Chapter 5
Constructed Wetlands for Wastewater Management in Egypt: An Overview of 30-Years Experiences in Small/Medium-Size Treatment Plants

Hussein I. Abdel-Shafy, Mohamed A. El-Khateeb, and Mona S. M. Mansour

Abstract Constructed Wetlands (CWs) are well known as an efficient treatment technology for many wastewater sources such as municipal and various industrial effluents. Different engineering designs such as horizontal and vertical flow and hydroponic channels can be implemented according to the required treatment strategies. Greywater and blackwater are also treated in CWs in Egypt and other countries. CWs can achieve high removal rates of various pollutants including total suspended solids, organic pollutants (COD, BOD), nitrogen compounds, phosphates, pathogenic contamination, as well as several heavy metals. There is a wide acceptance and interest in employing CWs due to their advantages such as simple construction, cost-effectiveness, low operation and maintenance cost, high ability to tolerate fluctuations in flow and inlet quality, high pathogens removal, potential for reuse and recycling, aesthetically accepted appearance. Several successfully full and pilot scale CWs are in operation in Egypt as well as in the Middle East and North African countries where the warm climate seems to favour the various CW processes and functions. This chapter presents existing full-scale CWs, hydroponic wetlands, as well as pilot plants using horizontal, vertical, and channel flow for the wastewater treatment in Egypt.

Keywords Constructed wetlands · Hydroponic wetland · Wastewater · Treatment · Water reuse · Pathogens and heavy metals removal · Egypt

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5.1 Introduction

Conventional wastewater treatment systems are energy-intensive and include many mechanical components that require high investment as well as high operation and maintenance cost [1], which makes it difficult to use in low-income reasons. On the other hand, constructed wetlands (CWs) have low construction cost, use local materials, very low operation and maintenance cost, minimum energy demand and are simple in operation [1–3], which gives them good prospective to be implemented in developing countries. Furthermore, CWs do not require high skilled engineers to operate; simple labor is enough. Thus, they are accepted as a reliable wastewater treatment technology representing an appropriate solution for the treatment of various types of wastewater [3]. This technology, in fact, acts as a natural-based solution for handling different types of wastewaters [4, 5, 6].

By comparing CWs with conventional wastewater treatment processes, the former have a higher rate of biological performance that enables the conversion of several pollutants into non-toxic by-products or plant nutrients that can be an advantage for water reuse in irrigation [7, 8]. CWs rely upon biological, physical, and chemical processes to remove the contaminants from all types of domestic, sewage and certain industrial wastewaters [9–13]. CWs are capable of removing hazardous pollutants such organic xenobiotics including pesticides, phenolic compounds, dyes, petroleum hydrocarbons, explosives, hormones, and pharmaceuticals [10, 12, 14–18].

CW can be planted with emergent and/or submergent vegetation and may be classified into four types according to their dominant plant species and characteristics [19]: (i) submerged macrophytes (e.g. *Potamogeton crispus*, *Littorella uniflora*), (ii) floating macrophytes (e.g. *Lemna minor*, *Eichhornia crassipes*,), (iii) emerged rooted macrophytes (e.g. *Typha latifolia*, *Phragmites australis*,), and (iv) floating-leaf macrophytes (e.g. *Nymphea alba*, *Potamogeton gramineus*). Another classification in based on their hydrology: (i) horizontal sub-surface flow (HSSF), (ii) vertical subsurface flow (VSSF), (iii) free water-surface (FWS) or surface flow (SF), and (iv) hybrid systems (combination of different designed wetlands) [2, 4, 20–22]. In addition, hydroponic wetlands are designed as isolated declined channels with 1–2% slope, where the inlet flows from the top [23]. For achieving a better removal of nitrogen compounds from wastewater, different designs and types of CW's could be combined as hybrid systems [3, 24].

CWs are receiving an increasing attention as a promising phytotechnology for handling agricultural wastewaters. Studies have shown the efficiency of these system for the treatment of the olive mill wastewater (OMW), fruit processing wastewater, water contaminated with the organic herbicide MCPA (2-methyl-4-chlorophenoxyacetic acid), swine wastewaters (SWW) contaminated with oxytetracycline, winery and distillery wastewater [18, 25–28], among others. In particular, CWs have been successfully employed for the treatment of different sources of wastewaters over the past decades in developing countries under hot and dry or tropical climates [29]. Wastewaters in these countries are characterized by conductivity, productivity, and higher biological activity resulting in higher treatment achievement compared to other countries in the cold climates [30].

5.1.1 Plants in Constructed Wetlands

Vegetation in CWs is an important factor for the efficiency of wastewater treatment. Generally, the common vascular plants in natural wetlands have been used in the CW's, although several ornamental flowering plants found in natural wetlands have also been used. Figure 5.1 illustrates the most common plants used in CWs such as floating aquatic plants, e.g., duckweed (*Lemna*) and water hyacinth (*Eichhornia crassipes*) and vascular plants e.g., common reeds (*Phragmites* spp.) and cattail (*Typha* spp.) These emergent plants grow well in both SF and SSF CWs, where they play an important and vital role in the removal of nutrients. A recent review on 87 CWs in 21 different countries around the world showed that the most common employed ornamental flowering plants are Iris, Canna, Zantedeschian and Heliconia [31].

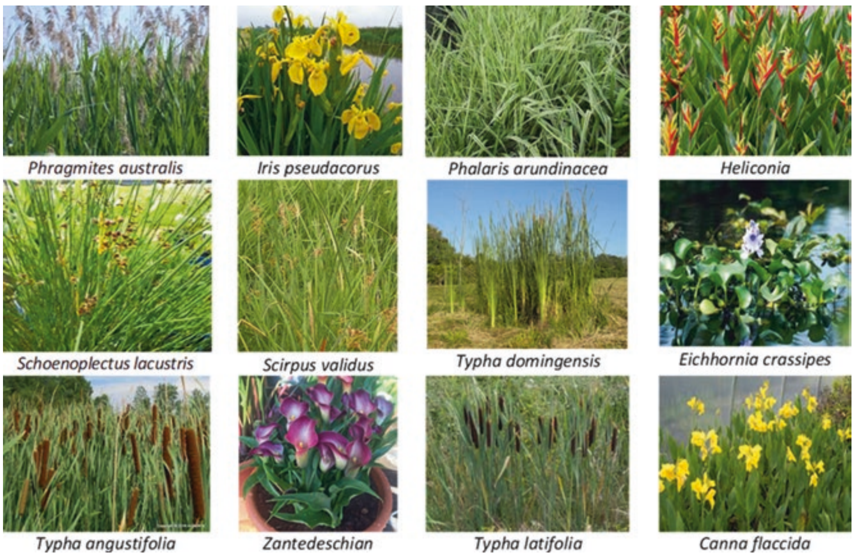

Fig. 5.1 The most common plants that are used in CWs

5.2 Domestic Wastewater in Egypt

5.2.1 Wastewater Production

The annual average collected wastewater during the last 5 years amounts to 6.5 billion m^3 (BCM) [32], corresponding to about 81% of the total annual produced domestic wastewater. It also reported that about 44% of the nationally produced wastewater is not treated, which is equivalent to 2.85 BCM/yr. This huge amount is about 5.1% of Egypt's annual share from the Nile River. There are 358 municipal wastewater treatment plants in Egypt producing 3.65 BCM/yr. treated water. About 0.73 BCM/yr. are primary treated wastewater and the rest of about 2.92 BCM/yr. are secondary treated wastewater [33]. Therefore, the primary and the secondary treated wastewater represent 20% and 80% of the total treated wastewater, respectively. It is worth mentioning that the sewage network has a total length of about 39,000 km. Figure 5.2 presents the future projected collected wastewater capacity through 2030. Moreover, there are three large tertiary treatment plants in Egypt where the sludge is anaerobically digested to produce biogas to compensate for the consumed energy by these treatment plants [33]. The indicator of sanitation access in Egypt is measured by the connectivity of wastewater to the sewerage systems. It complies with the Egyptian Law Number 48/1982 that regulates the protection of the Nile and waterways from any wastewater discharge. As a result, the average sanitation coverage in Egypt is about 50%; 90% in urban areas and only 12% in rural areas.

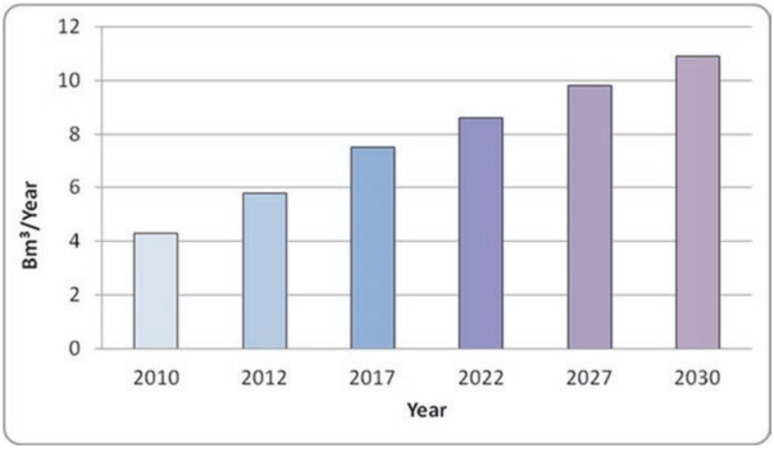

Fig. 5.2 Future projected wastewater collection capacity (BCM) [33]

5.2.2 Wastewater Reuse in Egypt

The reuse of treated wastewater is an important strategy to increase the water budget in Egypt as a nonconventional water that should meet the stringent limits and the increasing water demand for non-potable purposes. Guidelines concerning treated wastewater reuse have been developed and issued as Egyptian Code concerning the "Reuse of Treated Wastewater for Agriculture purposes". Treated wastewater can be reused directly in agriculture and/or indirectly for groundwater recharge. An amount of 300 MCM/yr. of treated wastewater is used for agriculture irrigation in Egypt [32, 35–37]. It is very costly to irrigate each hectare of agriculture land. The costs include the networks, seeding, and adjusting land levels, in addition to the cost of the pump stations and generators. Therefore, the average cost for cultivating 1 Feddan (equal to 4200 m^2) is about 10,000 Egyptian pounds (i.e., about $625).

Presently, a reasonable amount of the primary treated wastewater is reused for irrigating of forests trees in the desert of Egypt [32]. Table 5.1 shows a total of 24,000 feddans (about 10,032 hectares) are already cultivated by irrigation with primary treated wastewater, while Table 5.2 presents the types of cultivated plants. However, the total current and potential areas for irrigation with primary treated wastewater in Egypt are 82,000 feddans (34,439 hectares).

Nationally, there are two main essential options for handling the treated wastewater: either direct reuse for agricultural purposes or discharge into the main national agriculture drainage network. Figure 5.2a presents the amount of treated

Table 5.1 Forest areas irrigated by primary treated wastewater in different governorates in Egypt [32]

No	Governorate	Forest	Area (Feddan)	Area (Hectare)
1	Aswan	Elalafy	3000	1260
		Blana	1000	420
2	Sohag	Tahta	1000	420
		Elblyana	1000	420
		Grga	1000	420
		Tma	500	210
3	Bany Swaif	Bandil	265	111.3
		Bayad El-Arab	720	302.4
		East Beny Swaif	900	378
4	Red Sea	Ras Gharib	1000	420
		Safaga	500	210
		El-Qasir	500	210
5	Qena	Naga Hammadi	2000	840
		Farshot	1500	630
		Qena	3000	1260
6	Menya	Menya El-Gededa	5000	2100
		Samalot	1000	420
Total			23,885	10,031.5

Table 5.2 Types of cultivated plants irrigated with primary treated wastewater in different governorates in Egypt [32]

Governorate	Cultivated plants
Aswan	Jatrova, Kaya, J ujoba
Luxur	Sysaban, Jatrova, Kaya, Jujoba
Qena	Sysaban, Jatrova, Kaya, Jujoba
Sohag	Sysaban, Jatrova, Kaya, Jujoba
Asuitt	Casuarina, camphor
Beny Swait	Casuarina, camphor
Red Sea	Casuarina,
Matroh	Casuarina, camphor, Jatrova
North Sinai	Ornamental palm, casuarina, camphor
South Sinai	Kaya, casuarina
Monofia	Kaya, casuarina
Lsmaliia	Casuarina, camphor

wastewater discharged to the main drainage network and Fig. 5.2b the amount reused directly for agricultural purposes in different Egyptian governorates in 2011 [38] (Fig. 5.3).

5.3 Constructed Wetlands in Egypt

5.3.1 Lake Manzala CW Project

In Egypt, there are two major concerns: environmental and economic problems related to the poor quality of north flowing agriculture drainage waters mossed wit sewage water. In January 2001, the construction of the CW facility began on a 100-hectare area South-West of Port Said City, Egypt, one of the most poorly served areas in Egypt where local residents have no access to clean potable water, electricity, sanitation, as well as any other basic services.

The project was a cooperative effort between the Global Environmental Facility (GEF), the United Nations Development Program (UNDP), and the Egyptian Environmental Affairs Agency (EEAA). The CW was designed to treat 25,000–50,000 m^3/day of polluted drainage water from the Bahr-El-Baqar drain to improve the water quality in Lake Manzala that is connected to the Mediterranean Sea. Lake Manzala is located in the North-Eastern edge of the Nile Delta (Fig. 5.4). The Egyptian authorities were concerned over the discharged drainage water to Manzala Lake as a major environmental and economic problem. Such drainage waters are heavily polluted wastewater crossing the Nile Delta and enter large coastal lakes before discharging into the Mediterranean Sea. The resulting environmental contamination of the Mediterranean Sea coastal area violates the international agreements, signed by Egypt, including Barcelona Convention.

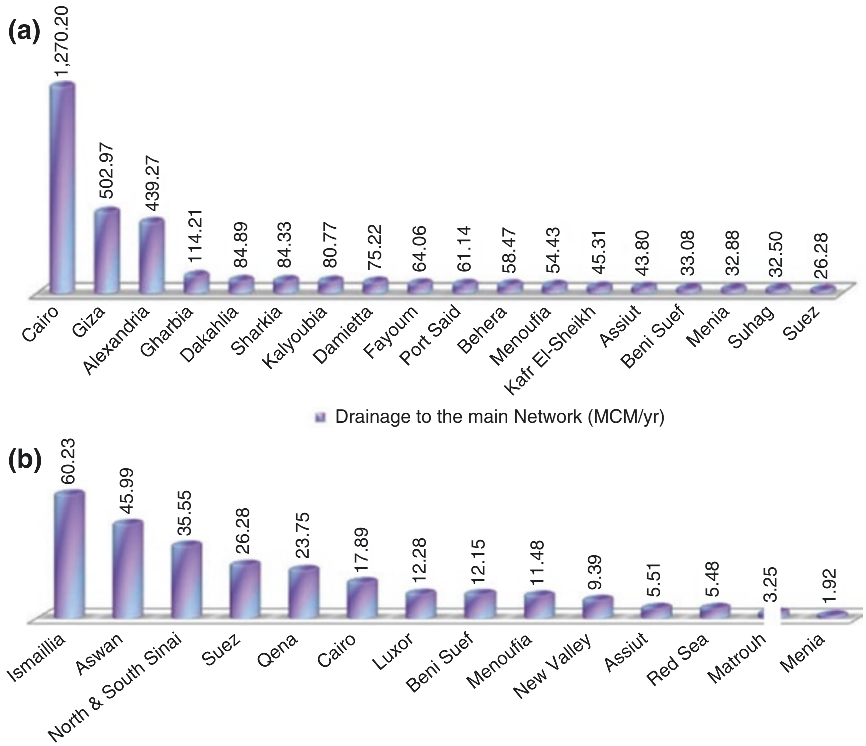

Fig. 5.3 (**a**) Discharge (MCM/Year) to the main drainage network, and (**b**) direct reuse (MCM/Year) of treated wastewater in Egyptian Governorates [32]

The facility includes intake screw pumps, surface treatment cells, sedimentation basins, subsurface reciprocating cells, fish rearing facility, pilot test cells, and the treated effluent reuse area. The 5 years demonstration project included 3 years for design and construction followed by 2 years of operation to demonstrate the performance, and optimize the implemented CW systems in Egypt. Within the CW facilities, the project includes a commercial scale of 60 feddans (25 hectares) for a fish farm, using the treated water for the purpose of compensating the plant operational costs. The long-term aim is to implement the innovative, and low-cost wastewater treatment technologies in the area and the region.

The total area of the lake is 250,000 feddans (104,207 hectares) and the inflow to the lake is 4 BCM/year of polluted water. Bahr El-Baker drain contributes with about 25% to the total lake inflow, which is mainly agriculture drainage water mixed with sewage water. The area of the CW is 200 f (83 hectares) (Fig. 5.5), i.e., about 1% of the total Lake area (Fig. 5.4). It receives the highly polluted water from many drains especially Bahr El-Baqr drain. Therefore, low dissolved oxygen was detected, aquatic bio-diversity declined, fish, produced by the lake or fish farms in the area were not suitable for human consumption. The pollution load of Lake namely BOD, TSS, total nitrogen, and total phosphates were 40, 160, 12, and 4 mg/L, respectively.

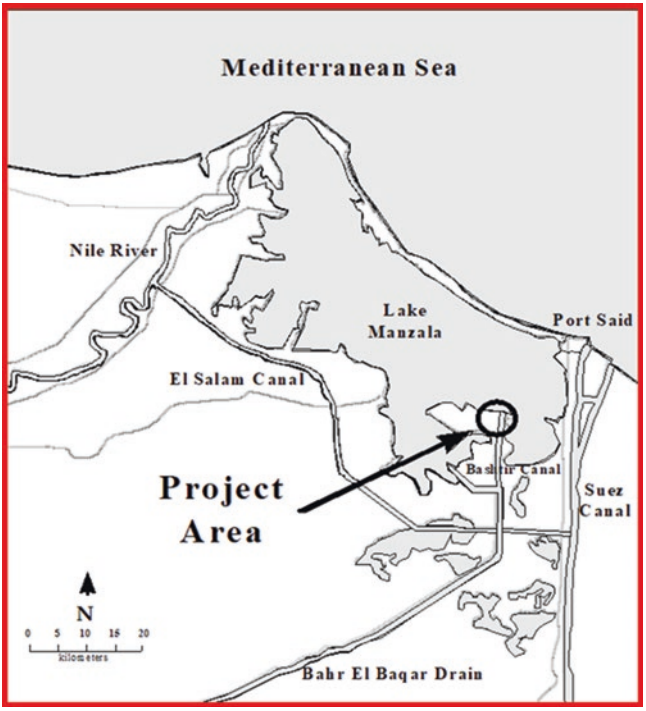

Fig. 5.4 Location of Lake Manzala at North-Eastern edge of the Nile Delta

Fig. 5.5 The 83 hectares CW at the Lake Manzala

This CW project has proved that adequate treatment can be attained and safe reuse at a wide range for non-potable purposes particularly for fish farming. It also helped to make Egypt a regional leader in CWs and self-sufficient in the reuse of innovative wastewater treatment technologies. The key advantages of the project are:

- It examined various technological processes onsite for the purpose of optimising the treatment efficiency, including various CW designs and different wastewater strengths.
- Further study will be carried out to determine the optimum treatment efficiency of the CW for handling higher flow rates, with stronger wastewater of higher pollutant loadings from the fish farm effluent. More work is considered to determine the most convenient wetland plant species that can be used effectively in the highly saline water.
- It will support the local community through education, training, and marketing of their bio-products.

Although successful, the CW project is unable to achieve broader environmental as well as economic goals. Achievement of these goals has not been reached due to a number of constraints related to project design and implementation. Overall, this CW offers a very useful model to investigate and to learn from for any future projects concerning the construction of an efficient, innovative, and low-cost wastewater treatment technology.

5.3.2 Gravel Bed Hydroponic Wetland for Municipal Wastewater Treatment in Ismailia

This system treats sewage water through a field-scale gravel bed hydroponic wetland (GBHW) in a remote area under the sub-tropical climate of Egypt at Abu-Attwa village [23]. In the previous times, the wastewater of this village and its surroundings was discharged to the nearby Temsah Lake. As a result, the lake became contaminated, aquatic plants were flourished, unpleasant smell existed, and nutrients and water of the sewage were lost. The GBHW has been implemented as secondary treatment process at this area. The treatment system consisted of two GBHW stages in series (Fig. 5.6a). Each stage consisted of six parallel channels. Each of the first stage channels was 120 m long, 2 m wide, and 0.5 m deep at 1% slope. They were planted with *Phragmites australis* (elephant grass). Each of the second stage channels was 50 m long, 2 m wide, 0.5 m deep at 1% slope, and were planted with *Cyperus papyrus* (Cyperaceae family) (Fig. 5.6b). The later plant is very common in Egypt and other countries [53]; it was used by the ancient Egyptians for manufacturing of papyrus paper.

The raw municipal wastewater was primary treated in sedimentation-settling basins followed by a trickling filter. The effluent was directed to the GBH wetland

Fig. 5.6 (**a**) The second stage of the GBH treatment system in Ismailia, Egypt [23] and (**b**) *Cyperus papyrus* of the Cyperaceae family

system where the flow rate was 20 L/min to each channel through the first stage, and the effluents were directed simultaneously to the second stage by gravity. The total daily treated wastewater volume was 100 m^3/d. The GBHW channels have been operated intermittently throughout the study period; the flow of wastewater was only 18 hr./day. The purpose was to provide sufficient period of time for the channels to dry and to allow atmospheric air to diffuse into the plant root zone. The physical, chemical and bacteriological characteristics of the sewage influent and effluent were studied for a period of 12 months. The removal rate of BOD_5, Total Suspended Solids (TSS) and Ammonium-Nitrogen (NH_4-N) ranged from 70.3% to 93.2%. Effective removal was also achieved for pathogenic bacteria and microorganisms. The overall results indicated that the GBH as a CW is capable of handling the municipal wastewater in Egypt up to the acceptable environmental level suitable for recycling in agriculture as an important process in arid and semi-arid areas [23].

5.3.3 Decentralized Wastewater Treatment in Sinai via Gravel Bed Hydroponics Wetlands

This GBHW was designed and implemented for municipal wastewater in Sinai Peninsula, Egypt, to serve a large village and the surrounding areas [39]. These areas have no industrial activities; therefore, the concerned municipal wastewaters (1270 m^3/d) were not mixed with any industrial discharge. The treatment system consisted of the main piping systems to transfer the wastewater to the treatment site. The inlet is subjected to three screening, followed by grit chambers (3×1.5×2.5 m each), followed by sedimentation basins. Each screening system dimensions are 1.5×2.0 m. The outlets of theses chambers are subjected to the distribution system through 6 valves. Each valve distributes the wastewater into two GBH channels.

The wastewater flows by gravity to 6 receiving small shallow basins controlled by giant valves. Each of these basins was split into two GBHW channels. Therefore, there is a total of 12 GBH channels. The dimension of each channel is 2.0 m width, 100 m length and 0.45 m depth. The slope of each channel is 2% to allow the flow of wastewater by gravity up to the end of the treatment channels. All channels were filled with gravel as a media for treatment and filtration (Fig. 5.7a) and planted with vascular plants, namely *Phragmittes australis* (Elephant grass). These plants grow in the Egyptian climate up to 3–4 m height. The treated effluents were allowed to flow further to a maturation pond (dimension of 50*20 m) at the depth of 2.0 m (Fig. 5.7b). The final treated effluent is reused for irrigating eucalyptus trees on the sandy soil of Sinai. However, other plants were also examined.

The results of this investigation (Table 5.3) indicated that the GBHW is very efficient in the removal of COD, BOD, TSS, TKN and the total phosphates (TP) with respective removal rates of 68.3%, 74.7%, 76.9%, 42.9% and 47.5% [39]. Further improvement was reached by the maturation pond where the removal of COD and BOD were 66.3% and 69.8%, respectively (Table 5.3). The overall removal of COD, BOD, TSS, TKN and TP was 89.4%, 93.2%, 98.0%, 71.4% and 62.5% respectively (Table 5.3).

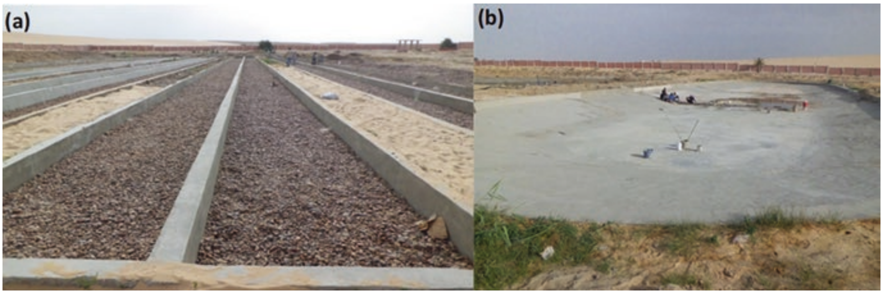

Fig. 5.7 (**a**) The 12 GBHW channels; each channel is 100 m long, 2.0 wide and 0.5 m deep, filled with flint of radius size from 2 to 2.7 mm, (**b**) maturation pond after construction

Table 5.3 Treatment of sewage water by GBHW followed by maturation pond in Sinai [39]

			GBHW Effluent		Maturation pond Effluent		Overall (%)
Parameter	Unit	Raw Sewage[a]	Conc	%	Conc	%	
TDS	μmhos	1377	1197	13.1	860	28.2	37.5
EC	mg/L	2311	2088	9.6	1644	21.3	28.9
COD	mg/L	857	271	68.4	91	66.4	89.4
BOD	mg/L	672	162	75.9	45.7	71.8	93.2
TSS	mg/L	390	90	76.9	75	16.7	98.0
TKN	mg/L	70	40	42.9	35	12.5	71.4
TP	mg/L	8.0	4.2	47.5	3.8	9.5	62.5

[a] After sedimentation

By correlating these results with the permissible Egyptian regulations [40], it was concluded that the final treated effluent can be safely reused for irrigation with regards to Class 2 (secondary treated water), in this case for irrigation of woody trees as an economical value. The latter is an environmentally friendly option, particularly in an area like Sinai Peninsula. In addition, the results indicated that there are no hygienic risks. This is mainly due to the long HRT in the CWs as well the maturation pond as passively affected by the sunlight that are very effective in the removal of fecal coliforms from the studied wastewater.

5.3.4 Cilioprotists as Biological and Pollution Indicators of GBHW Efficiency

A GBHW was constructed and implemented for sewage treatment in several Egyptian villages, where they provided an excellent environment for a very wide range of the ciliates species "Cilioprotists" (23 species). These organisms were very useful to study the biological system of the GBHW. They can be employed as good indicators for various saprobic conditions. In addition, these ciliates provided an excellent means to estimate the efficiency of the GBHW system for sewage treatment. The obtained results confirmed the ability of the GBHW in producing a high-quality treated effluent with excellent microbial reduction that meets the quality standards for reuse in irrigation according the local and the international regulations [41].

5.3.5 Hydroponic Rooftop Gardens in Informally Developed Areas in Egypt

This work investigated the development of the rooftop farming through a hydroponic system for the purpose of improving the quality of life for the majority of residents. The study aimed to explore the advantages and the potentials of green vegetative rooftops [42]. Rooftop gardens are presented mainly as a podium for urban farming [6]. The general main aim is solving social, environmental, as well as the economic problems in large cities like Cairo with a hot arid climate as well as in different developing countries. The investigation was based on extensive local studies that address such green-roof hydroponic in an arid climate. A long-term strategy of adopting roof farming could certainly support the sustainability for food security, as well as the addition of social, environmental and aesthetical advantages to cultivated areas.

Appropriate knowledge is required for implementing the hydroponic roof gardens in Egypt. The study showed that they are cost-effective, simple to design and to implement. Nevertheless, the important factors are: the construction restrictions and the climatic conditions, beside the social factors. The present application had great success as well as environmental and social benefits. However, a number of challenges that hinder the spreading of such hydroponic technology in Egypt including legal encouraging support to private sector in participating in these valuable projects. By overcoming such challenges, a reasonable ratio of environmentally friendly green areas can be reached in the near future at ratio of 4 m^2/pe [43].

5.3.6 Constructed Wetland in a Remote Area for Greywater Treatment

The study area is east of Sharquiya Governorate, 55 km NE of Cairo. Fifty years ago, this area was a desert without any agriculture activity. It is now a well-known organic farm that depends on groundwater and rain for irrigating the purely organic and pharmaceutical plants. The overall purpose was to reuse the treated wastewater, recycling the nutrients, and protecting the environment and the public health. The work was designed to implement integrated models of wastewater treatment and reuse [44].

A full-scale CW was established in this farm for greywater treatment and reuse of treated effluent to irrigate lumber trees. The greywater originated from children and boarding school, training workshops, offices, laundry, kitchen and few houses. The raw greywater characteristics were within the average strength in Egypt. The CW was designed for the treatment of 20 m^3/d. The greywater was primary treated in a three-chamber sedimentation/septic tank of 56 m^3 capacity (Fig. 5.8a) followed by a SSFCW of 200 m^2 area (Fig. 5.8b). The HRT for the septic tanks and the CW were 6, and 7 days, respectively.

The results showed that COD and BOD were eliminated by 87% and 89%, respectively. The fecal coliform count was also reduced by 5 log units. The physico-chemical characteristics of the treated wastewater were within the permissible limits of the Egyptian standards for irrigation [40] Meanwhile, no odor problems or

Fig. 5.8 (**a**) Construction of the septic tank, (**b**) Constructed wetlands before planting in Sharquiya

insects existed due to employing the SSFCW. Employing the proper engineering design of a CW and efficient primary treatment process has improved the quality of the treated effluent. The treated water was reused onsite for irrigating the lumber forest trees on the local sandy soil. The advantages are soil quality improvement, recycling nutrients, higher agricultural production and groundwater protection. Treated water reuse could save about 10 m^3/d of fresh water that were consumed for irrigating the lumber trees [44]. The CW system can achieve good performance all year around due to the sunny and moderate climate in Egypt. It was, therefore, concluded that CWs are simple, low-cost, and efficient treatment systems particularly appropriate for decentralized and remote areas in Egypt [44].

5.3.7 Greywater Treatment Using Different Designs of Gravel or Sand Bed Hydroponic Filters

Different designs of sand bed hydroponic filter as a secondary treatment for a primary treated greywater effluent were studied in order to optimize the treatment efficiency. The following hydroponic filters were examined: (1) Gravel bed filter down flow (GFDF), (2) gravel bed filter up flow (GFUF), (3) sand bed filter down flow (SFDF), (4) gravel bed filter followed by sand bed filter (GFSF), and (5) a horizontal flow sand bed filter (HFSF). The pilot plants were designed and implemented at the National Research Center of Egypt.

During the period of this study, the GFDF, GFUF, and SFDF were examined with a wastewater influent flow rate of 173 m^3/m^2/d, while the GFSF and HFSF were examined at a flow rate of 86.5 m^3/m^2/d [45]. The operation and dimensions of the designed hydroponic filters are given in Table 5.4. The raw greywater characteristics varied greatly from 319.6–491 mg/L for COD, 120–307 mg/L for BOD_5, and 26–201 mg/L for TSS. The biodegradability (BOD_5/COD) was 0.54, slightly lower than the average domestic wastewater. This confirms that the greywater contains non-biodegradable organic contents, particularly in dissolved forms. This greywater

Table 5.4 Design and operating parameters for the different GBHF and SBHF systems [45]

System	Area (m^2)	Depth (m)	Type and size (mm) of media	HLR** (m^3/m^2/day)	OLR** (g BOD/m^2/day)
Gravel bed hydroponic filter down flow (GFDF)	1.0	1	Gravel of 2–4 mm	173	18.3
Gravel bed hydroponic filter up flow (GFUF)	1.0	1	Gravel of 2–4 mm	173	18.3
Sand bed hydroponic filter down flow (SFDF)	1.0	1	Sand of 1–2 mm	173	33.9
Gravel filter followed by sand filter (GFSF)	2	03	Sand of 1–2 mm and gravel of 2–4 mm	86.5	9.3
Rough filter (HFSF)	2	03	Gravel of 2–4 mm	86.5	23.8

**OLR = Organic Loading Rate

was treated first by sedimentation as primary treatment followed by the different hydroponic filter systems. The only difference between downflow and upflow GBHF is the direction of wastewater feeding. Table 5.4 shows the design and operation parameters of these filters.

The COD of GFSF and HFSF effluent was lower than that the GFDF, GFUF, and SFDF systems. This may be attributed to the lower HRT applied to the GFSF and HFSF compared to the other systems (namely, GFDF, GFUF and SFDF). BOD_5 removal in the GFSF and HFSF systems was 82% and 81.2%, respectively. The level of detergents was also reduced in the effluent. The hydraulic loading rate (HLR) was controlled at 86 $L/m^2/d$ and the organic loading rate (OLR) was 23.7 g $BOD_5/m^2/d$.

For the treated effluent of the GFSF, the residual concentration of BOD**5**, COD, and TSS was 16 mg/L, 43 mg/L, and 7.5 mg/L, respectively. The corresponding concentration in the HFSF effluent was 17, 40, and 9 mg/L. It was, therefore, found that the physico-chemical characteristics of the treated effluent of both GFSF and HFSF complied with the National Regulatory Standards of the treated wastewater reuse in agriculture irrigation [40].

From these results, it was concluded that the designed gravel or sand bed hydroponic filter, such as the GFSF or HFSF, for greywater treatment is a promising system providing a treated effluent that can be reused for agriculture irrigation. Sand and/or gravel filters can be used for a broad range of applications, including single-family residences, small communities, and large commercial establishments due to the fact that these are low-cost and simple techniques.

5.3.8 Integration of UASB and Two Different CWs

The enhancement of treated effluent quality via CW systems is increasingly employed in different countries throughout the world. For this purpose, a pilot plant study focused on two treatment schemes for sewage water [46]: an Up-flow Anaerobic Sludge Blanket (UASB) reactor followed by SSF and/or SF CWs (Fig. 5.9). The common vascular macrophytes in Egypt, namely *Typha latifolia* (cattail), was used at a planting density of a three rhizomes/m^2. To evaluate the role of such vascular plants in the pilot CW, two unplanted gravel beds were used; one identical to the SSF unit and the other identical to FWF unit operated as the control ones.

During the 12 months study period, all wetlands were fed with the UASB effluent at an OLR ranging from 17.3–46.8 kg BOD_5/ha/d (55.1–134.6 kg COD/ha/d). The obtained results revealed that the level of COD and TSS in the treated effluent of the SSF was lower than that of the FWS. The overall performance of the SSFCW demonstrated much higher removal rates of the studied pollutants than the unplanted CWs. The FC elimination reached 4 log units [46].

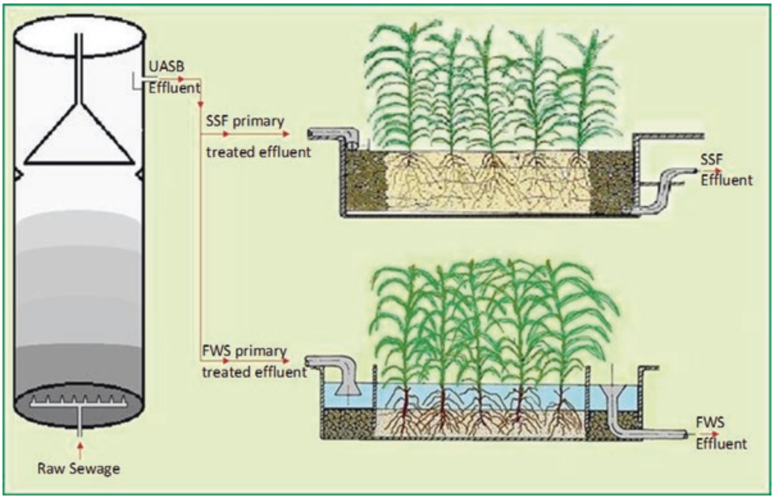

Fig. 5.9 UASB reactor followed by SSF and FWS CWs

5.3.9 Sewage Water Treatment by UASB Followed by CWs

A further study was carried out on the feasibility of employing the up-flow anaerobic sludge blanket (UASB) reactor followed by SSFCWs in a pilot plant for the treatment of sewage. The obtained results showed that the UASB reactor (as a primary treatment step) removed 67.7, 71.4 and 65.5% of COD, BOD and TSS, respectively, with corresponding residual concentration of 197, 120 and 79.3 mg/L. The count of Fecal Coliform was reduced by 1–2 log units in all cases. The residual count reached 1.6×10^6 MPN/100 mL.

This anaerobically treated wastewater effluent was subjected to the SSFCW. The later was highly efficient in the removal of COD, BOD and TSS with residual concentrations of 56.7 mg/L, 20.6 mg/L and 5 mg/L, respectively. Fecal coliforms were greatly reduced to $1.1 \text{x} 10^3$ MPN/100 mL. The quality of the obtained treated effluent complied with the National Regulatory Standards for agriculture irrigation [40]. Therefore, it was concluded that the combination of anaerobic UASB with the SSFCW is an effective treatment system for handling the sewage [47].

5.3.10 Blackwater and Greywater Treatment in UASB Followed by CW

Municipal sewage water separation into greywater and blackwater proved to be very effective strategy preventing the contamination of greywater by eliminating the fecal source, thus reducing the cost of wastewater treatment. The UASB reactor is known as a cost-effective system for organic wastewater, while CWs offer a

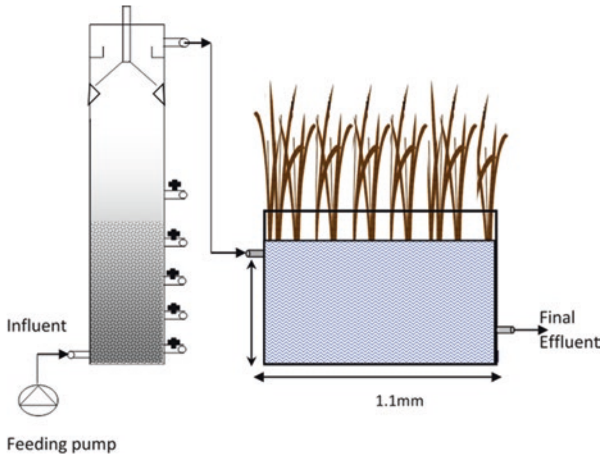

Fig. 5.10 Schematic diagram of the pilot system: UASB followed by HSSFCW [48]

low-cost treatment solution in developed and developing countries, particularly in semi-arid and arid areas. In this study, two separate UASB reactors were used as primary treatment step followed by CWs for the separate treatment of greywater and blackwater separately (Fig. 5.10). The HRT in the UASB was 24 and 6 h for the two reactors, while the OLR were 1.16 and 1.88 kg/m^3/day for the treatment of greywater and blackwater, respectively. The COD removal rate of in the UASB was 60% for greywater and 68% for blackwater. Further quality improvement was reached after the application of the HSSFCW. The overall removal rates for COD, BOD_5 and TSS was 87.7%, 89.5% and 94% for greywater and 94.2%, 95.6% and 94.9% for blackwater, respectively. Therefore, it was concluded that the integration of UASB and CWs is a promising technology for the treatment and reuse of blackwater and greywater, particularly in the arid and semi-arid areas [48].

5.3.11 Investigation of the CW Inlet Area Shape

The purpose of this study was to investigate the effect of two different shapes of the CW inlet. Four pilot-scale units were constructed and operated under a 2-days HRT in parallel in continuous feeding experiments. The treatment system consisted of a filtration unit followed by two CW units: one FWS and one SSF (Fig. 5.11). Two different shapes of the inlet works were tested per design: rectangle and triangle. The results indicated that the triangle-shaped inlet showed a higher removal of COD (73%), BOD_5 (83%), TSS (81%), fecal coliform (effluent: 104 MPN/100 ml), fecal streptococci (effluent: 103 MPN/100 ml), *pseudomonas aeruginosa* (effluent: 102 MPN/100 ml) and *Salmonellae* (100%). The removal rates in the FWS unit were slightly higher than the SSFCW unit in terms of COD and BOD. It was concluded that the inlet design has a slight effect on the CW efficiency (Kamel et al. 2010)

[40]. Therefore, the authors suggested that the well-designed inlet shape has a considerable effect on the efficiency of CW [49].

5.3.12 Agriculture Drainage Water Treatment in FWS CW Followed by Floating Aquatic Plant CW

The treatment of agriculture drainage water by two CW types has been studied in Egypt for the purpose of enhancing the treated water quality. The treatment scheme consisted of FWS CWs followed by floating aquatic plant (FAP) CWs (Fig. 5.12). In the FWSCW, *Typha latifolia* (cattail) was used as the macrophyte and water hyacinths in the FAP. The results showed that this combined treatment system was efficient in the removal of TSS, COD, BOD, ammonia and phosphates. The concentration of COD, BOD, TSS, ammonium compounds and phosphates was reduced from 115.2, 71.4, 79.4, 4.7 and 1.4 mg/L to 41.8, 13.9, 13.5, 1.8 and 0.5 mg/L, respectively. In all cases, the treated effluent complied with the National regulatory standards for reuse of wastewater treated effluent [50], demonstrating that the CW system is an efficient treatment system for agriculture drainage water [51].

Fig. 5.11 CW pilot units with different inlet shape designs [49]

Fig. 5.12 Combined system of FWS and FAP CWs for drainage water treatment; (**a**) FWS and (**b**) FAP units [51]

5.3.13 Combination of Sedimentation Process and CWs

The efficiency of two field-scale HSSF CWs was studied for the treatment of agriculture drainage water. One system was planted with three different plants (*Canna*, *Phragmites australis* and *Cyperus papyrus*) and the other was unplanted as a control (Fig. 5.13). The surface area of each CW was 654 m^2, the flow rate 20 m^3/d and the OLR ranged between 1.7–3.4 kg $BOD_5/m^2/d$, while the HRT was 11 days [52].

The results indicated that the planted HSSFCW had better removal rates for COD (88%), BOD_5 (91%), TSS (92%), and phosphates (60%). Furthermore, 4 logs of total coliform were eliminated from the wastewater in the planted CW compared to 3 logs in the unplanted. In the planted unit, the nutrient uptake by the plant species reached 29, 30.9 and 38.9 g P/m^2 and 63.1, 49.46 and 82.33 g N/m^2 for *Canna*, *Phragmites* and *Cyperus*, respectively. This indicated that *Cyperus papyrus* plant is capable for a higher phosphate and nitrogen uptake than the other studied plants. Moreover, a higher removal of microbiological parameters was reached in the planted CW compared to the unplanted one. Most plants in the CWs survived over the 12-month experimental period. These findings indicated the positive role of the vascular plants in bacterial removal from wastewater [53, 54]. The overall performance by the different vascular plants indicated that *Cyperus* species is suitable for CW due to its high ability for nutrients uptake and pathogens elimination. The unplanted CW exhibited a reasonable removal of COD, BOD_5 and TSS, but the removal of pathogens and nutrient elements was low. After disinfection, the reclaimed water could be recycled for the purpose of non-restricted irrigation according to the Egyptian Holding Code Standards for wastewater reuse in agriculture [39]. It was concluded that the use of HFCW planted with *Canna*, *Phragmites*

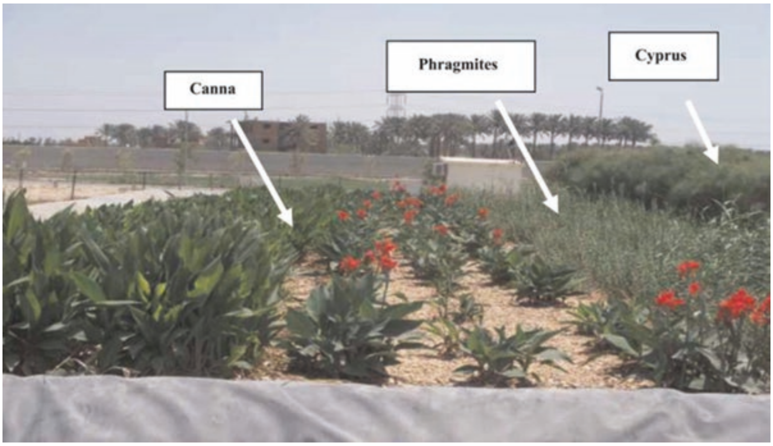

Fig. 5.13 Field-scale CW units planted with different plant species agriculture drainage treatment [52]

australis and/or *Cyperus* plants proved to be efficient in the treatment of this polluted water [52].

5.3.14 Combination of UASB and Hybrid CW for Sewage Treatment

The integration of an up-flow anaerobic sludge blanket (UASB) reactor followed by a hybrid CW system (FWS and SSF) has been investigated for the treatment of sewage in a pilot study (Fig. 5.14). Both CWs were planted with *Typha latifolia*, a common macrophyte in Egypt, at a planting density of three rhizomes/m^2. The CWs were continuously fed with the treated UASB effluent. During the study period, the OLR ranged between 41.4–74.5 kg BOD_5/ha/day and 84.5–152 kg COD/ha/day. The efficiency of this integrated system was high, resulting in effluent concentrations of 2.6, 6.4, and 21.4 mg/L for TSS, BOD, and COD, respectively. In addition, significant removal of the microbiological contaminants (total coliform, fecal coliform, fecal streptococci, *P. aeruginosa*, *Salmonellae*, total *Staphylococci*, and *Listeria monocytogenes*) was found [55].

5.3.15 Combination of Sedimentation Process and a Hybrid CWs for Blackwater Treatment

A further investigation was carried out on the efficiency of hybrid CWs for concentrated blackwater treatment [24] at pilot-scale. A pilot system was tested comprising a screening/sedimentation process as primary treatment, followed by a hybrid CW (HSSF and VFCW) (Fig. 5.15).

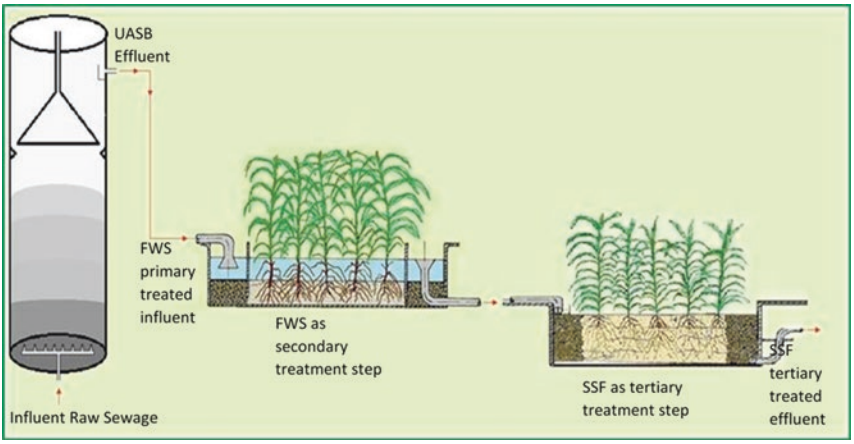

Fig. 5.14 A pilot UASB reactor followed by a hybrid CW system (FWS and HSSF) [55]

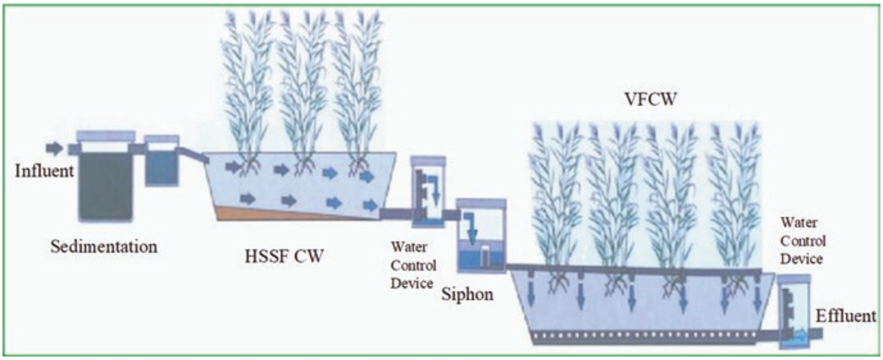

Fig. 5.15 Schematic diagram of the hybrid HSSF and VFCW for blackwater treatment [24]

The results showed that the sedimentation process was able to remove about 64.8%, 58.0%, and 56.8% of BOD_5, COD, and TSS, respectively. After the HSSF CW, the removal rates of BOD_5, COD, and TSS increased to 88.0%, 87.1%, and 82.9%, respectively. The overall removal (after the last VFCW stage) reached 98.0%, 98.5%, and 97.4%, for BOD_5, COD, and TSS, respectively. This, the final effluent complied with the National Regulatory Standards for unrestricted water reuse. This study showed that the hybrid CW represents a cost-effective technology for wastewater treatment that can be highly efficient in the climate of Middle East, Africa, i.e., in arid, and semi-arid areas. The hybrid CW enhanced the effluent quality, mainly due to the relatively low flow rate and the larger surface area. Such CWs act as gravel filters, thus, providing further sedimentation of the suspended solids as well as adsorption on the biofilm adhered to both the gravel and the plant roots. The combination of HSSF CW followed by VFCW proved to be a promising integrated system for the treatment of such strong blackwater. Such hybrid CWs can handle high hydraulic and organic wastewater loads [8, 24], as it has been proved in other cases under arid climates [56, 57].

5.3.16 *Enhancement of Degreasing/Settling Tank Followed by CW for Greywater Treatment*

Treated greywater can be reused for non-potable purposes such as landscape irrigation and toilet flushing. In this study, greywater was collected from five flats and connected to a pilot plant to examine different treatment processes for treatment and safe reuse of the treated water. The treatment system consisted of sedimentation/settling tank followed by a HSSF and VFCW (Fig. 5.16) [58]. To enhance the sedimentation tank, the "Effective Micro-organism (EM)" was added. The effect was examined firstly in "jar test" batch experiments to determine the optimum operating conditions. The experimental work involved monitoring of physico-chemical

Fig. 5.16 A pilot plant comprising of a sedimentation tank followed by a hybrid CW (HSSF and VFCW) for greywater treatment [58]

Table 5.5 Design and operation parameters of the hybrid CW treating greywater [58]

Dimensions and materials	
No. of units	2
Length	1.2 m
Width	1.0 m
Water depth	0.50 m
Plant	*Phragmittes austeralis*
No. of rhizomes/m^2	3
Substrate	Sand (0.20 ~ 0.45) mm, Rice straw (15 kg/m^3), and small gravel (0.50 ~ 1.00) mm
Metal piping inlet and outlet	PVC
Release and retain greywater	Valve
Operating conditions	
Hydraulic retention time (HRT)	2.2 d
Organic loading rate (OLR)	270.91 kg BOD/ha/d 356.36 kg COD ha/d

characteristics of greywater under varying operating conditions at different sedimentation periods. The design and operating conditions of this treatment system using the hybrid CW are given in Table 5.5.

The overall results showed that the addition of 1.5 ml/L of EM to the raw greywater in the settling tanks followed by 3.0 hr. retention resulted in remarkable removal of TSS, COD, BOD_5 and oil & grease at corresponding rates of 78%, 70%, 83%, and 89%. When this primary treated greywater was subjected to the hybrid CW, the removal rates reached 73%, 65%, 63%, and 84% for TSS, COD, BOD_5 and oil & grease, respectively. Overall, the combined system reached 94%, 90%, 94%, and 98% removal of TSS, COD, BOD_5 and oil & grease, respectively [58]. *E. Coli* count and the number of cells or eggs of Nimatoda reached 100/mL and “1 Count/L”, respectively in the outflow. The characteristics of the treated effluent were within the limits for unrestricted reuse according to the “Egyptian regulation, 2005” [50].

5.4 Role of CWs in Heavy Metals Removal

5.4.1 Gravel Bed Hydroponic Wetland

An experimental study was conducted for a period of 9 months on a gravel bed hydroponic wetland (GBHW) using artificially contaminated municipal wastewater by 5 different heavy metals. The metals were Cd, Cu, Ni, Pb, and Zn at a concentration of 5.0 mg/L each [59]. The dimensions of the GBHW were 30.5 m length, 0.6 m width, 1.2 m depth, and slope 2% (Fig. 5.17). The GBHW was planted with *Phragmites australis*. The study revealed that metals were greatly eliminated between 72% for Cd to 89% for Cu and Zn. Metals were mostly adhered to the solids that were precipitated between the gravel media of the GBHW. The reeds also contributed to such an elimination. The plant roots were the highest and the stems were the lowest in accumulating the studied metals. The distribution of metals in the plant was: roots > leaves > stems [59]. These results were also confirmed by other investigators, who studied similar GBHW with the same dimensions [60].

5.4.2 Fate of Heavy Metals in CWs for Greywater Treatment

A similar study was conducted to evaluate the fate of heavy metals in SSFCWs treating real greywater [61] (Fig. 5.18). The CW was planted with two different vascular aquatic plants; *Phragmites australis* and *Schoeneplectus lacustris*. Greywater was first applied to an Imhoff tank to remove the suspended solids, and

Fig. 5.17 A pilot gravel bed hydroponic wetland at 2% slope tested for heavy metals removal from wastewater [58]

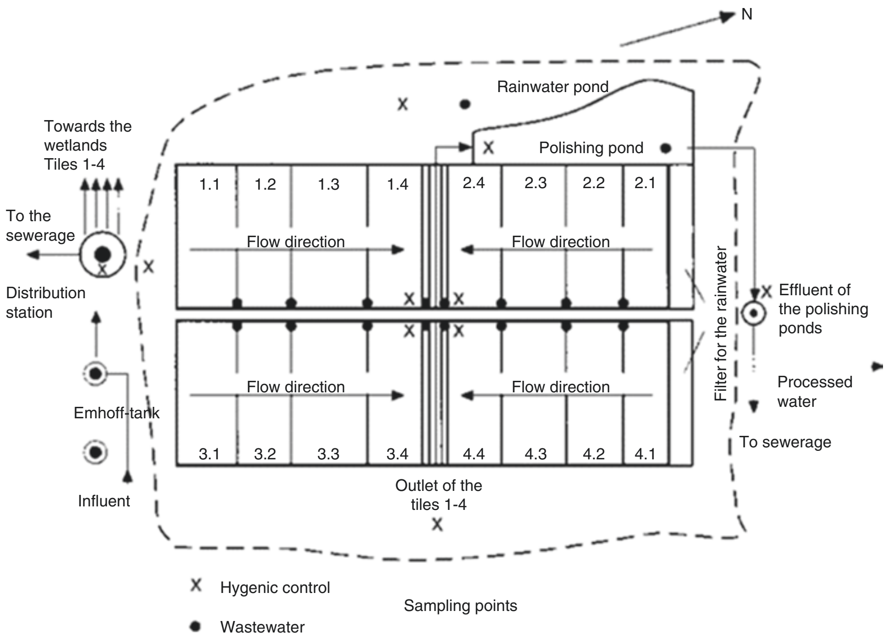

Fig. 5.18 Pilot SSFCWs for the treatment of greywater [61]

the effluent was directed to a CW. The CW effluent was then directed to a polishing pond.

The studied metals were Cr, Cu, Fe, Cd, Ni, Zn, and Pb. The translocation of these metals in the two plant roots, stems and leaves was also measured. The results showed that *P. australis* had a higher tendency to uptake metals than *S. Lacustris*. The level of metals was much higher in the roots, followed by leaves and stems. However, metals were concentrated mostly in the sludge than in the plants. Metals concentration was in the following order: Fe > Zn > Cu > Ni > Pb > Cd > Cr. The presence of such metals was attributed to the household greywater, therefore, iron and zinc both were enriched to a higher extent than the other ones. It was also confirmed that the level of studied metals in vascular plants grown in the CW were higher than in those grown in the "controlled" plant area.

Metal removal rates in CWs depend also on the type of element (Hg > Mn > Fe ¼ Cd > Pb ¼ Cr > Zn ¼ Cu > Al > Ni > As), as well as substrate conditions, metal ionic forms, season, and plant species [62]. It was found that the accumulation of metals in the greywater sludge was the factor controlling their elimination. In addition, that the vascular aquatic plants in the CW can be potential scavengers of metals accumulation. This study demonstrated that metal enrichment varies with metal type as well as the plant species.

5.5 Conclusions

CW system present several advantages. When the wetland system is constructed, there is no direct contact with the wastewater influent, no noise and odor generation, as compared with many other established treatment systems. CW systems can be implemented at any scale, enabling the onsite solution as a decentralized approach for wastewater treatment. CWs have also been proved efficient in reducing the pathogenic bacteria due to the HRT applied in these systems [3, 54], an issue of great importance for developing countries like Egypt. Generally, the pathogenic bacteria that are excreted in the sewage water live only for a short time depending on several factors including the surrounding environment and the bacteria own nature and characteristics [41]. It is found from the various experimental systems that pathogen removal in CWs is achieved via several mechanisms such as sedimentation, adsorption, filtration predation as well as inactivation due to the environmental stresses [23, 54].

Furthermore, CWs are a low-cost system in terms of construction, labor, maintenance and operation, since the labor needed to run the system are less than for other conventional technologies [1, 2, 39]. Typically, only one 1–2 hours weekly visit is required to control the site. Moreover, CW consume low amounts of energy or even no energy at all [29], since they use much less equipment than other systems. It is also worth mentioning that the CWs use no chemicals, therefore it is considered a green system.

A proper design of CW systems is crucial to obtain an acceptable effluent quality. The treated effluent has often a good quality suitable for land irrigation and safe reuse. This is mainly due to the removal of key pollutants such as ammonia, nitrates, phosphates, BOD5, COD, and TSS. Furthermore, the treated effluent can be safely reused for irrigation as the nutrient elements are recycled. In all cases, the treated effluent contains valuable nutrients (phosphates and nitrates) that give a high potential for agriculture irrigation. Moreover, reduction of sludge production can also be achieved through CWs [9, 62].

For these reasons, CWs have been efficiently used in Egypt for many years for treating various wastewaters, as a cost-effective, eco-friendly technology that could replace the conventional secondary biological treatment systems in many cases. The only drawback of these systems is the required land area for construction. However, usually this is not a problem in the arid and semi-arid areas where land is available and the water is highly needed. In Egypt, Middle Easter, North Africa, and generally in arid and semi-arid areas, and in many developing countries, the land area is often not a significant problem for the construction of a CW systems as a promising and attractive technique for decentralized wastewater management.

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