the design/configuration and operational optimization on enhancing the nitrification/denitrification and hence the contaminant removals (i.e., particularly nitrogen removal) of the CW process (Zhou et al., 2018; Huang et al., 2017; Al-Zreiqat et al., 2018; Sethulekshmi and Chakraborty, 2021; Jácome et al., 2016; Çakir et al., 2015).

This study aims to demonstrate a simple method to improve the treatment efficiency and contaminant removals of the CW process of domestic wastewater by combining CW with a flowform cascade (FC) system. Indeed, FC systems have been proposed as a cost-effective and environmentally friendly aeration method prior to wastewater treatment by stabilization ponds or CW (Ung et al., 2020; Mahapatra et al., 2013). FC systems rely on the swirls of vortices of the fluid to enhance oxygenation, thus they require much less energy and equipment as compared to other aeration methods such as air pump and artificial aeration. The hypothesis of this study is that in the combined FC/CW process, the FC system helps raise the domestic wastewater DO level and hence underpin the aerobic condition during the subsequent treatment in the CW process. By manipulating the operating conditions, both nitrification and denitrification occur in the CW process, thus enhancing the treatment of nitrogen and other contaminants (Lu et al., 2020). Given this hypothesis, in this study the effects of the FC system and the CW operating conditions on the DO level distribution along the CW process and its overall treatment efficiency and contaminant removals are systematically evaluated.

2. Materials and methods

2.1. Materials

The combined FC/WC system in this study is shown in Fig. 1. The flowform step (Fig. 1C) was made of green plastic to generate a turbulent flow and allow the water to cascade by gravity to the next step (Ung et al., 2020), thus promoting the dispersion of oxygen from air into the wastewater. In this study, the FC system consisted of up to 11 identical steps (i.e., each step had a height of 0.15 m), and a pump was used to transfer wastewater to the first FC step. The CW system was based on the horizontal subsurface flow configuration with effective length, width, and depth of 4.8 m, 1.2 m, and 0.8 m, respectively. The CW system had a 0.65 m-high porous media (i.e., porosity of 42%) which was consisted of crushed stone with nominal size of 20 mm. Water sampling points were uniformly allocated from the inlet to the outlet at 0.3 m from the bottom of the CW system as shown in Fig. 1D. *Cyperus involucratus* (i.e., known as umbrella plant) was used for the CW system. This is a reed-like plant with basal leaves and has been designated as a wetland indicator species. *Cyperus involucratus* has also been found in the natural ecosystem of Kim Lien Lake (Hanoi, Vietnam). An equalizing tank was placed between the FC and CW systems so that the FC flow rate and the CW hydraulic loading rate (HLR) could be independently regulated.

The wastewater tested in this study was from Kim Lien Lake, which is an urban lake receiving untreated domestic wastewater. Major characteristics of this wastewater are summarized in Table 1. Due to stormwater dilution and partial

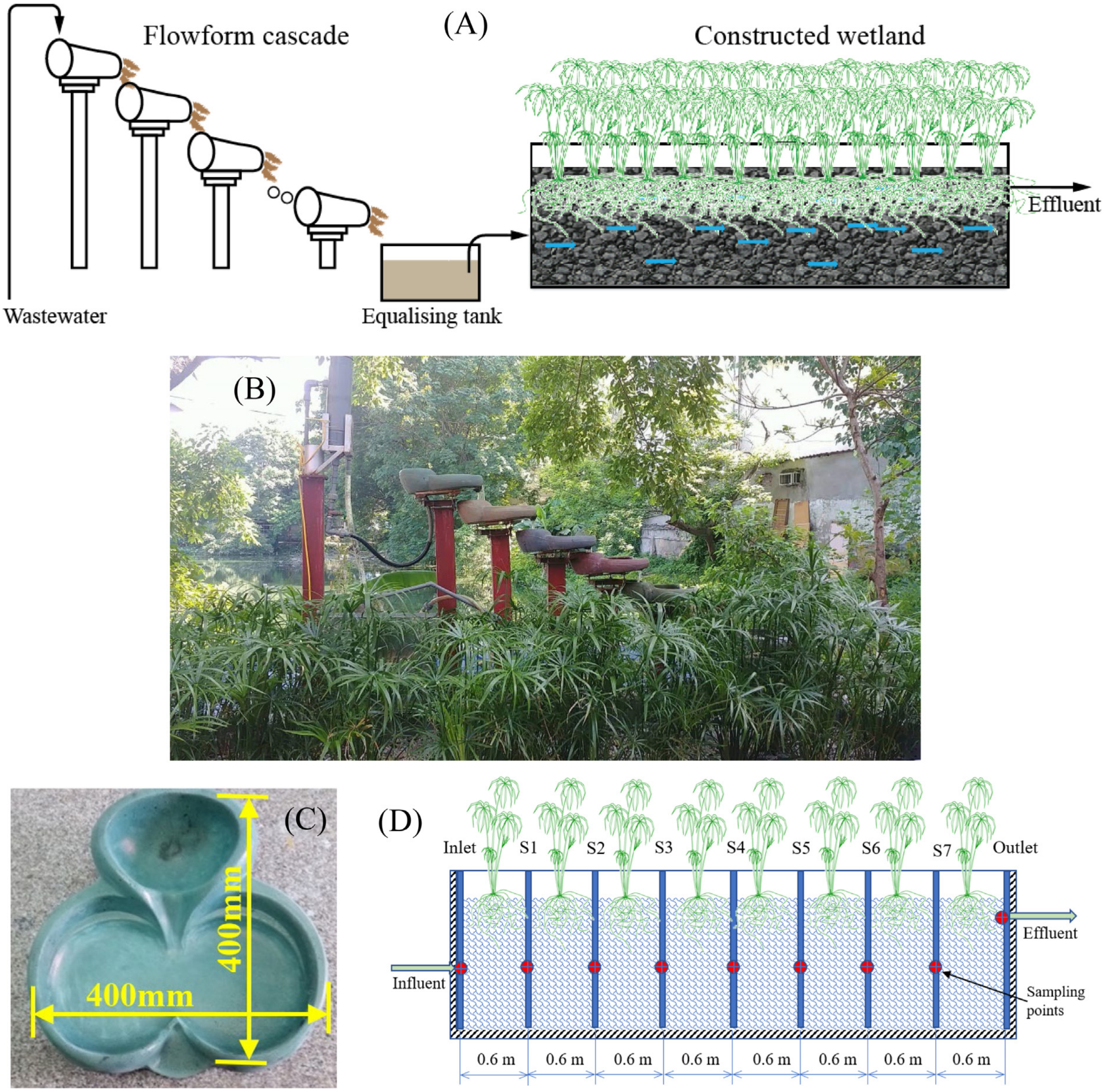

Fig. 1. (A) the schematic diagram and (B) the real photo of the combined FC/CW process for domestic wastewater treatment whereby the FC system is located prior to and acts as aeration for the CW process, (C) the real photo of a FC step, and (D) water sampling points along the CW system.

organic degradation, this wastewater has a low organic carbon content as evidenced by a low biochemical oxygen demand (BOD_5) value of 78.4 mg/L. The ammonia nitrogen and phosphate are, however, similar to those of medium strength wastewater (Table 1). The high nutrient content of this wastewater presents an unacceptable risk of eutrophication. Thus, according to the Vietnamese national technical regulation on domestic wastewater (i.e., QCVN 14:2008/BTNMT), this polluted wastewater would need to be treated to meet the requirement for environmental discharge.

2.2. Analytical methods

Major characteristics of water samples were determined using certified standards for water analysis. DO level was measured using a portable DO meter (Hanna HI 9142), while BOD_5, TSS, alkalinity, NH_4^+-N and PO_4^{3-} were measured using the ISO standards: 5815-1:2003, 11923:1997, 9963-1:1994, 7150-1:1984, and 6878:2004, respectively. NO_3^--N and TN were determined using the cadmium reduction method and persulfate/UV digestion procedure, respectively.

Table 1
Major characteristics of the wastewater collected at Kim Lien Lake in Hanoi.

Water characteristics	Value
Temperature (°C)	29.5 ± 1.8
pH	7.6 ± 0.4
Dissolved oxygen, DO (mg/L)	0.2 ± 0.1
Biochemical oxygen demand, BOD_5 (mg/L)	78.4 ± 7.1
Total nitrogen, TN (mg/L)	30.9 ± 3.9
Ammonia nitrogen, NH_4^+-N, (mg/L)	27.4 ± 4.2
Nitrate nitrogen, NO_3^--N, mg/L	0.4 ± 0.2
Alkalinity (mg/L)	187.0 ± 13.3
Phosphate, PO_4^{3-} (mg/L)	3.1 ± 1.0
Total suspended solid, TSS (mg/L)	75.1 ± 9.5

2.3. Operation of the FC and CW systems

The CW process for the domestic wastewater treatment was trialed at the shore of Kim Lien Lake with and without the FC system. When operating without the FC system, the wastewater was directly fed to the CW process, while with the FC system the wastewater was flowed through the FC steps and then to the equalizing tank before entering the CW process. The CW process was experimented at three hydraulic loading rates (HLR) of 31.25, 62.5, and 125 m^3/m^2·day, equivalent to hydraulic retention times of 8, 4, and 2 days, respectively. With each experiment, the CW process was stabilized for 14 days before water sampling and analysis were conducted. Water samples were taken in the morning of the 15th, 17th, 19th, and 21st day of the experimental trial, at 9 positions uniformly distributed along the CW system from the inlet to the outlet as demonstrated in Fig. 1D.

The FC system was operated at various flow rate, ranging from 100 L/h to 400 L/h to examine the effect of flow rate on raising the wastewater DO level before the CW process. During the FC system testing, the DO level of wastewater leaving each step was measured. The effectiveness of the FC system at enhancing the wastewater DO level was assessed using the oxygen transfer coefficient (E). This coefficient reflected the transfer of oxygen from air to the wastewater in the FC system, and it was calculated as below (Gulliver et al., 1990):

$$E = \frac{DO_a - DO_b}{DO_s - DO_b} \quad (1)$$

where DO_s was the saturated DO level of fresh water; DO_b and DO_a were the DO level in the wastewater before and after the FC system, respectively.

Overall contaminant removal of specific contaminants by the CW wastewater treatment process was calculated as below:

$$\text{Removal} = \left(\frac{C_r - C_e}{C_r}\right) \times 100\% \quad (2)$$

where C_r and C_e were contaminant (e.g., TN, BOD_5, PO_4^{3-}, TSS) concentrations in the raw wastewater and effluent (i.e., treated water), respectively.

3. Results and discussions

3.1. Influences of the FC system on the DO level of the wastewater

Prior to the FC system, the wastewater was almost depleted of oxygen with a DO level of 0.2 mg/L. After passing through the FC system (i.e., of 11 identical steps), DO level in the wastewater increased more than 22 times depending on the FC flow rate (Fig. 2). Of a particular note, at the flow rate of 200 L/h the DO level in the FC effluent reached the maximized value of 5.6 mg/L, which was 28-fold higher than that in the influent. Following this maximized value, the DO level in the FC effluent gradually decreased as the flow rate exceeded 200 L/h. The decreased DO level at the flow rate above 200 L/h could be attributed to the reduced hydraulic retention time of the wastewater in the FC system.

The increased DO level in the wastewater after passing through the FC system was attributed to the transfer of oxygen from the air into the wastewater induced by the FC system. According to Bayley and Prather (2003), the transfer and dispersion of oxygen into the wastewater stream are governed by molecular diffusion and turbulent mixing, both of which were facilitated by the FC system. Moreover, the turbulence of the fluid and its hydraulic retention time are regulated by the flow rate of the FC unit, resulting in the unit optimal flow rate of 200 L/h as discussed above. The calculated oxygen transfer coefficient (E) from the air to the wastewater stream throughout the FC system at the flow rate of 200 L/h using the Eq. (1) was 0.74. As shown in this equation, the E value of the wastewater approached unity when the DO level of the FC effluent equalled to the saturated DO level of fresh water. This low calculated E value indicates that the oxygen absorption capacity of the wastewater was far below that of fresh water due to the complex composition of the wastewater or/and the under performance of the FC unit.

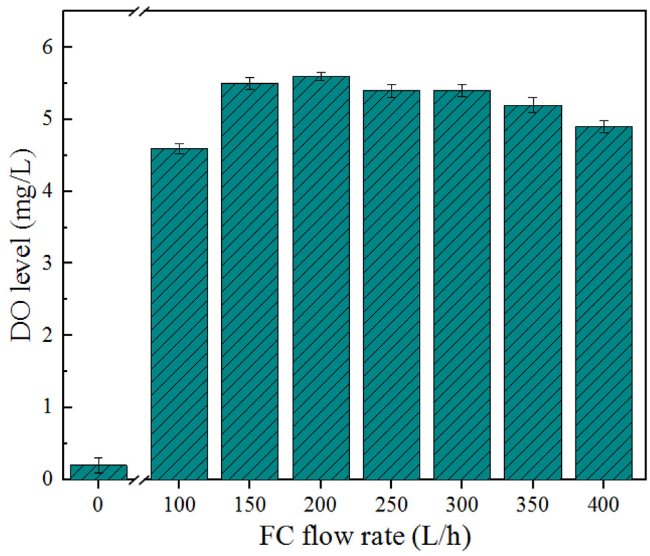

Fig. 2. DO levels in the FC effluent at various flow rates. The wastewater influent to the FC system (consisting of 11 steps) had DO level of 0.2 mg/L. Error bars represent the standard deviations of five replicated measurements.

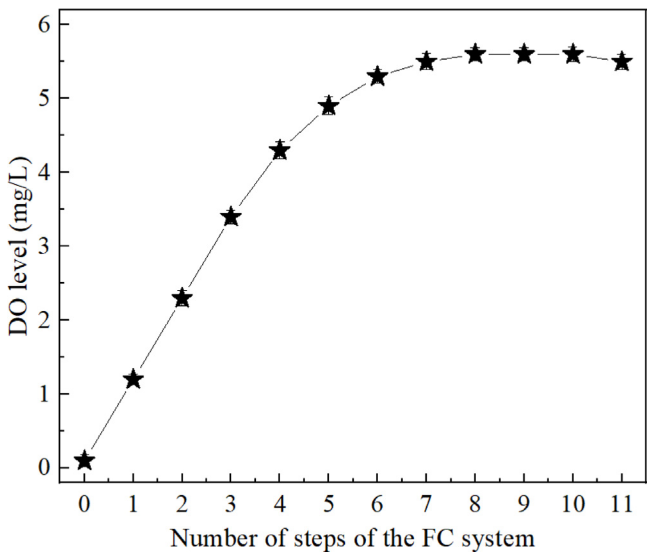

Fig. 3. DO level in the wastewater as it flowed along the FC system consisting of 11 steps at the flow rate of 200 L/h. The influent to the FC system had DO level of 0.2 mg/L. Error bars represent the standard deviations of five replicated measurements.

The measurements of the DO level in the wastewater along the FC system indicate that there existed an optimal number of FC steps with respect to increasing the wastewater DO content before CW treatment. As demonstrated in Fig. 3, the DO level linearly increased in the first five steps, then levelled off at 5.6 mg/L after the eighth step. It is noteworthy that the maximized DO level achieved by the FC system was also the saturated DO level of the wastewater. Thus, the low oxygen absorption capacity of the wastewater treated in the FC unit could be attributed to its complex and high organic content.

3.2. Treatment efficiency of the CW process with the domestic wastewater

3.2.1. The wastewater DO level distribution and contaminant treatment along the CW process

The distribution of the wastewater DO level inside the CW system was dependent on the hydraulic loading rate (HLR) and the FC system (Fig. 4). When combined with the FC system of 8 steps, the DO level at the inlet of the CW system was elevated to about 5.6 mg/L. Along the CW system, the DO level in the wastewater decreased at various rates depending on the operating HLR. The decreased DO level in the wastewater reflected the conditions under which the decomposition

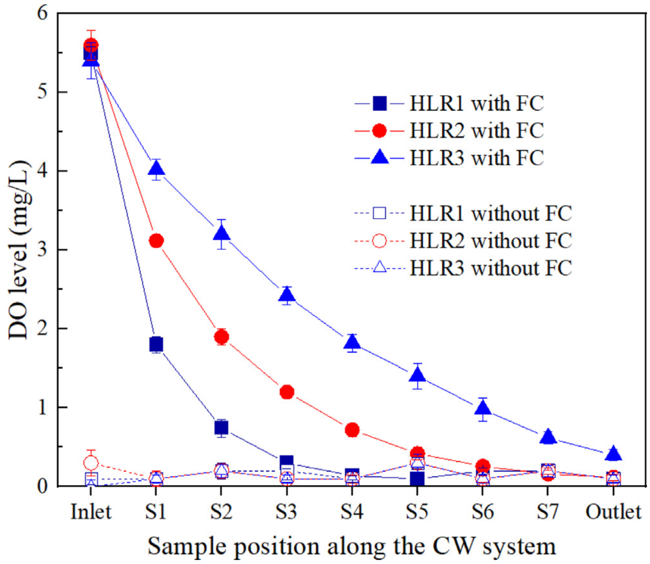

Fig. 4. DO level along the CW system from the inlet to outlet with and without FC aeration during the treatment of the domestic wastewater at three different hydraulic loading rates: HLR1 = 31.25 m^3/m^2·day, HLR2 = 62.5 m^3/m^2·day, and HLR3 = 125 m^3/m^2·day. The FC system consisted of 8 steps and was operated at flow rate of 200 L/h. Error bars represent the standard deviations of five replicated measurements.

of organic contaminants occurred in the CW process. For example, at the HLR of 31.25 m^3/m^2·day (HLR1), the DO level sharply declined from the inlet to the S3 position (i.e., equivalent to the hydraulic retention time of 3 days) then remained stable towards the outlet of the CW system (Fig. 4). At HLR of 31.25 m^3/m^2·day, from the inlet to the S2 position DO level above 0.5 mg/L represented the aerobic condition, which favoured the decomposition of organic matters and nitrification. From the S3 position to the outlet, the anoxic condition with very low DO level promoted denitrification. At the HLR of 125 m^3/m^2·day (HLR3), the DO level inside the CW system decreased but remained above 0.5 mg/L at the outlet. This reveals that the aerobic condition was dominant along the CW system from the inlet to the outlet when operating at HLR3.

When not combining with FC, DO level in the wastewater along the CW system slightly varied in a low range of 0.1–0.3 mg/L, reflecting the anoxic condition in the CW system. This low DO level was not beneficial to the CW treatment of the wastewater. Indeed, the decomposition and hence the treatment of organic matter during the CW process of wastewater occurs at a higher rate in the aerobic condition than that in the anoxic or anaerobic (Vymazal, 2011; Kadlec and Wallace, 2009). The effect of FC and the resultant DO level on the treatment efficiency of the CW process with the wastewater feed will be further clarified in the below section.

The measurements of NH_4^+-N, NO_3^--N, and alkalinity along the CW system demonstrate profound impacts of DO level in the wastewater on the treatment efficiency of the CW system. The results shown in Fig. 5 manifest that the increased DO level achieved by the FC system promoted the removal of NH_4^+-N from the wastewater. Along the CW system, NH_4^+-N concentrations of the wastewater aerated by the FC system (Fig. 5 A) were always lower than those of the wastewater that was directly fed to the CW system (Fig. 5B). Moreover, the CW system achieved the lowest effluent NH_4^+-N concentration of 5.7 mg/L when operated at the lowest HLR of 31.25 m^3/m^2·day and fed with the wastewater aerated by the FC system (Fig. 5A).

The treatment of NH_4^+-N along the CW system was subject to the nitrification process occurred along the CW system. The nitrification process itself was reflected by the NO_3^--N and alkalinity levels of the wastewater along the CW system. In the CW treatment of the raw wastewater, a stable and low NO_3^--N level was recorded at various positions along the CW system (Fig. 6 A). Alkalinity of the wastewater slightly reduced from the inlet to the outlet of the CW system with the raw wastewater feed (Fig. 6B). These stable NO_3^--N and alkalinity values indicate that the nitrification process hardly occurred in the CW treatment of the raw wastewater feed because of its limited DO content. The gradually reduced NH_4^+-N level along the CW system with the raw wastewater feed might be induced by the uptake of the CW plants.

On the other hand, NO_3^--N and alkalinity levels significantly varied along the CW system during the treatment of the wastewater aerated by the FC system (Fig. 6 A&B). When operating the CW system at HLR1 (i.e., 31.25 m^3/m^2·day) with the FC aerated wastewater, the wastewater NO_3^--N concentration peaked at the S2 position, equivalent to a hydraulic residential time of 2 days, then gradually decreased towards the system outlet (Fig. 6A). The wastewater alkalinity decreased from the inlet to the S2 sample position before levelling off in the remaining areas towards the system outlet (Fig. 6B). This indicates that the nitrification process occurred from the inlet to the S2 position under the aerobic condition whereby the wastewater DO level was above 0.5 mg/L. After the S2 position, the low DO level favoured the denitrification process; therefore, NO_3^--N gradually decreased while alkalinity slightly increased towards to outlet of the CW system.

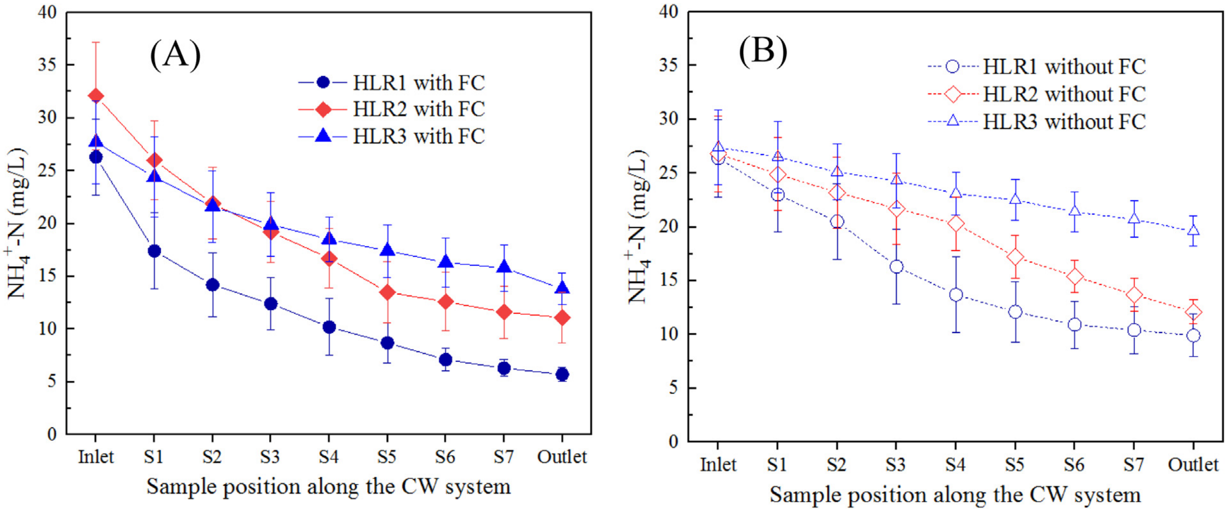

Fig. 5. NH_4^+-N level along the CW system during the treatment of the wastewater (A) with and (B) without FC aeration at three different CW hydraulic loading rates: HLR1 = 31.25 m^3/m^2·day, HLR2 = 62.5 m^3/m^2·day, and HLR3 = 125 m^3/m^2·day. The FC system consisted of 8 steps and was operated at flow rate of 200 L/h. Error bars represent the standard deviations of four replicated measurements.

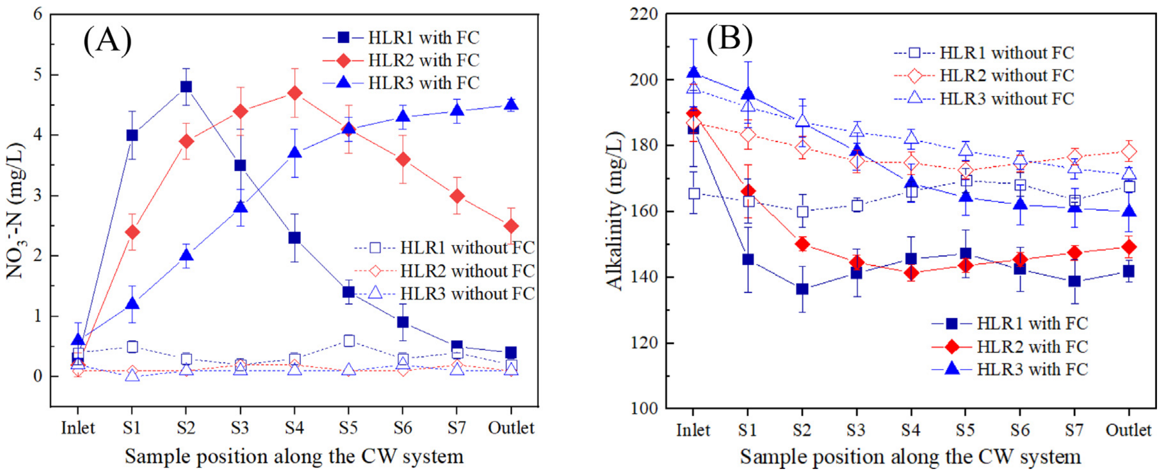

Fig. 6. (A) NO_3^--N and (B) alkalinity content of the wastewater along the CW system with and without FC aeration during the treatment of the domestic wastewater at various hydraulic loading rates: HLR1 = 31.25 m^3/m^2·day, HLR2 = 62.5 m^3/m^2·day, and HLR3 = 125 m^3/m^2·day. The FC system consisted of 8 steps and was operated at flow rate of 200 L/h. Error bars represent the standard deviations of four replicated measurements.

Elevating the hydraulic loading rate from HLR1 to HLR3 appeared to move the peaked NO_3^--N content towards the outlet of the CW system (Fig. 6A). Particularly, when operating the CW at HLR3 (i.e., 125 m^3/m^2·day), the wastewater DO level through the system was always higher than 0.5 mg/L, representing an aerobic condition in the whole CW system. As a result, only the nitrification process occurred in the CW system at HLR3, and hence the NO_3^--N concentration in the wastewater continuously increased along the CW system (Fig. 6A). Due to the absence of the denitrification process, the NO_3^--N content at the outlet of the CW system when operated at HLR3 was discernibly higher than that observed at HLR2 and HLR1. These observed results confirm the importance of the operational optimization during the combined FC/CW treatment of domestic wastewater to achieve maximized nitrogen removal.

3.2.2. The overall treatment efficiency and contaminant removals of the CW process

The treatment efficiency of the CW process with the wastewater feed was assessed with respects to the overall removal of TN, PO_4^{3-}, BOD_5, and TSS. The results demonstrate that integration of FC to increase the DO level prior to the CW process had noticeable impacts on the TN and BOD_5 removals but not on PO_4^{3-} and TSS removals of the CW process when treating the domestic wastewater (Fig. 7). The TN and BOD_5 removals of the CW process with the wastewater feed were greatly improved when combined with the FC system (Fig. 7 A&B). As demonstrated above, the FC system helped elevate the

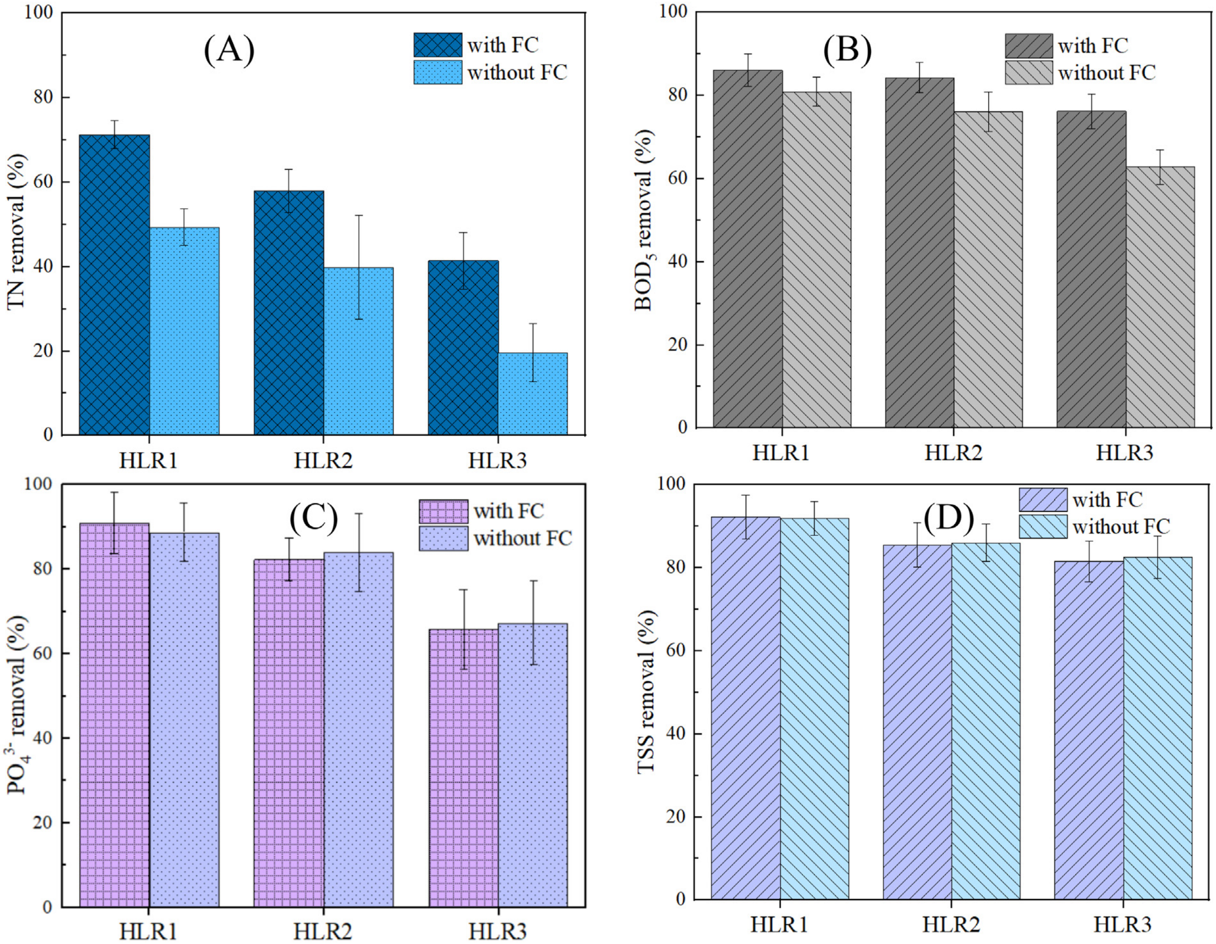

Fig. 7. The overall contaminant removals of the CW treatment of the domestic wastewater with and without FC aeration at various hydraulic loading rates: HLR1 = 31.25 m^3/m^2·day, HLR2 = 62.5 m^3/m^2·day, and HLR3 = 125 m^3/m^2·day. The FC system consisted of 8 steps and was operated at flow rate of 200 L/h. Error bars represent the standard deviations of four replicated measurements.

DO level in the wastewater and hence created the aerobic condition along the CW process. It is well-established that the aerobic condition facilitates the biodegradation of organic matter; therefore, the CW treatment of the wastewater after flowing through the FC system exhibited much higher TN and BOD_5 removals as compared to the CW process of the raw wastewater (Fig. 7 A&B). The TN and BOD_5 removals achieved by the combined FC/CW process were comparable to those reported in the study by Jehawi et al. (2020).

On the other hand, the FC system exerted little impacts on the PO_4^{3-} and TSS removals of the CW process (Fig. 7C&D). Indeed, unlike TN and BOD5, the treatment of PO_4^{3-} and TSS in the CW process is not subjected to the aerobic or anoxic condition along the CW system, but dependent on various factors including absorption onto the root zone, plant uptake, and settling and filtering effects (Vymazal, 2004). These factors are not directly controlled by the DO level in the wastewater. As a result, the CW process achieved mostly the same PO_4^{3-} and TSS removals regardless of the FC system. The PO_4^{3-} and TSS removals achieved in this study are lightly higher than the values reported in previous studies on the CW process when treating wastewater with various DO levels (Cao et al., 2022; Jehawi et al., 2020; Al-Zreiqat et al., 2018; Vega De Lille et al., 2021; Vymazal, 2004). This might be attributed to the low age of the bed-media used in the CW system reported here.

Like conventional CW systems, the combined FC/CW system achieved higher contaminant removals when operating at lower HLR. As shown in Fig. 7, the CW process with or without the FC system exhibited the highest removals of TN, BOD_5, PO_4^{3-}, and TSS at the lowest HLR of 31.25 m^3/m^2·day (i.e., equivalent to the CW hydraulic retention time of 8 days). This is because the treatment efficiency the CW process depends on the retention time of the wastewater inside the CW: the longer the retention time is, the higher contaminant removals can be achieved. Indeed, higher contaminant removals associated with lower HLRs have been reported in a field study using a large-scale CW process with a real domestic wastewater feed by Çakir et al. (2015).

Table 2
Characteristics of the CW effluent compared to allowable levels for safe environmental discharge and the overall contaminant removals of the combined FC/CW treatment of the domestic wastewater. The FC system consisted of 8 steps and was operated at flow rate of 200 L/h, while the HLR of the CW process was 31.25 m^3/m^2 day.

Parameters	FC/CW effluent	Allowable levels for safe environmental discharge (QCVN 14:2008/BTNMT, column B)	Overall removal (%)
Temperature (°C)	29.5 ± 0.6	–	–
pH	7.3 ± 0.4	5–9	–
DO (mg/L)	0.1 ± 0.1	–	–
BOD_5 (mg/L)	10.9 ± 2.1	50	86.6
TN (mg/L)	9.1 ± 0.9	–	71.2
NH_4^+-N, (mg/L)	5.7 ± 0.7	10	79.6
NO_3^--N, mg/L	0.4 ± 0.1	50	–
Alkalinity (mg/L)	141.8 ± 3.3	–	–
PO_4^{3-} (mg/L)	0.3 ± 0.2	10	86.9
TSS (mg/L)	6.6 ± 4.9	100	92.2

The characteristics of the effluent after the combined FC/CW treatment of the wastewater at the HLR of 31.25 m^3/m^2·day are shown in Table 2. The CW process combined with the FC system significantly reduced the concentrations of contaminants (e.g., BOD_5, NH_4^+-N, PO_4^{3-}, and TSS) in the effluent compared to the raw wastewater (Table 1). More importantly, the combined FC/CW treatment successfully brought all contaminants in the wastewater to allowable levels for safe environmental discharge (Table 2). Given these results, combined FC/CW could be a cost-effective and eco-friendly treatment process for domestic wastewater.

4. Conclusions

In this study, a flowform cascade (FC) was combined with constructed wetland (CW) to mitigate the depletion of oxygen in wastewater and thus enhance the nitrogen removal from the wastewater. The experimental results show that the FC system consisting of 8 units at the flow rate of 200 L/h raised the dissolved oxygen (DO) level in the wastewater from 0.2 mg/L to 5.6 mg/L, thus creating an aerobic condition that favoured nitrification and biodegradation of organic contaminants in the front zone of the CW. Given the increased wastewater DO level after the FC units, the CW system could maintain the sequence of aerobic and anoxic conditions required for nitrification and denitrification, respectively, by regulating the CW hydraulic loading rate. Particularly, when operating at the CW hydraulic loading rate of 31.25 m^3/m^2·day, the combined FC/CW process achieved total nitrogen and biochemical oxygen demand removals of 71.2% and 86.1%, respectively, compared to 49.4% and 80.9% of the single CW process. The removals of phosphate and total suspended solids of the combined FC/CW process were comparable to those of the CW operation without pre-aeration because they are not affected by DO.

CRediT authorship contribution statement

Ha Thi Thuy Ung: Investigation, Data curation, Writing – original draft. **Bach Tho Leu:** Supervision, Conceptualization, Methodology. **Hoa Thi Hien Tran:** Supervision, Conceptualization, Methodology. **Luong Ngoc Nguyen:** Conceptualization, Methodology, Writing – review & editing. **Long Duc Nghiem:** Conceptualization, Methodology, Writing – review & editing. **Ngoc Bich Hoang:** Visualization, Writing – review & editing. **Hung Tuan Pham:** Funding acquisition, Project administration, Writing – review & editing. **Hung Cong Duong:** Conceptualization, Formal analysis, Resources, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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