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Blackwater treatment via combination of sedimentation tank and hybrid wetlands for unrestricted reuse in Egypt

Hussein I. Abdel-Shafy*, Mohamed A. El-Khateeb*, Mohamed Shehata

Water Research and Pollution Control Department, National Research Center, Tahreer Street, Dokki, Cairo, Egypt, Tel. +201224018017 and +201124170008; email: hshafywater@yahoo.com (H.I. Abdel-Shafy), Tel. +201003282503; email: elkhateebcairo@yahoo.com (M.A. El-Khateeb)

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ABSTRACT

The present study aims at investigating the performance of hybrid constructed wetlands (CWs) for blackwater treatment. A pilot study of real blackwater samples was conducted in this investigation. This research describes an integrated system consisting of the sedimentation process as primary treatment followed by hybrid horizontal–vertical flow wetland for the treatment of concentrated blackwater as a strong wastewater. The results showed that the sedimentation tank was able to remove about 56.8%, 64.8%, and 58.0% for TSS, BOD, and COD, respectively, for the raw blackwater. When the effluent of the sedimentation tank was further treated by the subsurface horizontal wetland, the removal efficiency of TSS, BOD, and COD increased to 82.9%, 88.0%, and 87.1%, respectively. For upgrading the treated effluent, it was further subjected to vertical wetland. The overall removal of the pollution parameters of the combined system reached 97.4%, 98.0%, and 98.5% for TSS, BOD, and COD, respectively. As a result, the final effluent complied with the National Regulatory Standards for unrestricted water reuse. The present investigation concluded that the hybrid CWs offer a low-cost alternative for wastewater treatment, according to the climate of Africa, Middle East, arid, and semi-arid areas. Such hybrid system could be implemented easily if the land area is available.

Keywords: Blackwater; Sedimentation tank; Hybrid wetlands; Wastewater treatment; Unrestricted water reuse; Constructed wetland

1. Introduction

There is wide international acceptance and interest toward the constructed wetland (CW) system due to the many advantages including simple construction and operation, low capital cost compared with other treatment options, and very low energy consumption [1,2]. However, CWs have a high evapotranspiration rate as in other treatment systems (e.g., lagoons or ponds). On the contrary, they have the shortest hydraulic retention time (HRT) among the whole group of extensive treatment technologies. Minimization of water loss could be achieved by using a particular design and configuration of construction. The most powerful combination system is the coupling of the horizontal and vertical flow (VF) beds (i.e., hybrid system) [3].

Recent application of CW is related to the removal of pollutants [4,5]. Different types of wastewater, including agricultural, urban, or infrastructures runoff, can be handled using extensive natural treatments that are effective in the removal of phosphorous, nitrogenous compounds, persistent organic compounds, and other micropollutants [6–8]. This makes such kind of techniques attractive for watershed scale approaches wherever a specific local treatment is unsuitable.

Several tipology with different designs that are explained with more details are the most common used in Europe [9,10]. Such tipology can be categorized according to the flow pattern: (a) free water surface (FWS) and (b) horizontal subsurface flow (HF or SSF).

* Corresponding author.

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1.1. Hybrid systems

When designing of a CW system, the choice of plant configuration depends on many factors. The main ones are the treatment efficiency goals, the landscape of the area, and the type of wastewater. The hybrid system is basically a combination of the three tipologies: HF, VF, and FWS, to achieve the most effective and complete purification [11].

Each type of CW (HF, VF, or FWS systems) presents specific treatment efficiencies and functioning. Thus, it is obvious that the selected system is the controlling factor. Meanwhile, the design depends on many factors, for example, the available land areas, morphology, and quality of the treated effluent [2]. The plant selection comes to be often recommended (if not obliged). A hybrid system, in fact, is able to harness the potentialities of each topology of CWs and, hence, reduces the drawback of single components. The probable solutions are numerous according to the following [10,11]:

- VF + HF: The horizontal subsurface flow system has the aim to obtain more efficient removal of nitrogenous compounds through denitrification of the effluent by the vertical system.
- HF + VF: The stage with the horizontal subsurface flow has the capability of removing most of the organic load and the suspended solids that remain after the primary sedimentation. The vertical subsurface flow step ensures oxidation of the wastewater and an efficient nitrification without clogging problems. This design can be accomplished by recycling of the effluent at the beginning of the system, for efficient denitrification.
- HF + VF + HF + FWS: Denitrification of the wastewater is enhanced by the horizontal subsurface flow system. The free water surface removes the nitrogen compounds and almost all the microbial load.

This type of CWs consists, if properly designed, gravel or sand as substrate, vascular plants (reeds), and micro-organisms. The system is fed with primary treated wastewater by a simple inlet device [4].

The main role of the aquatic plants is to act as catalyst in the purification process. This process is a combination of microbiological and physico-chemical treatment system. The plants have no significant action or a direct removal of certain pollutants. Nevertheless, aquatic plants may contribute in the removal of N, P, and some organic matters in the order of 10%–20% as well as accumulation of heavy metals during the vegetative season [12–14]. However, aquatic plants offer an efficient attachment for the building up of aerobic bacterial colonies on their rhizomes. Convection mechanism may be attributed to pump air from the leaves toward the root zone [2,12].

On the other hand, a remarkable optimization of the treatment scheme can be obtained for handling black and gray wastewater by employing a properly designed CWs. However, gray water is easily treated compared with the black ones, with less possibility of pathogen contamination [15].

The aim of the present study is to investigate the efficiency of the hybrid CW system as simple, low-energy, and low-cost technology for blackwater treatment. This study describes the feasibility of integrated hybrid system including sedimentation process (using a sedimentation tank [ST]) as a primary treatment followed by hybrid horizontal–vertical subsurface flow wetland for the treatment of the concentrated blackwater (household toilet). A further aim is to throw light on the efficiency and the advantages of the studied wetlands for wastewater treatment in the arid and semi-arid countries.

2. Materials and methods

2.1. Source of raw blackwater

Real municipal wastewater was separated into black (B), gray (G) and yellow (Y) water segregated and collected from one house across the "Training Demonstration Centre (TDC)" site in the National Research Centre (NRC), Cairo, Egypt. This house comprises two separated sides. Each side has five apartments. The separated wastewater in one of these sides is presently connected to the TDC into separated manholes for B, G, and Y water located on the TDC site. The collected blackwater (B) is the subject of the present study. It represents wastewater from the toilet (i.e., feces, urine, and flushing water).

2.2. Sedimentation tank

The raw blackwater was first treated through three steps of successive baffled ST as the primary treatment to remove larger particles and suspended solids. For this purpose blackwater was pumped from the manhole up to the first ST. The STs are made of polyvinyl chloride with effective working volume of 0.7 m^3 each. The dimension of each tank is: 1.00 × 0.90 × 1.0 m for height, width, and length, respectively. The reactor has a rectangular basin and rose from the ground surface about 4 m. The first tank consists of two chambers separated with baffles at the dimensions of 0.5 m each in length, 0.9 m in width, and 1.00 m in depth. The outlet is then directed to the second, and then to the third STs. The last two chambers provide the quiescent condition necessary for settling.

The outlet of the STs was then directed to HF followed by the VF CW system. All the effluent from the HF unit fed directly to the VF through siphon tank. Generally, siphon tank cycle consists of fill and discharge 10 times a day. The substrate filling material media of each CW are fractions of coarse gravel (2–5 cm) on the top, followed by fine gravel (1–2 cm) in the bottom. The dimensions of the STs, HF, and VF wetlands are given in Table 1. Schematic representation of the hybrid CW is shown in Fig. 1.

The operating condition of the wetland systems is shown in Table 2. The feeding of VF unit was carried out by siphon using a submersible pump. As the water reaches to a certain level, feeding starts. The feeding time ranged from 3 to 5 min. The system was running automatically. The organic loading rate (OLR) was 45.7 g/m^3/d for HF unit, which is slightly higher than that recommended by EPA guidelines [16].

The use of hybrid systems (horizontal flow, followed by VF constructed wetlands) to produce high-quality effluent via shorter detention time compared with other configurations. Besides, the nitrogenous and phosphorus compounds can be removed more efficiently by the VF system.

Table 1
Dimensions of the sedimentation tanks, the horizontal and vertical wetlands

Unit	No of units	Length (m)	Width (m)	Depth (m)	WW flow (L/d)	Filling media	Plant
ST	3	1	0.9	1	1,500	–	–
HF	1	5.4	2	0.75	400	Gravel	Phragmites
VF	1	4.5	2	0.75	400	Gravel	Phragmites

Note: ST –Sedimentation tank, HF – horizontal flow wetland, and VF – vertical flow wetland.

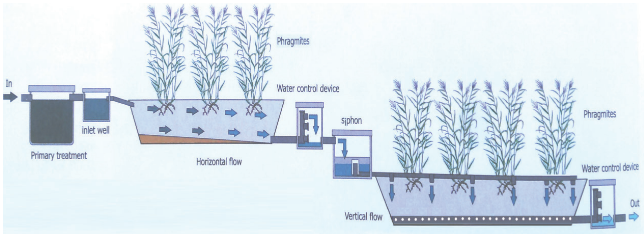

Fig. 1. Schematic diagram of the hybrid constructed wetland.

Table 2
Operating conditions of the treatment units

Treatment unit	SA[a]	HRT[b]	OLR[c], $g/m^3/d$	
			COD	BOD
HF	10.8	7.09 d	69.8	45.7
VF	9	1 h[d]	10.9	6.7

[a]Surface area.
[b]Hydraulic retention time.
[c]Organic loading rate.
[d]24 cycle/d.
Note: HF – horizontal flow wetland and VF – vertical flow wetland.

2.3. Hydraulic retention time "HRT" and organic loading rate "OLR"

Calculation of the flow rates, HRT, and OLR were carried out according to Crites and Tchobanoglous [17].

2.4. Physico-chemical characteristics

Composite samples of the raw blackwater and effluents of each treatment units were collected and analyzed for the physico-chemical characteristics. Analyses were carried out according to procedures described by APHA [18]. The studied parameters are pH, temperature (°C), turbidity (NTU), total dissolved solids (TDS), total chemical oxygen demand (COD_{tot}), suspended chemical oxygen demand (COD_{sus}), soluble chemical oxygen demand (COD_{sol}), colloidal chemical oxygen demand (COD_{col}), biological oxygen demand (BOD_5), total suspended solids (TSS), oil and grease, total phosphorus (TP), nitrates, nitrites, organic nitrogen, total Kjeldahl nitrogen (TKN), and ammonia and fecal coliform (FC).

2.5. Calculation of COD and BOD fractions

COD_{sol} = COD filtered through membrane filter paper (0.45 µm)

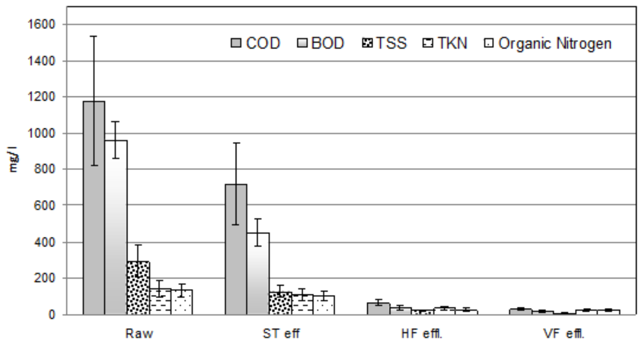

Fig. 2. Characterization of blackwater as well as treated effluents via successive treatment processes.

COD_{col} = COD of the filtrate from 4.4 µm filter paper – COD of the filtrate from membrane filter paper (0.45 µm)

COD_{sus} = COD_{tot} – COD of the filtrate from 4.4 µm filter paper

2.6. Statistical analysis

In order to reveal the trends of the results, statistical analysis of the data (minimum, maximum, average, standard deviation, and *XY* error in the figures) was carried out using Microsoft Excel 2007.

3. Results and discussion

3.1. Characteristics of raw blackwater

The characteristics of the raw blackwater are given in Table 3.

The blackwater characteristics indicated that such wastewater is relatively strong as exhibited by the COD, BOD_5, TKN, and TSS (Table 3). The difference between the maximum and minimum values in terms of temperature, COD, and TKN may be attributed to the seasonal variations and diet habits particularly during the fasting month of Ramadan. The BOD/COD ratio varied from 0.73 to 0.84 with an average value of 0.77 that reflects the biodegradability of the studied blackwater [19].

3.2. Pretreatment via sedimentation tanks

Effluent of the three baffled STs showed reasonable removal efficiency of TSS, BOD, COD, TKN, organic nitrogen, and phosphates at the rate of 56.8%, 64.8%, 58.0%, 23.0%, 23.0%, and 13.8%, respectively (Table 4). The corresponding characteristics of this effluent reached 126, 321, 495, 109, 103,

Table 3
Physico-chemical characteristics of the raw blackwater

Parameter	N	Max.	Min.	Ave. (SD)
pH	18	8.1	7.16	
Temperature, °C	18	35	10	
Turbidity, NTU	18	205	80	152.3 (44.5)
TDS, mg/L	18	983	716	841 (98)
TSS, mg/L	18	486	212	292 (89.4)
BOD, mg/L	18	1,420	420	911 (101)
COD, mg/L	18	1,680	835	1,178 (356)
Oil and grease, mg/L	18	75.3	51.5	68.04 (21)
TKN, mg/L	18	178	117	141.5 (20)
Ammonia, mg/L	18	9.3	3.7	7.1 (1.65)
Nitrates (NO_3), mg/L	18	0.22	0.1	0.16 (0.04)
Nitrites (NO_2), mg/L	18	0.06	0.01	0.02 (0.01)
Organic nitrogen, mg/L	18	171.48	109.30	134.1 (20)
Total nitrogen, mg/L	18	178.4	117.2	141.8 (22)
Total phosphorus, mg/L	18	35.4	17.9	26 (6.3)
Fecal coliform, MPN/100 mL	10	1.7×10^{10}	2.1×10^9	6.4×10^9 (4.8×10^9)

Note: N – number of samples, Max. – maximum, Min. – Minimum, Ave. – average, SD – standard deviation, Turb. – turbidity, TDS – total dissolved solids, TSS – total suspended solids, COD – chemical oxygen demand, BOD – biological oxygen demands, and TKN – total Kjeldahl nitrogen.

and 22 mg/L (Fig. 2). The FC count was reduced from 6.4×10^9 to 3.5×10^8 (only 1 log unit). By comparing such characteristics with the Egyptian national regulation of the EEAA [20] (Table 5), it can be concluded that the level of BOD and COD do not comply even with the permissible limits for water reuse under the category of third class "primary treated effluent".

3.3. Horizontal flow wetland

The outlet of ST was directed to the HF wetland. The removal efficiency of the later is given in Table 4. It is worth noticing that the TSS and the organic load as presented by BOD and COD were highly removed by the HF as indicated by the percentage of removal. The removal rate of TSS, BOD, COD, TKN, phosphates, and ammonia reached 82.9%, 88.0%, 87.0%, 78.3%, 39.3%, and 74.6%, respectively (Table 4). The corresponding concentrations were 21.5, 38, 64, 23.6, 13.6, and 1.5 mg/L, respectively. The removal efficiency that was achieved in the TKN and ammonia can be attributed to the nitrification/denitrification process as well as the slight uptake of the reed plant [10,21]. The FC count was reduced by 3 log units to reach 1.1 × 105 MPN/100 mL. The removal of FC is partly due to the sedimentation process [16,22]. The results were found to be in a good agreement with other investigators [7,9,23]. Similarly, removal efficiency of the phosphates, namely 39.3%, may be attributed to the plant uptake [11,12]. The effluent of the HF complies with Egyptian national standards for reuse (EEAA) [20] under the category of second class treated effluent (Table 5).

It is worth mentioning that the HF effluent is characterized by very low level of dissolved oxygen. Under these circumstances there will be no oxygen remaining to oxidize the ammonium nitrogen to nitrate. Because of this fact, designers and researchers started looking for alternative design of reed bed that could oxidize the ammonia to nitrogen [11,24,25].

3.4. Vertical flow wetland

The VF wetland is planted with common reed. Other emergent vascular plants such as cattails and bulrush can also be used. The system was fed intermittently. The wastewater was dosed on the bed in a large batch flooding the surface. The wastewater then gradually flew vertically down along the bed and was collected by the drainage network at the base. The bed was drained completely, allowed air to refill the bed. The next dose of liquid was able to trap the air. The rapid dosing caused aeration of the bed leading to good oxygen transfer and hence the ability to decompose the organic load (BOD) and to nitrify ammonia nitrogen [3,26].

In the VF systems, oxygen is partially transferred down into the root zone. Meanwhile, greater amount of oxygen is transferred through the phragmites plant from the air to the root. It was mentioned by Cooper et al. [26] that VF treatment systems are very similar in principles to a rustic biological filter. Thus, VF system is to ensure high oxidation and efficient nitrification.

The removal efficiency of the vertical wetland in terms of TSS, BOD, COD, TKN, phosphates, and ammonia was 64.7%, 53.1%, 52.8%, 28.2%, 34.6%, and 66.1%, respectively (Table 4). The highest removal rates were achieved in the TSS and ammonia. The later was probably converted to nitrite, then to nitrates by the aerobic bacteria [26]. Thus, great part of nitrate was available to be uptaken by the reed plant [12,13,25,26]. Meanwhile, the phosphates were partially consumed by the plant [25]. In this step the FC count was reduced from 1.1×10^5 to 1.4×10^2 MPM/100 mL (Table 4).

3.5. Overall hybrid wetland (HF + VF)

The overall removal by the HF–VF hybrid system reached 97.4%, 98.0%, 98.5%, 83.3%, 65.8%, and 93.0% for TSS, BOD, COD, TKN, phosphate, and NH_3, respectively (Table 4). The corresponding residual concentration of the final effluent was 7.6, 18, 18, 23.6, 8.9, and 0.5 mg/L, respectively. The final effluent characteristics were found to comply with the Egyptian national standards for unrestricted reuse [20] under the category of first class treated effluent (Table 5) as well as the international guidelines for safe reuse for irrigations [27,28].

Fig. 3 reflects the effect of the combined treatment steps of the different COD fractions. The major fraction in the raw wastewater was COD_{sus} followed by COD_{col} and finally COD_{sol}. The COD_{sus} decreased sharply in the ST effluent. A reasonable reduction in the COD_{sus} fraction in the effluent of

Table 4
Effluent characteristics of each treatment process (standard deviation in brackets)

Parameter[a]	N	ST effluent	Sed. %R	HF effluent	HF %R	VF effluent	%R	Overall cumulative removal %
pH	18	7.9 (0.35)		8.2 (0.32)		7.8 (0.3)		
Turbidity	18	110 (38.5)	27.8	28 (14.9)	73.7	10.79 (6.9)	61.5	92.9
TDS	18	800 (80.7)	4.9	833 (66)	–2.1	868 (112)	–4	–3.2
TSS	18	126 (30.5)	56.8	21.5 (3.4)	82.9	7.6 (2.1)	64.7	97.4
BOD	18	321 (75.7)	64.8	38.4 (12.8)	88.0	18.0 (8.2)	53.1	98.0
COD	18	495 (226)	58.0	64 (14.4)	87.1	18 (5.1)	52.8	98.5
Oil and grease	18	43 (2.4)	36.8	9 (5.5)	79.1	4 (3.8)	55.6	94.1
TKN	18	109 (12.1)	23.0	23.6 (2.7)	78.3	23.6 (2.72)	28.2	83.3
NH_3	18	5.9 (1.44)	16.9	1.5 (0.24)	74.6	0.5 (0.17)	66.1	93.0
Nitrates	18	0.02	87.5	6.2	–	1.9 (0.68)	69.4	–
Nitrites	18	0.004	80.0	0.0	–	0.01 (0.01)	–	50.0
Organic nitrogen	18	103.2	23.0	25.0	75.8	21.6 (2.9)	13.6	83.9
TP	18	22.4 (5.8)	13.8	13.6 (2.6)	39.3	8.9 (1.1)	34.6	65.8
Fecal coliform	10	3.5×10^8 (2.4×10^8)	90.2	1.1×10^5 (2.2×10^5)	99.4	1.4×10^2 (1.1×10^2)	97.5	–

[a]All the units are mg/L except turbidity in NTU and fecal coliform in MPN/100 mL
Note: %R – percentage of removal, HF – horizontal flow wetlands, VF – vertical flow wetland, overall %R – overall percentage of removal, N – number of samples, TDS – total dissolved solids, TSS – total suspended solids, BOD – biological oxygen demands, COD – chemical oxygen demand, TKN – total Kjeldahl nitrogen, TP – total phosphates, and NH_3 – ammonia.

Table 5
The Egyptian national standards for water reuse (EEAA)

Parameter	3rd class (primary treated water)	2nd class (secondary treated water)	1st class (advanced treated water)
BOD_5, mg O_2/L	300	40	20
COD dichromate, mg O_2/L	600	80	40
TSS, mg/L	350	40	20
Oil and grease, mg/L	0	10	5
Number of cells or eggs of nematode, count/L	5	1	1
E. coli count, count/100 mL	Not limited	1.0E+03	1.0E+02
TDS, mg/L	2,500	2,000	2,000
Na absorption ratio, %	25	20	20
Electric conductivity, µmhos	750–2,000	250–750	250

Note: Egyptian regulation: EEAA [20].
BOD – biological oxygen demands, COD – chemical oxygen demand, TSS – total suspended solids, and TDS – total dissolved solids.

HF and VF wetland was achieved, namely 14% by HF and 13% by VF. These findings were supported by the reduction in the TSS levels during the treatment steps (as shown in Table 4). The given results are in a good agreement with other researchers [2,7]. The COD and BOD removal are the functions of HRT and available oxygen [8]. The HRT is assumed to affect the rates of settling and oxidation, while vegetation is assumed to reduce BOD through shading and filtering of algae and suspended solids.

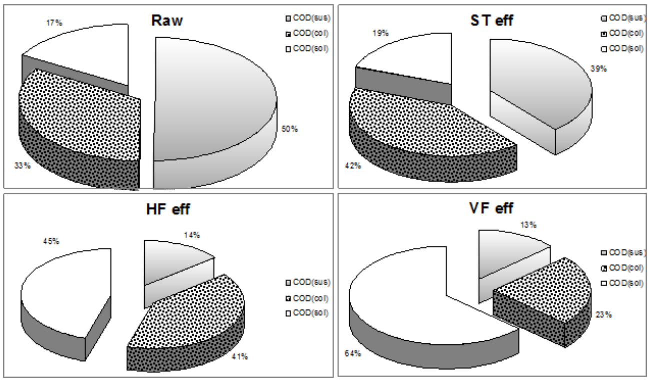

Fig. 3. COD fractions percentage throughout the combined treatment steps.

Fig. 4 illustrates the removal rate of nitrogenous compounds throughout the successive treatment units. It is clear that the HF unit is the most effective for the removal of the nitrogenous compounds followed by VF and the ST. This may be attributed to the long distance traveled in the horizontal wetland. Colleen et al. [29] attributed the removal of nitrogenous compounds to the ammonification (mineralization), nitrification, and denitrification, which are modeled as first-order or Monod-type reactions.

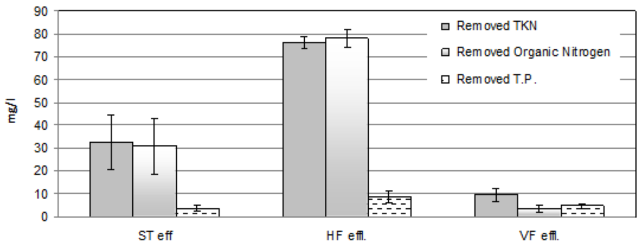

Fig. 4. Removal of the nitrogenous compounds by the combined treatment processes.

3.6. Advantages of the constructed wetlands

3.6.1. Environmental aspects

When the system is setup, there is no contact with the blackwater. There is no noise from the system as compared with many other conventional treatment systems, and there is no odor either. The system works effectively to reduce pathogenic bacteria, thus making it a lot safer to be on site.

3.6.2. Wetlands as low-cost system

The number of labors needed to run the system is fewer than conventional methods. Only a weekly control-visit to the site of about 1–2 h is required [30]. In addition, wetland is low-energy system. The only perceivable power consumption is by the pumps used to transport wastewater and to reject the treated effluent. Consequently, CW system uses much less power than other treatment systems. The treated effluent will be of a better quality and suited for reuse in land irrigation.

3.6.3. Green and environmentally friendly system

Wastewater treatment via wetlands uses no chemicals. This means a considerable improvement in the environment along with a reduction of the sludge of the treated wastewater that will be passed into the environment. As a general rule, pathogenic bacteria that are excreted and end in an alien environment live only for a short time. This depends on the surrounding environmental factors and the bacteria's own characteristics.

4. Conclusions

The overall results revealed that the hybrid wetland systems enhanced the effluent quality. This is mainly due to the relatively low velocity and high surface area of the HF–VF hybrid system. Such wetlands act like gravel filters and, thereby, provide opportunities for suspended solids sedimentation and adsorption on the biomass film adhered to gravel and root system. To obtain high-quality effluent by using HF or VF CW, separately, longer detention time is required. Thus, increasing the detention time water loss will increase. Meanwhile, certain nutrients are uptaken by the plant biomass [25,31]. Consequently, the combination of HF followed by VF proved a promising technology for the treatment of blackwater. The hybrid wetland system can handle high hydraulic and organic load of blackwater. CW technologies are simple in construction, maintenance, and operation, and low cost. Furthermore, the systems can be applied at any scale as less energy is required, enabling a decentralized (on-site) approach for the wastewater treatment application. Meanwhile, the treated effluent can be reused for irrigation for the purposes of nutrient recycling; since the characteristics are within the permissible limits (i.e., the final effluent contains valuable nutrient elements such as nitrates and phosphates that give high potential for crop cultivation). The drawback of such systems is the land area that is required for construction. In Egypt, as well as in many Middle Eastern countries, there are many cities that are surrounded by a huge desert area suitable for construction of wetland systems.

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