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Efficiency and kinetic modeling of removal of nutrients and organic matter from a full-scale constructed wetland in Qasr-e-Shirin, Iran

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Abstract

Background: This study assessed the removal of organic material and nutrients from full-scale subsurface flow (SSF) constructed wetlands (CWs) followed by anaerobic stabilization ponds under environmental conditions.

Methods: The effluents were distributed evenly in 12 reed beds. Samples were taken twice monthly for a total of 6 months from several points in the wetland. Biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and nutrient removal from the system and the longitudinal effect of the reed beds for removal of pollutions were determined. A full-scale model of flow, BOD, and nutrients in SSF in the CWs is presented.

Results: The flow rate and concentrations of parameters indicated that removal of organic matter and nutrients in the cold months decreased rather than in the hot months, as expected. The removal efficiency for BOD, COD, and TSS and the strongest biological interactions showed no uniform trends. The beds showed the highest removal rates in the first few meters of bed. The hybrid Monod-Plug flow regime and the Stover-Kincannon models showed the best fit for the kinetics of the processes. U_{max} in the Stover-Kincannon model was 3.64 mg/l.d for nitrogen and 0.24 mg/l.d for phosphorus. These values are very low, which indicates lower consumption and inefficiency of the system for removing nitrogen and phosphorus.

Conclusion: It can be concluded that the SSF in CWs are able to treat average wastewater as effectively as common mechanical systems at lower cost.

Keywords: Kinetic modeling, Nutrient, Organic matter, Wetland, Qasr-e-Shirin

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Introduction

Relatively simple wastewater treatment technologies can be designed to provide low cost sanitation and environmental protection while providing additional benefits from the reuse of water. Constructed wetlands (CWs) are essentially new developments for the utilization of wastewater and sludge. These wetlands provide cost-effective waste treatment options (1,2). For regulatory purposes under the Clean Water Act, the term "wetlands" denotes those areas inundated or saturated by surface or ground water, either permanently or seasonally. Wetlands vary widely according to regional and local differences in soils, topography, climate, hydrology, water chemistry, vegetation, and other factors such as disturbance by humans. These areas can be distinguished from other water bodies or land by their water levels and the types of vegetation and animal communities in the soil and at the surface (3). Different types of pollutant (nitrogen, phosphorus, organics, solids, metals, and coliforms) can be removed by CWs through a complex inter-connected system of plants, media, bulk water, and biomass population (4). They already function to filter water and trap sediment before it enters a body of water. As an interface between catchments and surface water, they play an important role in the control of water quantity and quality of surface water systems in general and in the reduction of diffuse pollution in catchments in particular (3,5).

CWs are an ideal environment to support the growth of organisms that break down pollutants in wastewater by biodegradation. The presence of bacteria is extremely important because they often act as catalysts for pollutant removal in subsurface flow (SSF) wetland bioreactors (6). In CWs, the wastewater is purified by the physical, chemical, and biological triple synergy of the natural ecosystem (7,8). CWs have the advantage of producing higher quality effluent without the input of fossil energy, thereby reducing operational costs (6,9,10). They are often categorized as surface flow (SF) CWs or SSF CWs. SSF CWs can be further subdivided into horizontal flow (HF) and vertical flow (VF) systems, depending on the direction of the flow of water through the porous media (sand or gravel) (8,11). The combination of a VF and HF system is known as a hybrid wetland and can be employed for the treatment of wastewater. This combination often optimizes nitrogen and organics removal with the presence of aerobic, anaerobic, and anoxic phases (12). SSF treatment wetlands are used worldwide to remove pollutants from wastewater because they are mechanically simple and require low operation and maintenance (O&M) in comparison with conventional wastewater treatment technologies (13). These systems are currently in limited use as unusual constructed reed beds in many parts of the world. Further and more detailed study of the method is needed.

Overviews of current developments on numerical modeling of SSF CWs based on modeling and model development have been presented by various authors (14-16); however, there is little information available about the use of wetlands as public remediation-sites for wastewater treatment purposes (17). This usage is not fully understood to date because of the lack of appropriate models. The most widely-employed modeling equations (Kickuth equation and KeC model) give only an exponential profile of inlet and outlet pollutant concentrations without considering the full range of pollutant variability in CWs (10,18).

Almost all available design guidelines are based on empirical rules of thumb, such as those using specific surface area requirements or simple first-order decay models. The main objective of numerical modeling is to obtain a better understanding of the processes governing the biological and chemical transformation and degradation occurring in CWs. Once reliable numerical models are developed and validated against experimental data, they can be used to evaluate and improve existing design criteria (8,19,20). Kinetic modeling and optimization of system parameters can be used to optimize the design, implementation, and O&M of such systems. The goal is to provide the highest efficiency filtration based on prior knowledge of local conditions at a reasonable cost. This will contribute to the development of technology for wastewater treatment using artificial reed beds. Langergraber (21) reported that few numerical models are able to describe the treatment processes in SSF CWs.

The present study investigated the removal efficiency of organic matter and nutrients and kinetically modeled the processes at work in a CW near the city of Qasr-e-Shirin in Kermanshah province in Iran. A wastewater treatment system consisting of an anaerobic stabilization pond combining with a SSF CW was selected for examination. In this system, wastewater passing from the screening and grit chamber enters two anaerobic stabilization ponds. The effluent from the anaerobic ponds is eventually distributed uniformly into 12 reed beds having similar physical and hydraulic forms. The effluent from the reed beds drains into a single collecting channel and flows into a chlorination pool. The pattern of removal of organic matter, nitrogen, phosphorus, and suspended solids on effluent quality are the main parameters.

Methods

Wetland characteristics

This empirical full-scale study was conducted over the course of 6 months that included both hot months (July, August, and September) and cold months (December, January, and February) at a wastewater treatment plant in Qasr-e-Shirin, Iran. This treatment plant having 14 hectares has been in operation since 2008. The projected plan for 2021 is to meet the requirements for a population of 30 thousand people.

Of the 12 subsurface constructed beds, 11 contain reeds (*Phragmites*) and one contains cattails (*Typha*). All beds have similar physical and hydraulic design conditions. The length of the beds is 25 m and the width is 125 m. Each bed contains 16 distribution tubes placed 7.5 m apart, providing a length to width flow ratio of 1:3. One reed bed was randomly selected for investigation (bed 11; Figure 1). All outlets were connected to a manhole from which the output was collected. The effluent of all reed beds flows into a single collecting channel and then into a chlorination pool. Substrate draining was facilitated by a 0.8% slope of the floor of the beds. The depth of gravels at beginning and end of the beds was 75 and 95 cm, respectively. Table 1 and 2 provide detailed characteristics of the ponds and reed beds.

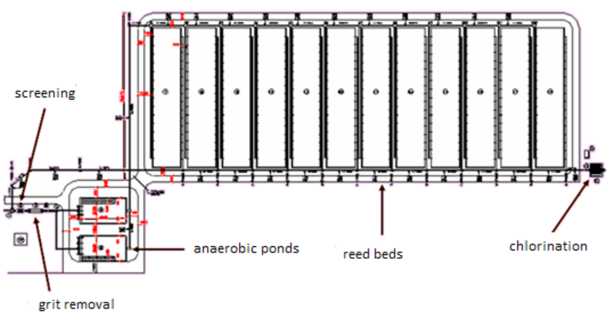


Figure 1. Unit arrangement at Qasr-e Shirin wastewater treatment plant.

Table 1. Characteristics of Qasr-e Shirin wetland beds

Parameter	Characteristic
System type	Subsurface horizontal flow
Type of plant	*Phragmites australis, Typhae*
Input flow to each bed	180 m^3/d
BOD_5 loading	450 kg/d
Total surface area	3,125 m^2
Length of each bed	25
Width of each bed	7.5
Length of all sand beds	25 m
Width of all sand beds	125 m
Average depth of sand bed	0.85 m
Bed porosity	35%
Hydraulic retention time	5.2 d
No. of input tubs in each bed	16
No. of output tubs in each bed	16
Floor type	Compacted clay
Distance between adjacent straws	5 m
Sand diameter	8-10 mm

Table 2. Characteristics of Qasr-e-Shirin anaerobic ponds

Parameter	Characteristic
Volume of each pond	4400 m^3
Area of each pond	880 m^2
Useful depth	5 m
Hydraulic retention time	4 d
Interval of sludge discharging	3 y
Floor type	Compacted clay: height 20 cm

Wetland efficiency

The temperature, pH, total biochemical on demand ($TBOD_5$), total chemicals on demand (TCOD), total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP) were determined using 24-h composite sampling 3 times/d (2-h samples) at 4 boreholes in the reed bed. The 3 samples were mixed (Figure 2) to provide a mean value. Sampling was done twice/mo over the 6 months study duration. A total of 252 samples were collected and analyzed. The reed bed effluent flow rate was also measured manually and ultrasonically using the existing Parshall flume.

The effect of bed length on pollutant removal was determined by selecting a bed of 25 m in width (bed 11) and dividing it into five parts at intervals of 5 m. Seven sampling sites were designated in consideration of the location of the 4 polyethylene sampling boreholes embedded in the bed and the entrance (anaerobic pond effluent) and exit points in the reed bed and entrance point to the treatment plant.

Data gathering

All experiments were performed at the Water and Wastewater Laboratory at the Western Higher Educational

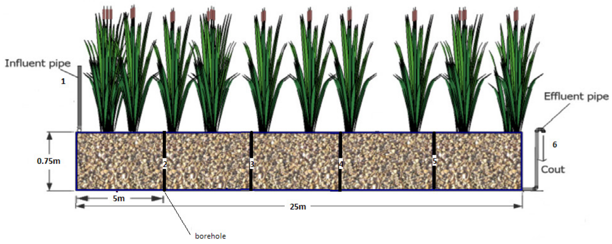


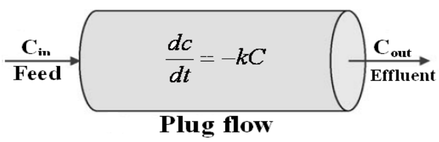
Figure 2. Surveyed wetland and sampling points.

Complex of the Department of Civil Engineering and Sewage Research. Testing for BOD_5, COD, TSS, and TP were performed using the Standard Methods for the Examination of Water and Wastewater (22). TN tests were done using ready-to-use vials (Hatch) according to manufacturer recommendations (Table 3).

Kinetic modeling

Kinetic equations are applied to explain the transport behavior of the adsorbate molecules per time unit. Four hybrid models were used for kinetic modeling of organic matter, nitrogen and phosphorous removal as follows (24):

Combined first-order kinetic equation and flow regime Plug flow model

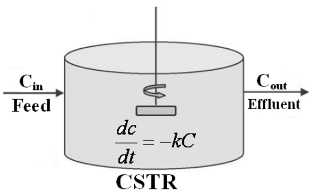


This creates the first design equation (Kickuth), which is the easiest and most commonly-used equation for design of wastewater stabilization ponds (WSPs):

$$A_h = \frac{Q(\ln C_{in} - C_{out})}{K_1} \quad (1)$$

where A_h is pond area (m^2), Q is flow rate (m^3/d), C_{in} is input BOD_5 concentration (mg/l), C_{out} is output BOD_5 concentration (mg/l), and k_1 is the velocity constant (m/d).

Combined first-order kinetic equation and CSTR model



This flow pattern results in the simplified equation shown below. Areal rate constant k_1 (m/d) is used to correlate the influent and effluent N and organics in the SSF CWs (10):

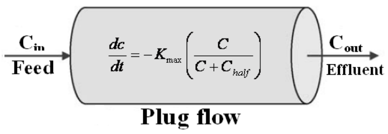
$$k_1 = \frac{q(C_{in} - C_{out})}{C_{out}} \quad (2)$$

where q is the hydraulic loading rate (m/d).

Table 3. Methods used to measure parameters

Test	Method	Headline
COD	Reflux titration and Hatch vials for control	C 5220
BOD_5	5-d method and using OXITOP (WTW) and Hatch vials for control	B5210
TSS	Drying at 103-105°C	D 2540
TP	Total phosphorus method	P 4500
TN	Hatch vials and Nessler's reagent method	Ref. (23)

Combined Monod kinetic equation and Plug flow regime



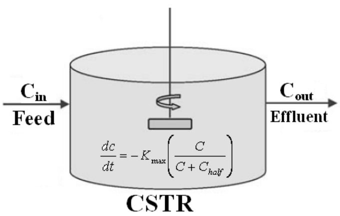
This equation is:

$$\frac{dc}{dt} = -k_{\max}\frac{C_{in}}{C + C_{half}} \tag{3}$$

$$A_h \frac{Q(C_{in} - C_{out} + 60\ln(C_{in}/C_{out}))}{K_3} \tag{4}$$

where k_{max} is the maximum BOD_5 removed in pond regardless of temperature (g/m^3.d), C_{half} is the wastewater BOD_5 when the organic matter is removed and equals half of k_{max} (60 mg/l; a common value for Monod's equation 3).

Combined Monod kinetic equation and continuously stirred reactors (CSTR) model



This is described by equation 5 below, which links inlet and outlet pollutant concentrations

$$\frac{C_{in} - C_{out}}{\tau} = K_{\max}\frac{C_{out}}{C_{half} + C_{out}} \tag{5}$$

Equation 5 is expressed in terms of hydraulic retention time (unit/d) and k_{max} represents maximum pollutant mass removal per m^3 of wetland volume per d. The relationship between hydraulic retention time, area (A, m^2), depth (h, m), and porosity (e) of packed media and inlet discharge (Q, m^3/d) can be expressed as:

$$\tau = \frac{Ahe}{Q} \tag{6}$$

Combining k_{max} (g/m^3/d) with h and e results in areal maximum pollutant removal (k_2: g/m^2/d) as expressed in Eq. 7 to correlate inlet and outlet pollutant concentrations as.

$$k_2 = \frac{q(C_{in} - C_{out})(C_{half} + C_{out})}{C_{out}} \tag{7}$$

Equation 7 can be used to predict N and organic degradation in SSF CWs. In the first step of NH_4-N transformation (NH_4-N to NO_2-N) during nitrification, the half saturation constant (C_{half} for Nitrosomonas degradation) was 0.05 mg/l (25). This value was used as C_{half} in equation (7) for nitrification. For denitrification of NO_3-N, the nitrate half saturation constant in the Monod kinetics was used at 0.14 mg/l (26). For heterotrophic BOD_5 removal, the recommended degradation half saturation constant is 60 mg/l for wastewater treatment (27). For COD, the COD half saturation constant used was 20 mg/l as suggested by Saeed et al (10) for sewage treatment.

Stover–Kincannon kinetic model

The Stover–Kincannon model was first employed to predict attached growth in wastewater treatment and was then modified and used to describe and predict the performance of the biological reactor. The linearized state of this model is (28):

$$\frac{1}{\frac{ds}{dt}} = \frac{V}{Q(S_o - S)} = \frac{K_B}{U_{\max}}\frac{V}{QS_o} + \frac{1}{U_{\max}} \tag{8}$$

where U_{max} is the maximum removal rate, K_B is the saturation rate, Q is the flow rate (m^3/d), and V is the the volume of the reactor (m^3).

Results

Performance evaluation of treatment plant

The data shows that the average flow rate and pollutant concentration in the cold months were lower than in the hot months, as expected. This is generally the reverse in urban areas without considering precipitation point. The current study indicates higher organics removal in SSF wetlands than in SF wetlands. During the study period, TSS and TP in the reed beds effluent were below standard levels (TSS = 12 mg/l; TP = 3.8 mg/l). The concentration of TN in the effluent was 17 mg/l (maximum 19.3; minimum 15.4 mg/l) which approaches effluent standards. The input and output of the parameters in each unit of the treatment system are shown in Table 4.

The amount of organic matter, even in the worst state (coldest month; January) was less than or close to standard levels. The proportion of BOD5, COD and TP eliminated from the anaerobic ponds and reed beds was almost equal, but in the hot months, the anaerobic ponds recorded higher removal efficiency than the reed beds (Figure 3). TN removal in the reed beds overall was greater than in the anaerobic ponds (Figure 4). Note that the total area used for the anaerobic ponds was 1760 m^2; the area occupied by the plant beds was 37500 m^2 (21 times larger than the anaerobic ponds), which shows the importance of the anaerobic ponds and their contribution to refining.

Table 4. Parameters during hot, cold, and total periods of study for all treatment plant units

Location parameter	Input to treatment plant (mg/l) (anaerobic pond)			Output of anaerobic pond (mg/l) (input of reed bed)			Output of reed bed (mg/l) (treatment plant)		
	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
Total study period									
BOD_5	193	265	224	86	155	123	13	45	27
COD	348	422	375	153	244	211	29	71	51
TSS	177	222	199	42	106	72	6	17	12
TN	23	39.2	33	23.5	37.2	31	14.2	19.8	17
TP	5	7.5	6.4	4.2	6.4	5.1	3.3	4.4	3.8
Hot months									
BOD_5	193	235	220	86	128	109	13	30	19
COD	348	389	367	153	244	190	29	52	38
TSS	177	215	200	52	88	70.8	7	15	11
TN	31	39.2	34.38	29	35.9	31.4	14.2	17.8	16.5
TP	5	7.5	6.48	4.2	6.4	4.9	3.3	4.1	3.6
Cold months									
BOD_5	212	265	228	123	155	137	24	45	35
COD	357	422	383	218	243	232	54	71	64
TSS	179	222	198	51	96	73.2	6	17	13
TN	23	39.1	31.62	23.5	37.2	30.6	15.2	19.8	17.5
TP	5.7	7.1	6.32	4.4	6.4	5.3	3.5	4.4	4

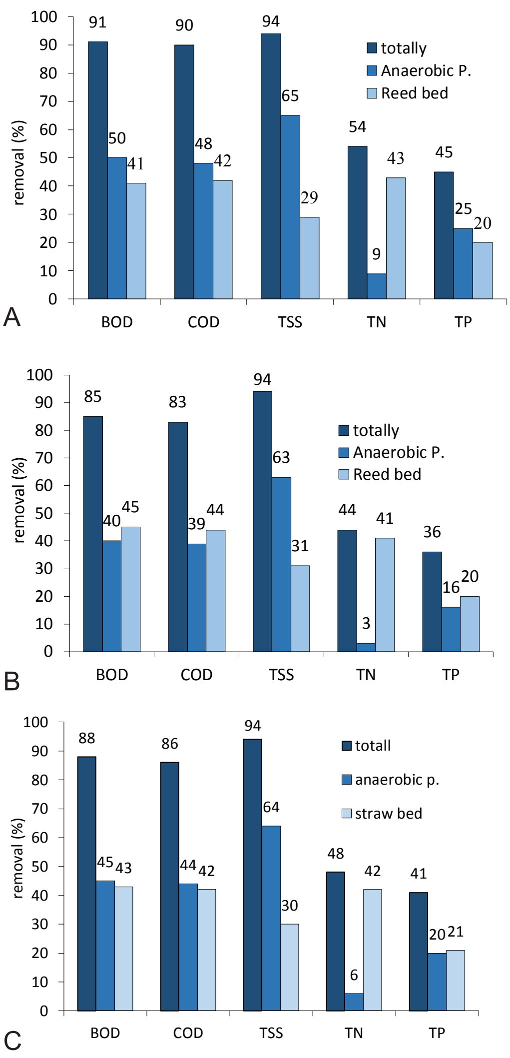


Figure 3. Average parameter removal in anaerobic ponds and reed beds in (A) hot months; (B) cold months; and (C) overall.

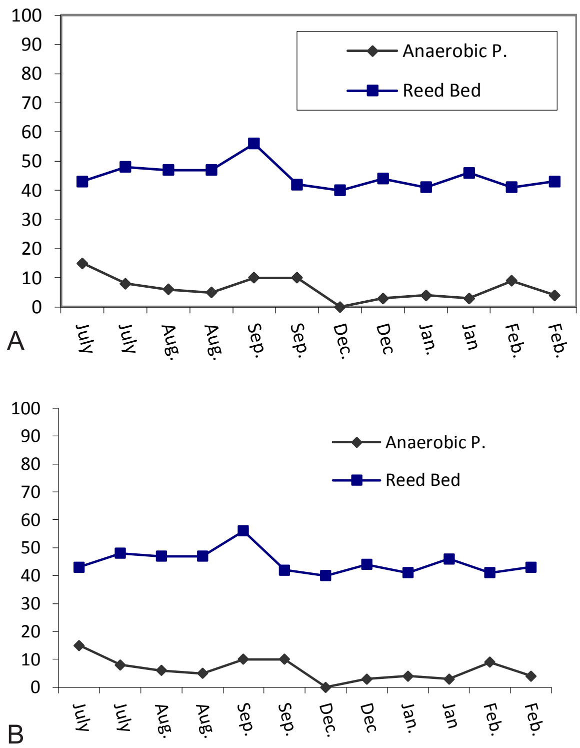


Figure 4. (A) Average TN removal; and (B) average TP removal in reed beds and anaerobic ponds for total study period.

Longitudinal effect on organic matter and nutrient removal

The BOD5, COD, TSS, TN, and TP removal showed no uniform trend in the reed bed (Figure 5). The highest removal efficiency was observed in the first few meters of the bed. The greatest biological interaction occurred in the first meters (27%, 30%, 47%, 13%, and 10%, respectively), but removal of the final 5 m of the bed was only

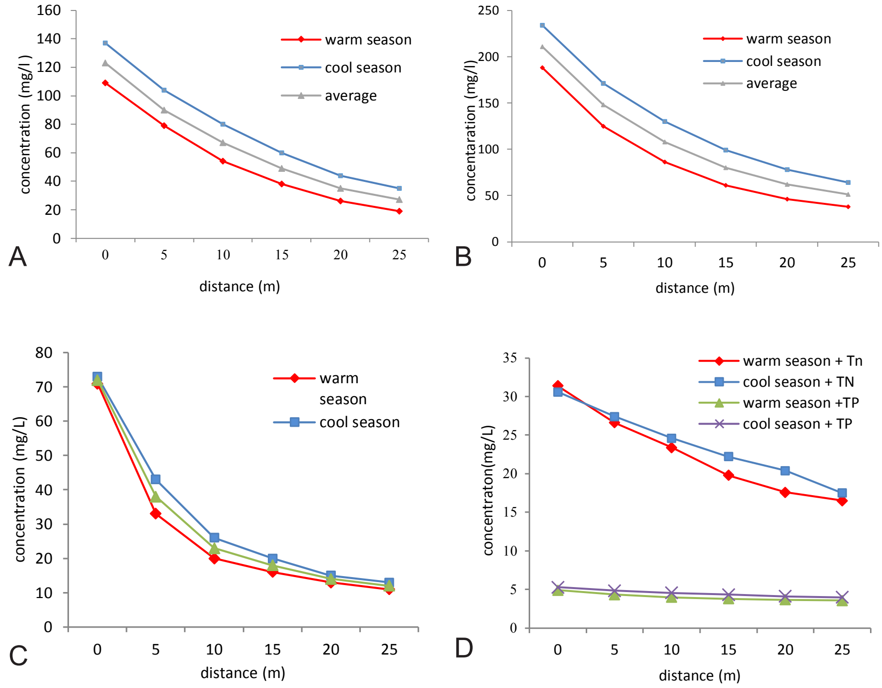


Figure 5. Average concentration of: (A) BOD5; (B) COD; (C) TSS; and (D) TP and TN in the hot and cold months along the length of the bed.

7%,5%, 3%, 6% and 2% for BOD5, COD and TSS, TN and TP, respectively. A greater amount of suspended BOD5 was removed than soluble BOD5 because of the porosity of the bed.

Evaluation of process kinetics

Organic matter

The hybrid Monod kinetics and Plug flow regime models showed good fit with the field data. To further investigate and achieve greater agreement, other valid models such as the Stover-Kincannon and pseudo-first-order kinetic models were examined (Table 5). The correlation coefficient (R^2) for the Stover-Kincannon was 0.95. The Stover-Kincannon model showed better fitness than the other model; R^2 was low for the other model, which indicates poor correlation with the field data.

The U_{max} (feed consumption rate) for BOD5 in the subsurface artificial straw bed at Qasr-e-Shirin was very low (50 mg/l.d). This low value indicates that the system (bed volume) was too large for this loading rate and that treatment plant has the capacity to receive more wastewater flow.

Nutrients

The Stover-Kincannon and first-order models were investigated for removal of N and P and the Stover-Kincannon model was determined to be the most applicable for removal of nutrients (Table 6). U_{max} for N was 3.64 mg/l.d and P was 0.24 mg/l.d, which is very low.

Discussion

CWs are typical of natural and environmentally-friendly systems using rooted water-tolerant plants and gravel or soil media to treat wastewater. As a green treatment technology, CWs have the unique advantage of producing higher effluent quality without the input of fossil energy, thereby reducing operation costs (6). The disadvantage of

Table 5. Kinetic parameters for removal of BOD5 from selected wetland

Equation	Parameter			
	R^2	k_1		Regression equation
Combined first-order and Plug flow model	0.484	0.079		Y = 0.079 x
Combined first-order and CSTR model	0.267	0.199		Y = 0.199 x
Combined Monod and Plug flow model	0.723	9.53		Y = 9.53 x
Combined Monod and CSTR model	0.393	16.76		Y = 16.76 x
Stover-Kincannon kinetic model	R^2	U_{max}	K_B	
	0.95	50	42.7	Y = 0.854 x -0.020

Table 6. Performance of kinetic models for TN and TP removal from wetland

Stover-Kincannon				
Coefficients	R^2	U_{max}	K_B	Regression eq.
N removal	0.859	3.64	13.45	Y = 3.696 × -0.275
P removal	0.754	0.24	1.87	Y = 7.791 × -4.251
First order				
Coefficients	R^2	k_1		Regression eq.
N removal	-0.15	0.138		Y = 0.138 ×
P removal	0.104	0.57		Y = 0.057 ×

HF wetlands include high area demand, clogging, sulfur transformation that can affect nitrification sensitivity, and loss of TP removal performance. Careful calculation of hydraulics are necessary for optimal oxygen supply and low ammonium oxidation.

The average flow rate and pollutant concentration in the cold months was lower than in the warm months. Because the boundary city of Qasr-e-Shirin is a border crossing point to the Holy Shrines in Iraq, the number of pilgrims traveling in autumn and winter is higher than in the hot summer months. This affects the quality and quantity of treatment plant influent.

The treatment plant has sufficient capacity, especially in summer, to treat the pollutants loaded into the system. The removal efficiency of COD in the hot months was somewhat lower than environmental standards, but did not meet the standard levels in the cold months. In the summer, wetland plants (macrophytes) typically grow in water or soil media subjected to oxygen deficiency (6). The removal of organics was higher in the SSF wetlands compared than in the SF wetlands, but the system exhibited poor TN removal, which agrees with the results of the previous studies (6,29). Several surveys conducted on mechanical systems and lagoons have reported removal efficiencies of 90% to 95% for BOD_5 and 90% to 95% for TSS, which agrees with the results of the present study. TN and TP removal were reported to be 10% to 20% and 15% to 25%, respectively, but these deficiencies have been better addressed in the present treatment system (27,30,31).

CWs provide an ideal environment that supports the growth of organisms that break down pollutants in wastewater by biodegradation. Bacteria, fungi, and algae are common organisms in wetlands (6). The physical components of wetland macrophytes (aerial tissue, plant tissue in water, and roots) contribute to wetland performance optimization to some extent (32).

Seswoya and Zainal (33) found that the SSF CWs performance for removal of high strength effluent in domestic wastewater is potentially good. The pollutant removal percentage depends upon the area of the CW. A large area is needed for higher removal. Chang et al (34) employed 2 pilot-scale integrated vertical-flow CWs with the plant species *Typha Orientalis* and *Arundo Donax* var. versicolor, and *Canna Indica* and *Pontederia Cordata*. The mean removal efficiencies, respectively, were 59.9% versus 62.8% for COD, 15.0% versus 12.8% for TN, and 52.0% versus 51.1% for TP. The mean mass removal rate (g m^{-2} d^{-1}) was 44.3 versus 46.4 for COD, 1.27 versus 1.08 for TN, and 0.393 versus 0.386 for TP, respectively. It was noted that nitrification was the limiting step for TN removal.

The organic matter content, even in the worst state (coldest month; January) was below or close to the standard level. This can be explained by the high performances in anaerobic ponds, as the first unit, which increased the treatment plant efficiency and reduced pollution-loading into the plant bed. The proportion of anaerobic ponds and reed beds for elimination of BOD5, COD, and TP were almost equal, but, in the hot months, the anaerobic ponds showed higher removal efficiency than the reed beds.

Saeed and Sun (35,36) and Tee et al (37) asserted that the substantial organic and TN removal observed in VF and HF systems is caused by: (*a*) atmospheric oxygen diffusion through porous media; and (*b*) leaching of C from the employed organic media to the bulk water, stimulating denitrification.

The performance disparity of CWs for TN and organics removal could be attributed to: (*a*) the presence of excessive organic compounds in wastewater that inhibits nitrification (38) because faster heterotrophic organic degradation depletes dissolved oxygen (DO) availability (10); and (*b*) lack of biodegradable organics often hinders classic denitrification metabolism from dependency on organic carbon in wetland systems (39). The current target of wetland performance optimization (40) was heavily dependent on overcoming the conflicting dependency, between TN and organics removal.

In SSF wetland systems, the transformation and removal of TN are accomplished by both classic and newly-discovered routes. The classic pathways include biological (ammonification, nitrification, denitrification, plant uptake, biomass assimilation, dissimilatory nitrate reduction), and physicochemical routes (ammonia volatilization, and adsorption). The newly-discovered nitrogen removal routes are solely dependent on microbiological metabolism such as partial nitrification-denitrification, anammox, and Canon (Figure 6). The presence of macrophytes is essential for wetlands to improve TN removal performance (6,41,42)

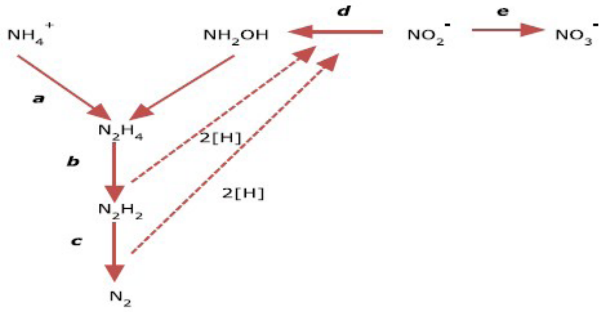


Figure 7. N removal kinetics using anammox. Step a: NH4 þ is oxidized to hydrazine by hydroxylamine; Steps b, c, d: Hydrazine is oxidized to N_2 and the reducing equivalents reduce nitrite to hydroxylamine; Step e: NO_3 forms as the by-product of anammox kinetic metabolism.

Longitudinal effect on organic matter and nutrient removal

BOD5, COD, TSS, TN and TP removal showed no uniform trends in the reed bed. The highest removal efficiency occurred in the first few meters of bed for which the highest level of biological interaction occurred. A greater amount of suspended BOD5 was removed than soluble BOD5 because of the porosity of the bed. The subsurface wetland systems acted similarly to a sand filter (29).

Process kinetics

Organic matter

The R^2 for Stover-Kincannon was 0.95, meaning that it showed a better fit than the other models. Since this model assesses entrance-loading against removed load, it is well-adapted for real-scale systems, such as adsorption, suspended growth, and attached growth and was first designed for attached-growth systems (43).
The value of U_{max} for a system of this size for approximately 6 days retention time was very low. This system was inefficient for removal of organic matter. This could be the result of improper design and the very broad surfaces compared to the small amounts of feed, which decreased the amount of biomass in the system (21,44).

Nutrients

The Stover-Kincannon and first-order models were investigated for removal of TN and TP. The Stover-Kincannon model was most applicable for removal of nutrients (Table 6). The U_{max} for TN was 3.64 and for TP was 0.24 mg/l.d. These values are very low, indicating decreased consumption and inefficiency of the system for removing TN and TP.
Most recent modeling efforts evaluate the performance of CWs for the treatment of wastewater. One approach is to model a CW as an infinite number of CSTRs. This assumes a wetland to possess many through-flow channels flanked by side regions of limited flow.

Conclusion

Anaerobic ponds integrated with subsurface CWs operated satisfactorily when compared with expensive, complex mechanical conventional systems that consume energy and are inefficient during cold months. The system was also more efficient for removal of TSS, TN and TP than the classic systems. Elimination of BOD5, COD and TSS in SSF CWs was significant. During the study period, TSS and TP in the reed bed effluent was below standard levels and the concentration of TN in the effluent was close to effluent standards.
The reed bed showed the highest removal efficiency in the first few meters because there was greater biological interaction in this area. The hybrid Monod-Plug flow regime and the Stover-Kincannon models showed the best fit with the kinetics of the process. It can be concluded that the SSF CWs have the ability to treat average wastewater about as effectively at lower cost than many common mechanical systems.

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Ethical issues

There were no ethical issues for all phases of experimentation and writing of the article.

Authors' contributions

All authors were involved in all stages of article preparation. We confirm that the article has not been published previously and is not under consideration for publication elsewhere. On behalf of all co-authors, the corresponding author bears full responsibility for this submission.

Competing interests

We affirm that the article is the original work of the authors and we have no conflict of interest to declare.

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