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A comparative estimate of life cycle greenhouse gas emissions from two types of constructed wetlands in Tianjin, China

Xinhua Zhao, Lei Liu*

Department of Environmental Engineering, School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China
Tel. +86 13821504473; Fax: +86 22 87402072; email: ebll@tju.edu.cn

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ABSTRACT

Constructed wetlands (CWs) are widely used for wastewater treatment, but may also be sources of greenhouse gas (GHG). This study focuses on comparing the GHG emissions from a vertical flow constructed wetland (VFCW) and a horizontal flow constructed wetland (HFCW) in the city of Tianjin, China. Two methods are used in this paper to estimate the indirect and direct GHG emissions. It is found that the VFCW emits 0.09, 1.34, and 3.31 kg equivalent CO_2 (CO_2 Eq.) to remove 1.00 m^3 wastewater, 1.00 kg COD, and 1.00 kg BOD in the studied life cycle, respectively, in contrast to 0.18, 2.10, and 5.42 kg CO_2 Eq. for the HFCW. The results indicate that the adoption of VFCW is a more effective option with respect to GHG emissions when treating the same amount of pollutants. In addition, the operation phase which includes GHG emissions from water treatment process and energy consumption for pump dominates the GHG emissions. For different kinds of GHG from CWs, CO_2 dominates the influence on climate change. The CH_4 and N_2O emissions should also deserve more attention due to their greater global warming potential. This paper further suggests that GHG emissions can be mitigated in the design, construction, and operation stages through some feasible measures. It would reduce GHG emissions in CWs by adopting hybrid CW system (e.g. HF–VF or VF–HF) or choosing suitable plant species which can mitigate GHG emissions. In addition, aeration could contribute to the control of GHG emissions from CWs.

Keywords: Constructed wetlands; GHG emission; Wastewater treatment; Vertical flow; Horizontal flow

1. Introduction

The utilization of constructed wetlands (CWs) for reducing the amount of pollutants in wastewater from different sources has been considered as a promising technology to improve water quality [1,2]. Apart from physical and chemical processes, pollutants removal by CWs also attributes to biological processes which drive the removal of organic matter and nitrogen by microorganisms and vegetations [3,4]. However, the microbial transformations generate greenhouse gasses (GHG) as by-products [3,5]. Some of these gasses, including CO_2, CH_4, and N_2O, could have adverse effects on global warming control [6]. Thus, there is a risk that CWs could cause an atmospheric pollution problem by generating GHG while dealing with water pollution [3,4].

Flux of CH_4 is generated by methanogenic bacteria which could facilitate the anaerobic conditions and organic material of CWs. The rate of methanogenesis depends on the availability of carbon source and oxygen. The CH_4 emissions are also regulated by other factors, such as water level, plant species, and temperature [7,8].

*Corresponding author.

Nitrogen is transformed through mineralization, nitrification, and denitrification. N_2O could be produced in the process of nitrification, denitrification, and disimilatory reduction of nitrite to N_2. Nitrification and denitrification are commonly recognized as dominant processes responsible for N_2O emissions in CWs [1]. N_2O emissions are likely to be highly variable in CWs with a wide range of environmental conditions including C/N ratio, dissolved oxygen, and hydraulic loading rate [8].

The GHG emissions in CWs depend also on climate conditions. Some climatic factors determine the location and extension of aerobic and anoxic conditions, especially temperature, water level, and humidity conditions. Therefore, the seasonal and temporal variations should be taken into consideration when evaluating the environmental impact of GHG emissions comprehensively [7].

Fortunately, some assessments such as Life Cycle Assessment (LCA) [9–11] have been utilized for estimating environmental impacts of wastewater treatment systems [12–14]. Global warming is one of the most effective indicators that can be measured and estimated [15]. Therefore, most studies conducted recently just took the GHG emissions as the main factor with specific adjustments following the recommendation of the Intergovernmental Panel on Climate Change (IPCC) [16]. Given that GHG emissions could partially mitigate the beneficial effort of CWs, the contribution of CWs to GHG emissions has received increasing attention [6,17–22].

Recently, some researchers have paid attention on indirect GHG emissions from CWs. In contrast to direct GHG emissions, which generate from the wastewater treatment process including denitrification, nitrification, and methanogenesis, indirect GHG emissions, which can provide valuable insights into the hidden sources of GHG, are closely related to the construction, operation, and management of CWs. The extraction, manufacture, transportation, and recycling of different components, such as substrates and plants, would ultimately result in large amount of GHG emissions in other ways. In addition, energy consumption for CWs also account for a large part of indirect GHG emissions [12,15,23].

Although previous studies have demonstrated that indirect and direct GHG emissions can be used as critical indicators to evaluate the environmental impact of CWs, very few studies compared different types of CWs about their total GHG emissions and their effects on global warming, which is very important for designers to select an appropriate type or design a best combination of different types of CWs for global warming control purpose. Thus, this paper aims at comparing the indirect and direct GHG emissions as well as the GHG production in different phases from a vertical flow constructed wetland (VFCW) and a horizontal flow constructed wetland (HFCW) system. Furthermore, different mitigation methods are also discussed comprehensively in order to decrease the effect of CWs on climate change.

2. Materials and methods

2.1. Site description

Tianjin is located near Bohai Bay, northern China. With the rapid industrialization and urbanization as well as accelerated economic development, many cities in China, especially large-sized city like Tianjin, have experienced excessive water pollution. Traditional centralized wastewater treatment systems, which have prevailed in many countries, have been considered as the optimal solution for domestic and industrial wastewater treatments. However, complete replication of conventional wastewater treatment systems has been proved to be rather limited for small- and medium-sized communities when solving the multifold water problems in China. Therefore, different types of CWs recognized as an effective and stable alternative for their low cost, environmental friendliness, and energy savings [1,2] are built in the rural region of Tianjin, China. In this paper, a VFCW and a HFCW, both of which are used for the treatment of eutrophic water from adjacent rivers, are selected as the examples to estimate the GHG emissions. Although the two CWs are not in the same place, the quality of water they use and the condition around CWs are comparable for further study. The original data of all materials inputs are presented in Table 1. Both the VFCW and the HFCW with a designed lifetime of 20 years have a daily treatment capacity of 200 m^3 eutrophic water. The average removal efficiencies for major pollutants are listed in Table 2. The schematic and process diagram of VFCW and HFCW in this case is shown in Figs. 1 and 2.

During the operation stage, there is one water pump installed with a power rating of 5 kW, while the other is used for standby. The eutrophic water is pulse-pumped every 4 h to the VFCW and HFCW for treatment. Each pulse lasts for 20 min. The pump operates discontinuously for a maximum of 2 h per day. The electricity power consumed by the pumps is the main energy input which is estimated as 73,000 kWh during its lifetime.

Table 1
Material inputs inventory of VFCW and HFCW

Item	VFCW	HFCW	Price per unit ($)
Substrate (m^3)			
Peat	50		7.13
Shale	100		6.41
Gravel	250	600	6.65
Vegetation (rhizome)	2,000	3,500	0.67
Pump	2	2	239.62
PE pipe (m)	110	240	5.02
PE valve	7	12	6.96
Electrical control	1	1	199.64
Bricks and cement (m^3)	150	420	1.99
Geotextile (m^2)	900	1,500	2.00
Electricity (kWh)	73,000	73,000	0.07

Table 2
The mean value of influent and effluent water qualities and the removal rates of VFCW[a] and HFCW[b]

CWs	Item	COD	BOD_5	TSS	TP	TN
VFCW	Influent (mg/L)	76.24 (17.8)	50.62 (7.6)	22.33 (13.6)	0.55 (0.85)	3.27 (5.12)
	Effluent (mg/L)	26.27 (14.9)	26.47 (3.2)	5.93 (4.7)	0.3 (0.63)	1.53 (3.17)
	Efficiency	65.54% (9.6)	47.71% (8.9)	73.44% (11.8)	45.45% (8.4)	53.21% (7.8)
HFCW	Influent (mg/L)	133.06 (10.9)	42.71 (11.4)	35.43 (6.6)	1.51 (0.52)	4.16 (2.54)
	Effluent (mg/L)	51.37 (5.2)	21.35 (4.5)	12.79 (4.9)	0.77 (0.37)	2.23 (1.59)
	Efficiency	61.39% (6.5)	50.01% (13.6)	63.90% (9.3)	49.01% (7.9)	46.39% (5.1)

[a]Arithmetic mean (standard error in parentheses) from samples collected from VFCW twice a week for a half-year period.
[b]Arithmetic mean (standard error in parentheses) from samples collected from HFCW once a week over one-year period.

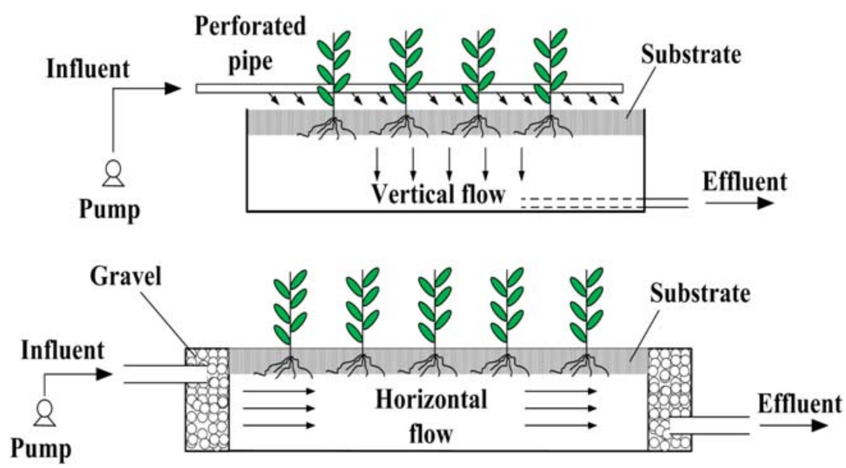


Fig. 1. Schematic diagram of the studied VFCW and HFCW system.

2.1.1. Vertical flow constructed wetland

The VFCW system is located at Konggang district, which is 20 km from the center of Tianjin. It was built in 2009 for nutrient retention purpose. This system consists of four cells and each of them has a surface area of approximately 120 m^2 with a dimension of

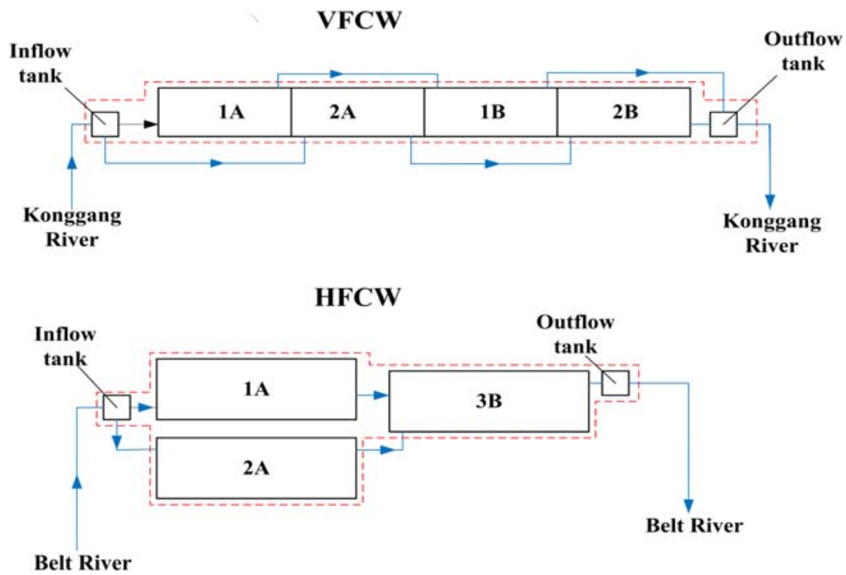


Fig. 2. Pan view and process chart of the studied VFCW and HFCW system.

12 m long and 10 m wide. All of the cells are filled with peat (effective diameter of particle ranging from 5 to 10 mm), shale (effective diameter of particle ranging from 15 to 40 mm), and gravel (effective diameter of particle ranging from 5 to 25 mm) to a depth of 0.8–1.6 m and the average porosity is equal to 0.45. Two of them are planted with common reed (*Phragmites australis*), while cattail (*Typha angustifolia* L.) and yellow flag (*Iris pseudacorus* L.) are cultivated in the other two cells. Plants are native to Tianjin and collected from nearby natural wetlands. The system could achieve hydraulic retention time (HRT) of 1–2 d and hydraulic loading rate (HLR) of 0.21–0.42 m/d. The organic loading rate (OLR) was 15.38–31.77 $g/m^2/d$ in VFCW. The eutrophic water is fed to each bed via perforated pipe and the outflow pipe collects wastewater at the end of the bed (see Fig. 1). Fig. 2 shows the routes of the flow in CWs. Samples were taken from the inflow tank and outflow tank. The experiment was conducted from April 2010 to November 2010.

2.1.2. Horizontal flow constructed wetland

The HFCW system is near the Belt highway of the city. It was constructed for nutrient retention purpose in 2008. This system is comprised of three cells and each of them has a total surface area of approximately 330 m^2 with a dimension of 30 m long and 10 m wide. Each cell is only filled with gravel (effective diameter of particle ranging from 15 to 40 mm) to a depth of 0.6–0.8 m. The eutrophic water enters the HFCW through a large gravel (effective diameter of particle ranging from 100 to 150 mm) layer for a good distribution across the width of the bed. The effluent end of the cell is established with 50–100 mm diameter gravel. The system could achieve a nominal hydraulic retention time (HRT) of 3–4 d as well as hydraulic loading rate (HLR) of 0.15–0.2 m/d. The organic loading rate (OLR) was 20.16–26.88 $g/m^2/d$ in HFCW. This three cells are planted with common reed (*Phragmites australis*), cattail (*Typha angustifolia* L.), and yellow flag (*Iris pseudacorus* L.), respectively. The eutrophic water was fed to each bed via inflow pipe as shown in Fig. 1 and the flow route can be seen in Fig. 2. Samples were taken from the inflow tank and outflow tank. The experiment was conducted for two periods, one is from May 2010 to December 2010 and the other is from March 2011 to September 2011.

2.2. GHG emission accounting principles

The gasses evaluated in this study for GHG emissions are CO_2, CH_4, and N_2O. The total GHG emissions include the estimate from indirect and direct sources. The indirect GHG emissions are estimated by using the input–output ecological analysis [23–26]. Fig. 3 shows a flow diagram of the CW system under study during its life cycle. As it can be seen, for the entire life cycle, different inputs can indirectly influence the production of GHG emissions in phases of design, construction, and operation. Due to the lack of data, direct GHG emissions are estimated according to relevant studies with real measurement data.

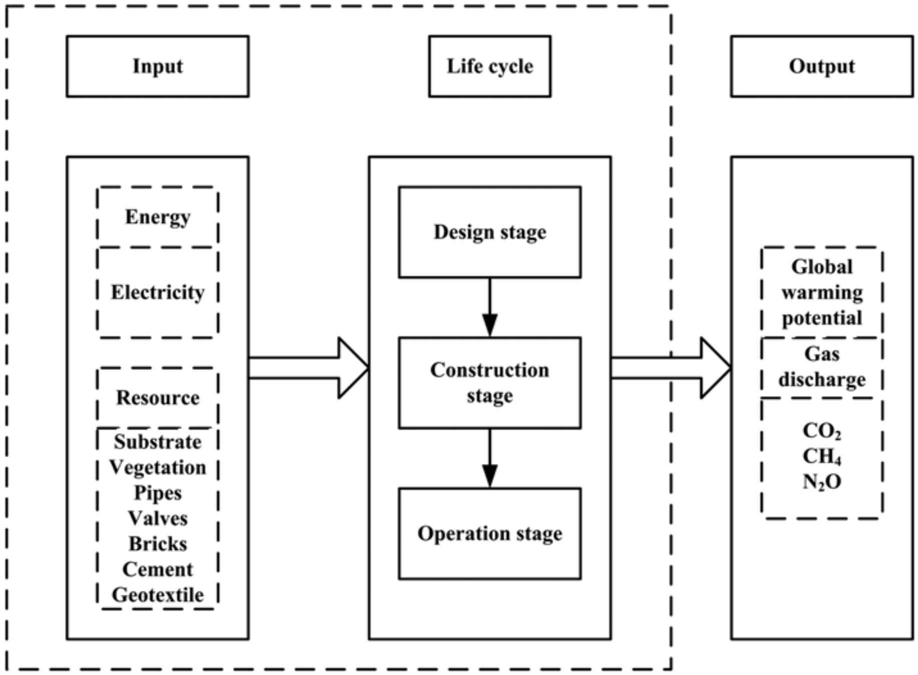


Fig. 3. The input–output ecological analysis flow diagram for indirect GHG emissions.

2.3. Indirect GHG emission accounting

This study adopts the method of eco-systems accounting method which is based on the latest GHG emission intensity database obtained from the input–output ecological analysis corresponding to the Chinese economy of 2007 with 135 industrial sectors, to assess the indirect GHG emissions of two types of CWs [23–25].

This estimation begins with the process analysis for all the materials and energy consumption of CWs to form an inventory. The accounting of the indirect GHG emissions (I_e) for each item from CWs can be achieved through multiplying its economy value (E_j) by the corresponding embodied GHG emission intensities (I_j) (Table 4). The economy value (E_j) of the input raw material and sources are calculated by multiplying each item's quantity (Q_j) to its unit price (P_j) (shown in Table 1). I_j represents the indirect GHG emissions that stems from unit economy cost due to materials and energy consumption. The GHG emissions intensity database from the studies of Chen et al. [24,25] and Zhou et al. [25] were used to get the corresponding embodied GHG emission intensities (I_j). Finally, indirect GHG emissions of each item are added to get total amount of indirect GHG emissions (I_e) from VFCW and HFCW.

$$E_j = Q_j \times P_j \tag{1}$$

$$I_e = \sum_{j=1}^{n} (E_j \times I_j) \tag{2}$$

2.4. Direct GHG emission accounting

In this paper, direct GHG emissions from water treatment are estimated based on real measurement data. The values of VFCW and HFCW from Koo wetland (Estonia) are used for the estimation of GHG emissions in this paper for consistency. The ratio of influent BOD and TN emitted as CO_2, CH_4, and N_2O from the study of Søvik et al. [18] is adopted as emission factor for direct GHG emissions calculation (shown in Table 3). The direct GHG emissions are estimated for life cycle as follows:

For VFCW,

$$CO_2 = 0.783 \times Q \times D \times BOD^* \tag{3}$$

$$CH_4 = 0.012 \times Q \times D \times BOD^* \tag{4}$$

$$N_2O = 0.009 \times Q \times D \times TN^* \tag{5}$$

For HFCW,

$$CO_2 = 1.703 \times Q \times D \times BOD^* \tag{6}$$

Table 3
Influent concentration, initial loading, and GHG emissions in relevant constructed wetlands

Country	CW type	Influent[a] (mg/L)		Initial loading[a] ($g/m^2/d$)		Emissions[a] ($mg/m^2/d$)			Reference
		TN	BOD	TN	BOD	CO_2	CH_4	N_2O	
Japan	VFCW	9.80	38.00	0.41	1.60	–	<72.00	< 0.24	[22]
Japan	VFCW	18.40	60.00	0.77	2.52	–	<240.00	< 0.48	[22]
Japan	VFCW	36.70	163.00	1.54	6.85	–	<480.00	< 1.44	[22]
Estonia (Koo wetland)	VFCW	50.90	142.00	0.42	0.43	5,200.00	77.46	10.87	[18]
China	VFCW	3.27	50.62	1.36	21.09	7,881.00[b]	116.01[b]	6.22[b]	This study
Estonia (Koo wetland)	HFCW	43.10	62.80	3.82	25.07	1,301.00	96.51	2.88	[18]
Estonia (Kodijarve wetland)	HFCW	96.50	125.00	9.26	12.00	2,490.00	182.42	4.52	[18]
Germany	HFCW	–	500.00	–	1.70	–	–	3.23	[2]
China	HFCW	4.16	42.71	0.84	8.63	7,347.00[b]	539.66[b]	4.18[b]	This study

[a]The average values of influent concentration, initial loading, and GHG emissions are adopted in this paper.
[b]The direct GHG emissions estimated for our CWs according to the study of Søvik et al. [18].

$$CH_4 = 0.125 \times Q \times D \times BOD^* \quad (7)$$

$$N_2O = 0.011 \times Q \times D \times TN^* \quad (8)$$

In these functions, the factors in the front of the equation are the conversion rate of CO_2, CH_4, and N_2O. Q is the inflow rate of CWs. D represents the lifetime of CWs which is recommended to be 7,300 day (20 years). BOD^* and TN^* is the amount of BOD and TN removed by VFCW and HFCW, respectively.

2.5. The determination of GHG emissions during construction and operation phase

This paper also calculates the GHG emissions from construction phase and operation phase. The construction phase includes material extraction, transportation, and relevant energy consumption, while the operation phase is mainly comprised of GHG emissions from direct sources and energy used for the management of CWs. The extraction and transportation of materials and energy consumption are regarded as the main sources of GHG emissions in the construction phase. The energy consumption is embodied in each item to make the calculation more clear. For the operation phase of CWs, the electricity consumed by pumps and the gaseous emissions in the process of water treatment are taken into consideration. The GHG emissions during their life cycles are determined as follows:

$$GHG_{construction} = GHG_{substrate} + GHG_{vegetation} + GHG_{pump} + GHG_{electical-control} + GHG_{bricks\&cement} \quad (9)$$

$$GHG_{operation} = GHG_{electricity} + GHG_{direct} \quad (10)$$

3. Results and discussion

The estimate of indirect GHG emissions is conducted based on the GHG emission intensity database obtained from several studies [23–25]. The currency unit of the data used was converted from Yuan (Chinese currency unit) to dollar to make the estimate comparable with other countries (shown in Table 4). The GHG emissions are converted to CO_2 equivalent emissions according to 2006 IPCC Guidelines for National Greenhouse Gas Inventories [16] by the factors of 1:21:310 for CO_2, CH_4, and N_2O. The total

Table 4
GHG emission intensity of VFCW and HFCW (adapted from [23–25])

Item	Contents	CO_2 intensity ($t\ CO_2$ Eq./10^4 $)	CH_4 intensity ($t\ CO_2$ Eq./10^4 $)	N_2O intensity ($t\ CO_2$ Eq./10^4 $)	GHG intensity ($t\ CO_2$ Eq./10^4 $)
Substrate	Gravel, shale, peat	5.94E+01	3.69E−01	1.72E−03	6.79E+01
Vegetation	*Phragmites australis*, *Typha latifolia* L., *Iris pseudacorus* L.	1.17E+01	2.92E−01	4.42E−02	3.16E+01
Pump	Manufacture of pump, valve	2.69E+01	1.77E−01	1.07E−03	3.09E+01
PE pipe and valve	Manufacture of plastic	2.88E+01	1.89E−01	1.52E−03	3.33E+01
Electric control	Manufacture of equipments for power transmission and control	2.32E+01	1.54E−01	1.14E−03	2.69E+01
Bricks and cement	Manufacture of cement and lime and Plaster	1.09E+02	3.65E−01	1.68E−03	1.17E+02
Geotextile	Manufacture of plastic	2.88E+01	1.89E−01	1.52E−03	3.33E+01
Electricity	Production and supply of electric power and heat power	8.20E+01	5.54E−01	1.95E−03	9.50E+01

GHG emissions for VFCW and HFCW are listed in Tables 5 and 6.

3.1. The performance of VFCW and HFCW

The GHG emissions are closely related to the initial loading of BOD and TN [18]. These two CWs are both applied for nutrient retention in polluted river which is regarded as a main environmental concern in China. Although the influent concentration of BOD and TN may be lower than CWs treating domestic or industrial wastewater, the initial loading of BOD and TN was in the scope of data from several literatures (Table 3). Moreover, the direct GHG emissions estimated in our study are similar to the typical CWs where GHG emissions could attract much attention. Therefore, GHG emissions are supposed to be the main concern for these systems.

The total amount of GHG emissions for VFCW is 123.27 tonne (t) CO_2 Eq. The VFCW emits 0.09, 1.34, and 3.31 kg CO_2 Eq. to treat 1.00 m^3 wastewater, 1.00 kg COD, and 1.00 kg BOD in the studied life cycle. Indirect GHG emissions account for 65.20% of the total GHG emissions, which is much higher than that of direct GHG emissions. The operation phase accounts for 71.17% of GHG emissions from VFCW, indicating that construction phase has less effect on gaseous emissions. The GHG emissions generated from electricity (36.37%) and substrate (14.61%) occupy a large part of indirect GHG emissions. Following in the degrees of significance are emissions from geotextile (4.84%), vegetation (3.40%), and bricks and cement (2.84%), while the others have less impact on GHG emissions (<2%). In addition, various kinds of GHG have different environmental impacts on climate change. For VFCW, the influence of CO_2, CH_4, and N_2O having on climate change are 77.79, 14.73, and 7.48% in the unit of kg CO_2 Eq., respectively, demonstrating that the large parts of environmental impact are derived from CO_2 emissions (see Fig. 4).

For HFCW, the total amount of GHG emissions is 249.21 t CO_2 Eq., in which the direct part and indirect part are close to each other. The incomplete denitrification and methane formation potential is considered to be high in HFCW for its anoxic and anaerobic conditions, which explains why the direct GHG emissions have a greater influence on the total estimate compared to VFCW. The HFCW generates 0.18, 2.10, and 5.42 kg CO_2 Eq. to treat 1.00 m^3 wastewater, 1.00 kg COD, and 1.00 kg BOD. The operation phase accounts for 75.91% of GHG emissions from HFCW, indicating that operation phase has a higher global warming potential compared with construction phase. The elec-

Table 5
GHG emissions of VFCW

Item	CO_2 (t)	CH_4 (t)	N_2O (t)	GHG (t CO_2 Eq.)	Proportion (%)
Substrate	1.58E+01	9.82E−02	4.58E−04	1.80E+01	14.61
Vegetation	1.56E+00	3.89E−02	5.87E−03	4.20E+00	3.40
Pump	1.29E+00	8.46E−03	5.11E−05	1.48E+00	1.20
Pipe and valve	1.72E+00	1.13E−03	9.10E−05	1.78E+00	1.44
Electric control	4.64E−01	3.08E−03	2.28E−04	5.99E−01	0.49
Bricks and cement	3.26E+00	1.09E−02	5.02E−05	3.50E+00	2.84
Geotextile	5.18E+00	3.39E−02	2.73E−04	5.97E+00	4.84
Electricity	3.90E+01	2.64E−01	9.26E−04	4.48E+01	36.37
Indirect GHG emissions	6.83E+01	4.59E−01	7.95E−03	8.04E+01	65.20
Direct GHG emissions	2.76E+01	4.06E−01	2.18E−02	4.29E+01	34.80
Total GHG emissions	9.59E+01	8.65E−01	2.97E−02	1.23E+02	100.00

Table 6
GHG emissions of HFCW

Item	CO_2 (t)	CH_4 (t)	N_2O (t)	GHG (t CO_2 Eq.)	Proportion (%)
Substrate	2.37E+01	1.47E−01	6.87E−04	2.70E+01	10.84
Vegetation	2.73E+00	6.81E−02	1.03E−02	7.34E+00	2.95
Pump	1.29E+00	8.46E−03	5.11E−05	1.48E+00	0.60
Pipe and valve	3.71E+00	2.43E−03	1.96E−04	3.83E+00	1.53
Electric control	4.64E−01	3.08E−03	2.28E−04	5.99E−01	0.24
Bricks and cement	9.13E+00	3.05E−02	1.41E−04	9.81E+00	3.94
Geotextile	8.63E+00	5.65E−02	4.55E−04	9.95E+00	3.99
Electricity	3.90E+01	2.64E−01	9.26E−04	4.48E+01	17.99
Indirect GHG emissions	8.87E+01	5.80E−01	1.30E−02	1.05E+02	42.08
Direct GHG emissions	5.31E+01	3.90E+00	3.02E−02	1.44E+02	57.92
Total GHG emissions	1.42E+02	4.48E+00	4.32E−02	2.49E+02	100.00

tricity (17.99%) and substrate (10.84%) are also the main sources for indirect GHG emissions. Apart from geotextile (3.99%), bricks and cement (3.94%), and vegetation (2.95%), the fractions of the others are lower than 2%. Fig. 4 shows that the influence of CO_2, CH_4, and N_2O having on climate change are 56.94, 37.70, and 5.36% in the unit of kg CO_2 Eq., respectively, suggesting that CO_2 and CH_4 generated by HFCW have a greater effect on climate change.

The GHG emissions from CWs varied with different impact factors, especially for seasonal and temporal variations which have a great influence on the amount of GHG emissions. Søvik et al. [18] analyzed six CWs in Estonia, Finland, Norway, and Poland and found that CWs have a higher CH_4 and N_2O emissions in summer due to increasing microbial activity responsible for GHG emissions. In their study, for VFCW and HFCW, the influence of N_2O emissions on global warming potential in winter was up to 23.58 and 27.92%, which is higher than our results obtained in spring and summer. However, the fraction of CH_4 emissions from VFCW and HFCW decreased to 3.55 and 10.38% in winter. Vanderzaag et al. [8] compared the direct GHG emissions from subsurface flow wetland during different months. They reported that CH_4 emissions ranged from 143.00 to 259.00 $mg/m^2/d$ in April to September, while N_2O emissions were generally in the range of 1.00 to 4.00 $mg/m^2/d$ but they could be up to 30.00 $mg/m^2/d$ in July to September. The CH_4 emissions may be as low as 8.00 $mg/m^2/d$ in November to March because the activity of micro-organisms slowed down with cold weather when plants withered and could not provide habitats and enough oxygen for micro-organisms which have the ability to generate GHG emissions [7]. Moreover, indirect GHG emissions also range in a large scale since

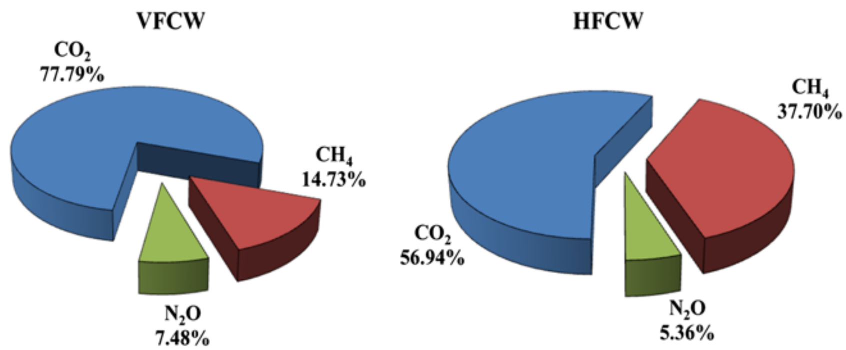


Fig. 4. Environmental impact percentage of CO_2, CH_4, and N_2O emissions (kg CO_2 Eq.) for the VFCW and HFCW in the life cycle.

CWs located in different countries seldom have the same amount of construction materials and energy requirement.

Table 7 listed several literatures which showed that the operation phase dominates the impacts of GHG emissions on climate change for CWs due to much higher emissions of CO_2 and CH_4 from energy consumption and direct sources, which is consistent with our results (VFCW, 71.17% and HFCW, 75.91%). Although direct and indirect GHG emissions from CWs are different because of seasonal and temporal variations, the fractions of GHG emissions from construction and operation phases are similar between our estimation and relevant studies. Moreover, the GHG emissions per unit of wastewater, COD, and BOD were estimated to be 0.20, 2.21, and 4.75 kg CO_2 Eq. in the research of Chen et al. [23], which is also similar to our results. Therefore, the estimation obtained in this paper was comparable to other studies.

3.2. Comparison between CWs and CWTPs

The data of a conventional wastewater treatment plant (CWTP), which has been described by Chen et al. [23], are selected for comparison purpose. The CWTP designed to have the lifetime of 20 years can achieve the treatment capability of 1,700 m^3/per day for domestic wastewater. The materials and energy inputs from the construction and operation stages are taken into consideration for the CWs and CWTP. The GHG emissions in treating per unit water, COD, and BOD are compared between CWs and CWTP (see Fig. 5). The total GHG emissions of CWTP were calculated as 9,140.00 t compared to 123.27 and 249.21 t for VFCW and HFCW. The results suggest that CWTP cause remarkably more GHG emissions than CWs if treating the same amount of pollutants.

Several researchers have also obtained results very similar to ours. Ogden [20] estimated that CWTP uses 3.90 kg of fossil fuel carbon to remove 1.00 kg of carbon, while CWs use only 0.16 kg of fossil fuel carbon to remove 1.00 kg of carbon [21]. Pan et al. [15] also reported that the GHG emissions generated by CWs are only half the amount of that emitted by CWTPs. Although the efficiencies of wastewater treatment by CWTPs are generally higher than CWs, CWs are still more favorable for wastewater treatment compared to CWTPs considering environmental impact, ecological benefit, and economical cost comprehensively. This confirms the previously drawn conclusion that CWs as decentralized systems for the treatment of wastewater from small- and medium-sized communities are

Table 7
The fraction of global warming potential for construction phase and operation phase

Construction phase	Operation phase		Reference
Material and energy consumption (%)	Energy consumption (%)	Water treatment (%)	
3.57	59.67	36.76	[17]
4.00	26.75	69.25	[12]
21.84	36.93	41.23	[23]
28.83	36.37	34.80	This study (VFCW)
24.09	17.99	57.92	This study (HFCW)

better choice compared with CWTPs [15,20,23,27]. In addition, the life cycle impacts of indirect GHG emissions are greater than that for direct sources of CWTPs [15,23,27]. About 75.00% of the GHG emissions are indirect for CWTP, of which about 90.00% is caused by energy consumption. The GHG emissions from the operation phase characterized by energy consumption for management of CWTP account for 93.34% which is higher than that from CWs (VFCW, 71.17% and HFCW, 75.91% for operation phase), and consequently the adoption of CWs for wastewater treatment will make less environmental stress and gain larger ecological benefit with environmental friendliness and sustainability.

3.3. Comparison between VFCW and HFCW

The GHG emissions emitted by HFCW are much larger than that from VFCW partly because of higher contents of pollutants for HFCW. The GHG emissions in treating per m^3 wastewater and removing per kg COD and BOD by VFCW and HFCW (see Fig. 5) demonstrate that VFCW studied in this case could bring less environmental impact on climate change during its life cycle when treating the same amount of pollutants. This is consistent with the findings of Fuchs et al. [11], whose research illustrated that VFCW with less land requirement and better treatment performance would achieve more ecological benefit with respect to GHG emissions and suggested that VFCW is efficient at nitrification which is regarded as a crucial step before denitrification, methanogenesis, and other processes in connection with GHG emissions because of the effective oxygen transportation [28]. The incomplete denitrification and methanogenesis, during which large quantities of N_2O and CH_4 are produced, are considered to occur frequently in HFCW for its anoxic and anaerobic conditions [29]. Hence, GHG emissions correlated with dissolved oxygen (DO) are much higher for HFCW.

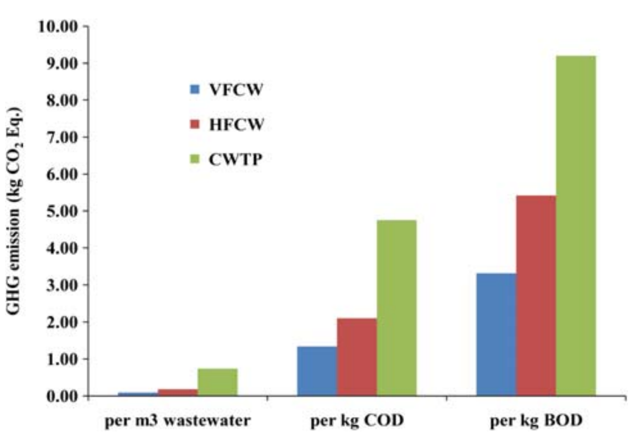
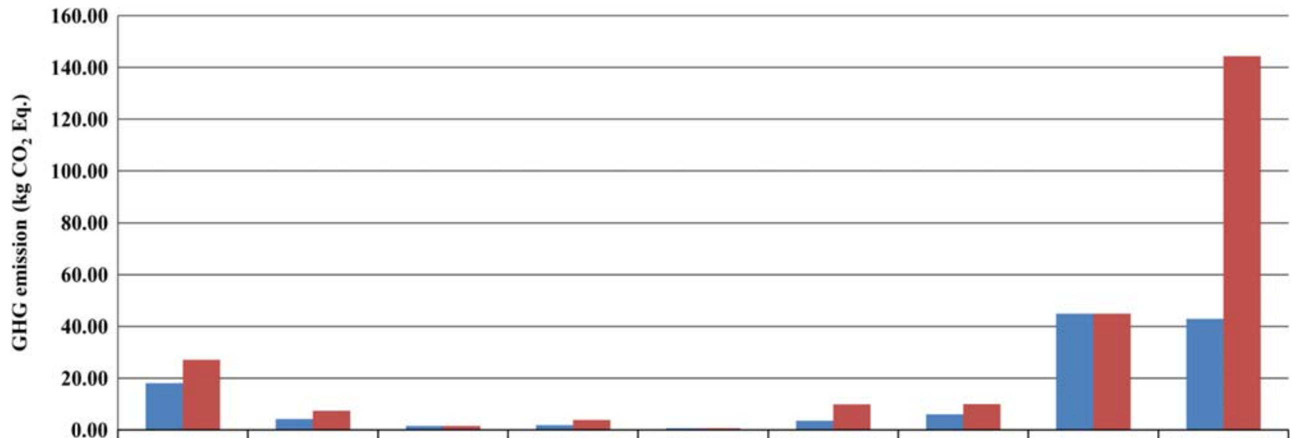


Fig. 5. Comparison of GHG emissions per m^3 wastewater, kg COD, and kg BOD between CWs and CWTP.

Different CWs would have different GHG emissions due to temporal and seasonal variations. The GHG emissions from CWs located in different regions, such as temperate and tropical zone, were distinct from each other. The difference of GHG emissions between VFCW and HFCW also depends on climate conditions. Søvik et al. [18] analyzed two VFCWs and four HFCWs in Estonia, Finland, Norway, and Poland and found that HFCW could emit 300.00 mg $CH_4/m^2/d$, while VFCW only generate 110.00 mg $CH_4/m^2/d$ in summer. However, N_2O and CH_4 emissions were very low for two types of CWs in winter. In addition, VFCW requires less construction materials due to higher treatment efficiency and consequently lower land area [11]. Fig. 6 shows the main sources of GHG emissions for HFCW and VFCW. The GHG emissions from most of the materials and energy inputs of VFCW are lower than that of HFCW. The substrate and electricity power produce large amounts of indirect GHG emissions both in VFCW and in HFCW, which is consistent with the study of Chen et al. [23] who reported a corresponding proportion of 10.95 and 36.92%. The quantities of GHG emissions from geotextile as well as bricks and cement are larger for HFCW, which suggests that HFCW emits more GHG emissions in the construction stage as a result of higher consumption of material. For the two types of CWs, the biggest indirect emission source of N_2O is vegetation, while the electricity generates most of indirect GHG emissions of CO_2 and CH_4, which is also supported by Chen et al. [23].

The HFCW also causes a higher amount of CO_2, CH_4, and N_2O emissions than VFCW does. The margin of the amount of CO_2 emissions between HFCW and VFCW is evident in this case. In this estimate, the impact of CO_2 emissions on climate change account for 77.79% in VFCW, while 56.94% of that is for HFCW, indicating that CO_2 emissions play an important role in climate change for CWs. Chen et al. [23] also reported that carbon dioxide from CWs could account for 77.75% of the total GHG emissions, which is similar to our results. The higher fraction of CO_2 emissions for VFCW is partly because of the significant influence from indirect GHG sources which could lead to large amounts of CO_2 emissions. Generally, VFCW would restrain the direct production of CH_4 and N_2O due to greater oxygen transport capacity and higher treatment efficiency [28] as well as a lower consumption of materials [11]. This is also consistent with our study which shows that direct CH_4 and N_2O



	Substrate	Vegetation	Pump	Pipe and valve	Electric control	Bricks and cement	Geotextile	Electricity	Direct GHG emissions
VFCW	18.00	4.20	1.48	1.78	0.60	3.50	5.97	44.83	42.90
HFCW	27.01	7.34	1.48	3.83	0.60	9.81	9.95	44.83	144.35

Fig. 6. The GHG emissions from different materials and direct sources for VFCW and HFCW.

emissions of VFCW are lower than HFCW. As the same quantities of CH_4 and N_2O have a remarkably higher influence on climate change, it can also reach a conclusion that HFCW has a greater impact on global warming with a relatively higher generation of CH_4 and N_2O. When considering the climate effect using kg CO_2 Eq. as unit, the sum of CH_4 and N_2O emissions account for 22.21 and 43.06% for VFCW and HFCW, respectively. Even if the amount of CH_4 and N_2O emissions in both CWs is only a minor fraction of total amount of GHG emissions, they may also have greater effect on climate change due to their long life and great global warming potential of up to 21 and 310 times than CO_2 [16]. Therefore, given that CWTPs are recognized as one of the sources of GHG emissions, CWs may be a good choice for reducing environmental impacts while attention should be paid to CH_4 and N_2O emissions of different types of CWs especially for HFCW due to their greater influence on climate change [12,15,23,24].

To date, the reduction of environmental impacts and conservation of resource is becoming a priority for choosing the type of CWs [11]. It would underestimate the actual ecological benefit just conducting comparison of GHG emissions between different types of CWs. VFCW requires significantly less land area than HFCW and achieves the same water quality standards at much lower environmental cost. The life cycle assessment conducted by Fuchs et al. [11] showed that VFCW has less environmental impacts than HFCW during the life cycle due to better treatment efficiency as well as smaller quantities of materials input and consequently less GHG emissions.

3.4. Mitigation of GHG emissions

Recently, there is a considerable interest in managing the design, operation, and construction stages of CWs to mitigate GHG emissions [3,13,14,19,30]. The results of this case are significant for the establishment of mitigation strategy due to comprehensive comparison of GHG emissions in different phases.

3.4.1. Design and construction phases

Different types of CWs can be analyzed through some assessment such as LCA which can be used in the design phase for choosing the appropriate systems with similar performance by accounting for the environmental impacts of GHG emissions caused by each system over its life cycle [11]. Generally, VFCW is smaller than HFCW in treating the same amount of pollutants, which means that VFCW has less indirect GHG emissions in the construction stage. Moreover, VFCW generates less GHG emissions in the operation stage, while they also have higher capability of wastewater treatment and economical benefit. Thus, generally, VFCW tends to be selected for wastewater treatment in the design phase if taking GHG emissions, treatment efficiency, and resource reservation into account.

The different fractions of direct and indirect GHG emissions also deserve our attention in the design phase, because VFCW and HFCW both emit large amounts of GHG in the process of nitrification and denitrification. Nitrification and denitrification are directly related to oxygen concentration, C/N ratio, temperature, and influent nitrogen concentration. Therefore, it can also reduce the GHG emissions through applying a new method of design to optimize the conditions for nitrification and denitrification and achieving the target of decreasing the amount of construction material such as bricks and cement as well as geotextile at the same time on the basis of maintaining the efficiency of wastewater treatment in CWs. For example, the adoption of hybrid CW system (e.g. HF–VF or VF–HF) could provide favorable conditions for nitrification and denitrification and consequently contribute to a good treatment performance [31], which would ultimately decrease the amount of GHG emissions. The materials used in the construction stage also act as an important GHG sources. Optimizing the design for nitrification, denitrification, and oxygen transfer process will simultaneously reduce the amount of materials and energy used in the construction phase and eventually results in lower GHG emissions. Moreover, the items responsible for large amount of GHG emissions, such as some substrate, bricks and cement, and geotextile, could be substituted by other materials or reduced in the design and construction phases. It will decrease the amount of GHG emissions if the materials used in the construction phase are sourced locally and thus generate lower energy consumption and environmental emissions. As mentioned above, the biggest indirect emission source of N_2O stems from vegetation input process, while the electricity generates the largest part of indirect GHG emissions of CO_2 and CH_4. Therefore, appropriate selection of plants species and diversity as well as design pattern for energy conservation will also reduce the GHG emissions.

3.4.2. Operation phase

For the CWs that had already been constructed, there are also some approaches to mitigate the GHG emissions in operation stage. DO is the greatest factor influencing the GHG emissions [30,31]. Lower CH_4 and N_2O emissions would be produced via methanation and incomplete denitrification due to higher DO concentration in VFCW [15,31]. Vymazal [31] also reported that the nitrite could be denitrified to N_2O without being converted to N_2 under low DO conditions during the process of partial nitrification–denitrification and anaerobic ammonium oxidation (ANAMMOX) in CWs. Meanwhile, Maltais–Landry et al. [30] found that the CH_4 emissions were higher in non-aerated CWs, while redox potential and DO concentration by plants and artificial aeration were negatively correlated to CH_4. Therefore, GHG emissions can be reduced significantly through manipulating DO as well as the density and type of plant in CWs. On the other hand, water temperature is also a good predictor of GHG emissions for CWs. Denitrification proceeds at very slow rates below 5 ℃, during which large amounts of N_2O generated in CWs [31]. In the research of Stadmark and Leonardson [4], CH_4 emissions increased in a constructed pond when water temperature exceeded 15 ℃ and the emissions nearly stopped at temperatures below 10 ℃. They also illustrated that the existence of nitrate might restrain the production of CH_4 compared to the treatment with no nitrate addition. This demonstrates that the control of N_2O and CH_4 emissions may conflict with each other. Thus, further study about the seasonal effect and interaction between different gasses on the GHG emissions may be beneficial for the formulation of mitigation strategy.

Some efforts also have been made toward using continuous regime, instead of intermittent hydrologic one, to reduce GHG emissions. Several studies have shown that CWs with continuous loading emitted less emissions of CH_4 and N_2O compared to intermittent hydraulic loading [5,6]. Continuous loading, which is a kind of pulsing hydrological regime of natural wetland, increases the aeration rate and supports more effective removal processes. It can lead to complete removal of BOD, COD, NH_4, and total N and consequently lower CH_4 and N_2O emissions compared to intermittent loading [1,2,7,8]. In addition, electricity as a main indirect source for GHG emissions in the operation phase may also be reduced through changing the operational regime such as the optimization of water quantity and the control of HRT as well as inflow and outflow patterns.

Recently, GHG emission inhibitors which can be applied in CWs were discussed by several researchers. Pangala et al. [3] investigated the effect of addition of two potential inhibitors for CH_4 emissions for a CW in Scotland, UK. The study indicated that CH_4 emissions could be suppressed by 51.00–77.00% in the pilot-scale experiment and more than 90.00% if the experiment was conducted in laboratory incubations through utilizing iron ochre. The Gypsum could also reduce CH_4 emissions by 28.00% after the amount used in CWs doubled. Clough et al. [13] and Wolt [14] also reported that inhibitors such as nitrapyrin were capable of reducing the risk for N_2O emissions by 60.00%.

4. Conclusion

Beyond other reported GHG emissions estimates, which showed that CWs have more environmental benefit than CWTPs, this estimate demonstrates that different types of CWs have distinct GHG emissions under similar conditions. The global warming assessment characterized by GHG emissions in this paper can offer a comprehensive analysis for environmental impacts when choosing alternative wastewater treatment systems from different types of CWs. This study shows that VFCW generates less GHG emissions in treating same amount of pollutants, while the two types of CWs have less influence on climate change compared with CWTPs throughout the life cycle. It is further proved that VFCW has less environmental impacts than HFCW when resource conservation and treatment efficiency are also taken into consideration. From this point of view, VFCW is more suitable for the treatment of eutrophic wastewater due to its higher capability of treatment efficiency and lower level of indirect and direct GHG emissions. Moreover, GHG emissions from operation phase account for most of the GHG emissions from CW systems. Although CO_2 dominates the GHG emissions, CH_4 and N_2O emissions should deserve more attention due to their higher global warming potential. In order to reduce the GHG emissions, different kinds of mitigation methods could be applied in the design, operation, and construction stages to reduce the GHG emissions. Further work is needed to be carried out to know more about the behavior of different kinds of GHG in CWs and come up forwards more feasible mitigation strategies.

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