Chapter 3
A Review of Constructed Wetlands Types and Plants Used for Wastewater Treatment in Egypt

Mohamed S. Gaballah, Ayman N. Saber, and Jianbin Guo

Abstract Egypt is considered one of the world's driest and most water-stressed regions. A considerable amount of wastewater produced annually in Egypt attracts a variety of treatment technologies based on several factors, most notably cost and efficiency. Natural treatment methods such as constructed wetlands (CWs) are a rapidly growing technology. CWs have been applied in Egypt for almost 30 years. Horizontal subsurface flow (HSF) CWs represent 60% of the experimental and/or full-scale and/or pilot-scale systems. In comparison, 25% of the literature refers to Free water surface (FWS) CWs, and the remaining to Vertical flow (VF) and Hybrid Systems. Water hyacinth (*Eichhornia crassipes*) as a floating plant and *Cyperus papyrus* and *Typha angustifolia* as emergent plants are widely used in CWs in Egypt. In general, CWs have shown a high treatment potential to treat wastewater under the climatic conditions of Egypt with an increasing number of applications.

Keywords Water scarcity · Wastewater · Constructed wetlands · Floating plants · Emergent plants

M. S. Gaballah (✉)
College of Engineering (Key Laboratory for Clean Renewable Energy Utilization Technology, Ministry of Agriculture), China Agricultural University, Beijing, People's Republic of China

National Institute of Oceanography and Fisheries, Alexandria, Egypt

A. N. Saber
Pesticide Residues and Environmental Pollution Department, Central Agricultural Pesticide Laboratory, Agricultural Research Center (ARC), Giza, Egypt

National Engineering Laboratory for Industrial Wastewater Treatment, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, China

University of Chinese Academy of Sciences, Beijing, China
e-mail: Ayman.nabil89@gmail.com

J. Guo
College of Engineering (Key Laboratory for Clean Renewable Energy Utilization Technology, Ministry of Agriculture), China Agricultural University, Beijing, People's Republic of China

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_3

3.1 Introduction

Water scarcity and wastewater management are considered significant challenges that affect the ecosystem and the urban environment worldwide. Many countries and regions worldwide continuously face growing pressure on their limited freshwater resources, particularly in arid countries such as Egypt [1]. Egypt is classified among the driest areas and the most water-stressed regions in the world, with an average annual temperature of 25 °C and even higher in summer months, and with limited annual precipitation below 250 mm, resulting in an extremely freshwater scarcity [2, 3]. Moreover, the Grand Ethiopian Renaissance Dam (GERD) in Ethiopia threatens Egyptian water security, and negatively impacts on Egypt's freshwater since Egypt depends on the Nile River to secure 95% of its total water needs [4–8]. Thus, in Egypt, wastewater reuse is encouraged when it is safe and economically feasible to increase the water demand [9]. Several methods exist to treat wastewater based on different factors, mainly cost and efficiency, while nature-based solutions [10, 11], such as constructed wetlands (CWs), are the most growing technology.

Developing countries fail to use nature-based solutions to solve wastewater crises [1, 12]. About 95% of wastewater is discharged without treatment into lakes, seas, or other reservoirs, posing a threat to water sources and other serious environmental problems. CWs could offer an affordable and accessible solution for lower-income countries. CWs are defined as engineered eco-systems initiated and operated to treat different types of wastewater by manipulating the simultaneous physical, chemical, and biological processes [13, 14]. CWs have been rapidly developed to cover several types of wastewaters, such as municipal and industrial, due to their cost-effectiveness and eco-friendly character [1, 9, 15–20]. As a result of the growing attention to CW technology, the hydraulic design, construction, and operation have been extended to introduce various new configurations that facilitate the process as a whole and improve the performance for pollution removal [21–24, 25]. Locally, this technology has been applied in Egypt for almost 30 years.

From exploring the scientific literature, the significant number of publications related to CWs as individual experimental research or reviews on the Web of Science might be a good indicator of the increased transparency of this field's knowledge. A Web of Science database research (a tool from Clarivate Analytics, August 15, 2020) using the keyword "constructed wetlands, constructed wetlands in Egypt" resulted in 13,426 and 31 studies, respectively. This indicates that although there is a flourishing publication record available on CWs worldwide, it is limited in Egypt. Figure 3.1 depicts the number of papers per year from 2010 to 2020, showing that the topic has experienced a gradual growth in the number of studies. In addition, many books have been published recently, for instance, CWs hydraulic design [15], CWs as a suitable technology for sustainable water management [26], and CWs for industrial wastewater treatment [16].

Several review papers discussed CWs' performance in removing a wide range of pollutants from different wastewater types. These reviews have undoubtedly discussed the dynamics of pollutants, emerging organic pollutants such as antibiotics

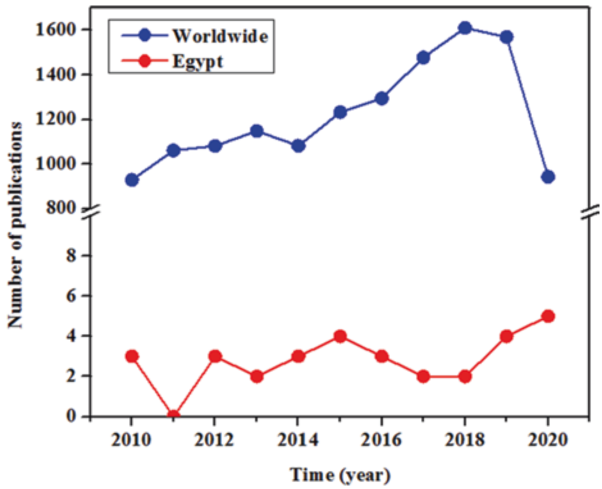

Fig. 3.1 Number of studies in the last 10 years on constructed wetlands

and pharmaceutical contaminants, and mechanisms of pollutant transformations. As a result of the increased attention to water scarcity in arid and hot regions such as Egypt, authorities have focused on wastewater reuse to protect the limited freshwater resources. Although CWs present a promising technology in Egypt, individual experiments and review papers are rarely reported.

Within this context, this chapter summarizes the current knowledge on CWs applications in Egypt along with the current status of water scarcity, taking into consideration different system configurations, operational parameters, and removal efficiencies. For this, an update on the application of CWs in Egypt is provided through a literature review of the last 10 years. Publications on CWs treating different types of wastewater in Egypt as pilot-scale and full-scale were also reviewed.

3.2 Water and Wastewater in Egypt

Egypt has a dry climate, with 95% of its area being a desert. There is a narrow strip of fertile lands alongside the major stream of the Nile and a comparatively small delta in the north [27]. It became the basis of one of the most distinctive old civilizations' societal and economic life, where the primary human activity was agriculture [28]. The total precipitation is around 25.7 mm/year; in summer, there is an evapotranspiration rate of about 0.7 mm/day. The relative humidity varies from 45–75%, and the mean daily temperature ranges from 13–38 °C. There are also limited amounts of rain and flash floods. The Nile River is Egypt's principal and almost sole freshwater supply. The country depends on Lake Nasser's accessible water to meet Egypt's annual water quota requirements, which amounts to 55.5 billion m^3/year [29].

Over the last few decades, the pollution load to the Nile system (e.g., the Nile River, canals, and drains) has grown due to population increase, many new industrial projects, and new projects for agricultural irrigation, and other activities along the Nile River. As a result, the quality of Nile water has declined significantly in the last few years [30, 31]. The Nile system's dilution capacity is likely to decrease as the policy of expanding irrigated farming progress and industrial capacity development increases the amount of pollutants discharged into the Nile [32]. The primary sources of most hazardous contaminants to the Nile and main canals are effluents from agricultural drains (including heavy metals, pesticides, fertilizers, and microbes) and the treated or incompletely treated municipal and industrial wastewaters. The most contaminated region in the Nile is between Cairo and the Mediterranean Sea within the two branches of the Nile, Rosetta and Damietta [33–35].

The industrial sector is the second essential source of water consumption and a contributor to pollution. The Egyptian factories use about 7.8 billion m^3/year of water, 4050 million m^3/year of which are discharged back to the Nile system. Hence, industrial wastewater is the second source of Nile water pollution due to hazardous organic and inorganic chemical loads in this wastewater. Industrial activities are clustered around large cities like Cairo, Giza, and Alexandria, which use 40% of total water [36]; however, small-scale private agro-industrial factories in Upper Egypt have recently begun contributing to Nile system pollution as well. Roughly 129 plants discharge their wastewater into the Nile River system. Untreated discharge of large amounts of this wastewater impacts river water used for both irrigation and drinking and has a harmful impact on aquatic life [28, 29, 37]. Food processing industries are responsible for more than 50% of the biological oxygen demand (BOD), while more than 60% of heavy metal discharges come from chemical factories. Wastewater from electroplating plants in the Helwan region (south Cairo) has a high content of Fe, Zn, Cr, Cu, and Mn [38]. Several studies have also reported the occurrence and concentration of Lead (0.001–330 μg/L) and cadmium (0.001–80 μg/L) in the Nile water [39–44]. Despite all official efforts to avoid these dangerous pollutants, 34 plants still do not comply with the Egyptian regulations for water disposal into the Nile systems [45].

The municipal wastewater effluent is considered as the third main source of Nile system pollution. The increasing population in Egypt along the Nile River leads to more wastewater generation, and policymakers are expected to expand the number of wastewater treatment plants (WWTPs). There are nearly 239 WWTPs in Egypt with an annual flow of 4.5 billion m^3, of which 1.3 billion m^3/year are discharged to the Nile water system. Toxic chemicals such as organic micro-pollutants and heavy metals are released in this wastewater because of domestic mixing with commercial and industrial activities [29]. These elevated values are higher than the standard limit and, in some areas of the Nile, higher than the permissible limits for healthy water streams. The two Nile branches, Damietta and Rosetta, downstream Delta Barrage, represent the worst River Nile quality. Some antibiotics such as sulfamethoxazole, azithromycin, and ciprofloxacin have been detected in the effluent of municipal WWTP in Beni-Suef city. Additionally, the detection of azithromycin in these municipal WWTP was higher than that detected in municipal WWTP in central Greece, China, and Thailand [46].

3.3 Constructed Wetlands (CWs)

CWs are defined as low-cost wastewater treatment techniques based on natural processes, which simulate the natural wetlands (e.g., swamps, marshes, and boglands) in a controlled environment [47]. CWs can be an effective treatment system, which can be very useful in developing countries [48], as they can remove most pollutants (e.g., pathogens, nutrients, organic and inorganic pollutants).

3.3.1 Constructed Wetland Types

As known, there are four typical types of CWs, i.e., Free water surface (FWS), Horizontal subsurface flow (HSF), Vertical flow (VF), and Hybrid Systems. In Egypt, all those types have been investigated and applied for different types of wastewaters, as shown in Table 3.1. About 60% of the experimental studies indicated that HSF is used either in full-scale or pilot-scale. HSF system in Egypt showed a high potential ability for pollutants removal compared to other systems. Approximately 25% of the reviewed literature revealed that FWS is also applied, while only one study was found on VF and another for a hybrid system.

3.3.2 Plants Used in CWs in Egypt

Local plant species can be used and grow in CWs. The plants in CWs in Egypt are classified into two types; floating plants, and emergent plants (Table 3.2).

In Egypt, the water hyacinth (*Eichhornia crassipes*) plant is an emerged plant and grows in natural waters (Lakes, Nile river, irrigation channels). It is considered an invasive aquatic weed and was found 100 years ago in the Nile Delta for the first time but entered Egypt 200 years ago. *Eichhornia crassipes* are intensively found in Northern Lakes, creating many problems such as clogging of irrigation canal intakes and flooding, disturbing the operation of hydropower and water supply systems, and resulting in the degradation of the local biodiversity [59]. It is also considered a hyper-accumulator species; however, it has many benefits, and remediation through CWs is one of them. The policies in Egypt concerning *Eichhornia crassipes* eradicating and controlling the plant from water bodies through mechanical or biological control [57], presented an efficient management scenario for its coverage percentage to enhance the phytoremediation of different pollutants and reduce the water losses instead of fall eradication. *Eichhornia crassipes* in CWs have a significant

Table 3.1 Overview of CWs applied and tested in Egypt

CW Type	Scale	Area (m^2)	Capacity (m^3/day)	Type of wastewater	Plants / media	Pollutants removal		References
						Parameter	Removal (%)	
HSF	Full-scale	231	1000	Primary treated domestic wastewater	*Cyperus papyrus* / gravel, pieces of plastic pipes, and shredded tire rubber chips	BOD	60.7	[49]
						COD	48.34	
						TSS	45.1	
HSF	Pilot-scale	181.5	8	Municipal wastewater	*Cyperus papyrus*, *Canna flaccida*, and *Phragmites australis* / gravel	BOD	83.4–88.6	[50]
						COD	83.5–89.1	
						TSS	57–68.7	
						NH_3	16–42.7	
						TKN	27–46.4	
HSF	Pilot-scale	70	2	Domestic wastewater	*Cyperus papyrus* / plastic, rubber and polystyrene foam	BOD	88	[51]
						COD	88	
						TSS	88.5	
						NH_3	78	
						P	85	
HSF	Pilot-scale	1	0.4	Polluted lake water	*Typha angustifolia* / gravel	BOD	83.3	[21]
						COD	95.8	
						Turbidity	98.4	
						NH_3	99.9	
						TN	94.7	
						TP	99.7	
						E. coli	100	
						Total bacterial count	92.3	
						Anaerobic bacteria	97.5	

HSF	Pilot-scale	654	20	Municipal wastewater	*Canna*, *Phragmites*, *Cyperus Papyrus* / gravel	BOD	91	[52]
						COD	88	
						TSS	92	
HSF	Pilot-scale	200	500	Municipal wastewater	*Phragmites australis* / gravel	BOD	89	[53]
						COD	87	
						TSS	92	
						TKN	73	
						TN	72.4	
						NH_3	76	
HSF	Pilot-scale	1.5	0.05	Agricultural and municipal wastewater	*Typha latifolia*, *Cyperus Papyrus* / gravel	BOD	68.5, 86.2	[54]
						COD	71, 85.5	
						TSS	70, 83.9	
						NH_3	82.3, 92.3	
						Bacteriological parameters	99.9	
						Salmonella sp	100	
						Cu, Zn	72, 84	
HSF-VF	Pilot-scale	10.8–9	0.4	Municipal wastewater	*Phragmites australis* / gravel	BOD	98.0	[55]
						COD	98.5	
						TSS	97.4	
						Turbidity	92.9	
						TKN	83.3	
						NH_3	93	
						TP	65.8	

(continued)

Table 3.1 (continued)

CW Type	Scale	Area (m^2)	Capacity (m^3/day)	Type of wastewater	Plants / media	Pollutants removal		References
						Parameter	Removal (%)	
VF	Pilot-scale	458	20	Primary treated municipal wastewater	*Canna*, *Phragmites australis*, and *Cyperus papyrus* /gravel	BOD	90	[48]
						COD	88	
						TSS	92	
FWS	Full-scale	125,000	21,500	Agricultural and municipal wastewater	*Phragmites australis*, *Typha latifolia*	BOD	52	[56]
						COD	50	
						TSS	87	
						NH_3	66	
						PO_4	52	
						Fe, cu, Zn, Pb	51, 36, 47, 52	
FWS	Pilot-scale	0.4	0.1	Polluted lake water	*Eichhornia Crassipes*	BOD	75	[57]
						TN	82	
						TP	84.2	
						NH_4	97.4	
						Fe, Pb, cu, Ni	62.5, 88.9, 81.7, 80.4	
FWS	Pilot-scale	0.4	0.1	Polluted lake water	*Pistia stratiotes*	BOD	83.5	[58]
						TN	90.3	
						TP	87	
						NH_4	97.53	
						Fe, Pb, cu, Ni	90.6, 97.3, 90.4, 70.2	

role in efficient nutrient absorption and high potential pollutants removal at high rates. *Pistia stratiote* is a floating aquatic plant, and its leaves spread in a rosette on the water surface that inhibits algae growth. *Pistia stratiote* is found in Egyptian waters in the spring and fall seasons. It has a high potential ability for contamination removal, as shown by [58]. *Lemna* spp. (Duckweed) the plant is an aquatic plant amongst the promising aquatic plants having the enormous capacity to treat eutrophicated wastewaters [60]; however, it's rarely used in Egypt phytoremediation studies. Duckweed is an invasive plant and is found in fresh Egyptian waterbodies. All of floating plants are used in FWS (CWs).

Cyperus papyrus plant is originated in Egypt, which has a historical benefits such as paper made and others. *Cyperus papyrus* is intensively used in CWs worldwide as a result of its high efficiency for pollutants removal [61]. Also, its root structures provide more microbial fixation sites, sufficient residence time of wastewater, entrapment, and settlement of suspended particles, the surface area for adsorption of contaminants, absorption, assimilation in plant tissues, and oxygen for the oxidation of organic matter and inorganic in the rhizosphere [62]. *Canna flaccida* is an invasive plant for the Egyptian environment; it hashing high growth rates with big roots, which may be a potential plant species that can be utilized effectively to remediate emerging organic contaminants [48, 63]. *Canna flaccida* has a colorful blossom, which can add an esthetically pleasing element to treatment sites. Phragmites are a native plant with many different species in Egypt; it usually distributes channels, lakes, and other water bodies. It has a high salinity tolerance so that it can grow on beaches.

Phragmites plant, especially *Phragmites australis* species, are widely used worldwide in CWs for treated wastewater [64]; in Egypt, many studies have used it, revealing their high ability and tolerance for heavy pollutants removal, as noted in Table 3.2. CWs widely use *Typha angustifolia* in Egypt, classified as an emergent plant with a high growth rate. *Typha angustifolia* is an invasive plant that originated from Europe and is distributed widely in many parts of the world [24]. There are many species of *typha*; *Typha angustifolia* has12–16 narrow and flat leaves [65]. *Typha angustifolia* is found in Northern lakes and the Nile River in Egypt. *Typha angustifolia* is known to have potential phytoremediation ability for various contaminants and has an antimicrobial effect against many pathogenic bacteria [22]. *Typha angustifolia* has approved its capacity for uptake the pollutants and performed efficiently in CWs. *Typha latifolia* (Cattails) is a native plant in Egypt found intensively in Lakes and the Nile River. Cattails plant has a wide range of applications, especially for its ability for pollutants removal through CWs.

3.4 Conclusions

Water scarcity and wastewater management are considered significant challenges that affect the ecosystem and the urban environment worldwide, especially in Egypt. With limited freshwater resources, Egypt has a huge amount of wastewater

Table 3.2 Plant species used in CWs in Egypt

Plant type	Plant name	Common name	Plant height	Growing season	Optimum conditions	Origin
Floating plants	*Eichhornia Crassipes*	Water hyacinth	1–2 m	Seasonally	28–30 °C	Invasive
	Pistia stratiotes	Water lettuce	0.2–0.3 m	Seasonally	22–30 °C	Invasive
	Lemna spp	Duckweed	0.01 m	Seasonally	6–33 °C	Invasive
Emergent plants	*Cyperus papyrus*	Papyrus, paper reed	4–5 m	Perennial plant	20–30 °C	Native
	Canna flaccida	Canna	1–1.5 m	Perennial plant	15 °C	Invasive
	Phragmites	Phragmites	5 m	Perennial plant	10–30 °C	Native
	Typha angustifolia	Typha	3 m	Perennial plant	25–30 °C	Invasive
	Typha latifolia	Cattails	1.5–3 m	Perennial plant	25–30 °C	Native

annually, partially treated using different methods, with Constructed wetlands (CWs) technology among them. CWs literature for wastewater treatment in Egypt has been reviewed for a period of the last 10 years. The HSF system was found to be the most widely applied system in either full-scale or pilot-scale, followed by the FWS design. Also, the commonly used plants in this technology were reviewed and showed a wide range of suitable plants growing in the Egyptian environment. This green technology has become increasingly known in Egypt and has a wide implementation potential; however, the number of publications is growing slowly. The currently limited experiences with CWs in Egypt imply the ability of this technology to contribute to addressing the water scarcity issues in Egypt effectively.

References

1. Stefanakis AI (2020) Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challenges and case studies in the Middle East. Water 12. https://doi.org/10.3390/w12061665
2. FAO (2014) AQUASTAT Database 2014
3. Prăvălie R (2016) Drylands extent and environmental issues. Global Approach Earth-Sci Rev 161:259–278. https://doi.org/10.1016/j.earscirev.2016.08.003
4. Abdelhaleem FS, Helal EY (2015) Impacts of grand Ethiopian renaissance dam on different water usages in upper Egypt. British J Appl Sci Technol 8(5):461–483. https://doi.org/10.9734/BJAST/2015/17252
5. Walsh D, Sengupta S (2020) For thousands of years, Egypt Controlled the Nile. A New Dam Threatens That. New York times
6. El-Nashar WY, Elyamany AH (2018) Managing risks of the grand Ethiopian renaissance dam on Egypt. Ain Shams Eng J 9:2383–2388. https://doi.org/10.1016/j.asej.2017.06.004

7. Hamada YM (2017) The grand Ethiopian renaissance dam, its impact on Egyptian agriculture and the potential for alleviating water scarcity. Environ Policy. https://doi.org/10.1007/978-3-319-54439-7
8. Abdelwahab O, Gaballahab MS, Barakata, Khouloud M, Aboagye D (2021) Pilot modified settling techniques as a novel route for treating water influent from Lake-Marriott. J Wat Proc Eng 42:101985. https://doi.org/10.1016/j.jwpe.2021.101985
9. Elzein Z, Abdou A, ElGawad IA (2016) Constructed wetlands as a sustainable wastewater treatment method in communities. Procedia Environ Sci 34:605–617. https://doi.org/10.1016/j.proenv.2016.04.053
10. Stefanakis AI, Calheiros CS, Nikolaou I (2021) Nature-based solutions as a tool in the new circular economic model for climate change adaptation. Circ Econ Sust 1:303–318. https://doi.org/10.1007/s43615-021-00022-3
11. Oral HV, Radinja M, Rizzo A, Kearney K, Andersen TR, Krzeminski P, Buttiglieri G, Ayral-Cinar D, Comas J, Gajewska M, Hartl M, Finger DC, Kazak JK, Mattila H, Vieira P, Stefania PP, Palermo A, Turco M, Pirouz B, Stefanakis A, Regelsberger M, Ursino N, Carvalho PN (2021) Management of Urban Waters with nature-based solutions in circular cities—exemplified through seven urban circularity challenges. Water 13(23):3334. https://doi.org/10.3390/w13233334
12. Morris JC, Georgiou I, Guenther E et al (2021) Barriers in implementation of wastewater reuse: identifying the way forward in closing the loop. Circ Econ Sust 1:413–433. https://doi.org/10.1007/s43615-021-00018-z
13. Stefanakis AI (2020) Constructed wetlands: description and benefits of an eco-tech water treatment system. In: Khosrow-Pour M (ed) Waste management: concepts, methodologies, tools, and applications. IGI Global, Hershey, pp 503–525
14. Stefanakis AI (2019) The role of constructed wetlands as green infrastructure for sustainable urban water management. Sustainability 11(24):6981. https://doi.org/10.3390/su11246981
15. Eslamian S, Okhravi S, Eslamian F (2020) Constructed wetlands: hydraulic design. CRC Press-Taylor & Francis Group, Boca Raton
16. Stefanakis AI (2018) Constructed wetlands for industrial wastewater treatment, 1st edn. Wiley, Chichester
17. Gomes AC, Silva L, Albuquerque A, Simões R, Stefanakis AI (2018) Investigation of lab-scale horizontal subsurface flow constructed wetlands treating industrial cork boiling wastewater. Chemosphere 207:430–439
18. Ramírez S, Torrealba G, Lameda-Cuicas E, Molina-Quintero L, Stefanakis AI, Pire-Sierra MC (2019) Investigation of pilot-scale constructed wetlands treating simulated pre-treated tannery wastewater under tropical climate. Chemosphere 234:496–504
19. Gholipour A, Zahabi H, Stefanakis AI (2020) A novel pilot and full-scale constructed wetland study for glass industry wastewater treatment. Chemosphere 247:125966
20. Schultze-Nobre L, Wiessner A, Bartsch C, Paschke H, Stefanakis AI, Aylward LA, Kuschk P (2017) Removal of dimethylphenols and ammonium in laboratory-scale horizontal subsurface flow constructed wetlands. Eng Life Sci 17(12):1224–1233
21. Andreo-Martínez P, García-Martínez N, Quesada-Medina J, Almela L (2017) Domestic wastewaters reuse reclaimed by an improved horizontal subsurface-flow constructed wetland: a case study in the southeast of Spain. Bioresour Technol 233:236–246. https://doi.org/10.1016/j.biortech.2017.02.123
22. Gaballah MS, Abdelwahab O, Barakat KM, Aboagye D (2020) A novel horizontal subsurface flow constructed wetland planted with *Typha angustifolia* for treatment of polluted water. Environ Sci Pollut Res 27:28449–25462. https://doi.org/10.1007/s11356-020-08669-5
23. Mustafa A (2013) Constructed wetland for wastewater treatment and reuse: a case study of developing country. Int J Environ Sci Dev 4. https://doi.org/10.7763/IJESD.2013.V4.296
24. Shingare RP, Nanekar SV, Thawale PR, Karthik R, Juwarkar AA (2017) Comparative study on removal of enteric pathogens from domestic wastewater using *Typha latifolia* and *Cyperus rotundus* along with different substrates. Int J Phytoremediation 19:899–908. https://doi.org/10.1080/15226514.2017.1303809

25. Al-Wahaibi BM, Jafary T, Al-Mamun A, Baawain MS, Aghbashlo M, Tabatabaei M, Stefanakis AI (2021) Operational modifications of a full-scale experimental vertical flow constructed wetland with effluent recirculation to optimize total nitrogen removal. J Clean Prod 296:126558. S0959652621007782 126558. https://doi.org/10.1016/j.jclepro.2021.126558
26. Duran-Dominguez-de-Bazua M, Del C, Navarro-Frometa AE, Bayona JM (2018) Artificial or constructed wetlands: a suitable technology for sustainable water management. CRC Press, Boca Raton
27. Abd Ellah RG (2020) Water resources in Egypt and their challenges, Lake Nasser case study. Egypt J Aquat Res 46:1–12. https://doi.org/10.1016/j.ejar.2020.03.001
28. Loutfy NM (2010) Reuse of wastewater in Mediterranean region, Egyptian experience. In: Barcelo D, Petrovic M (eds) Waste water treatment and reuse in the Mediterranean region, Hdb Env Chem. Springer, Berlin Heidelberg, pp 183–213. https://doi.org/10.1007/698_2010_76
29. Shamrukh M, Abdel-Wahab A (2011) Water pollution and riverbank filtration for water supply along River Nile, Egypt, in: Ray, C., M. Shamrukh (Eds.), pp 5–28. https://doi.org/10.1007/978-94-007-0026-0_2
30. Abdel-Dayem S, Abdel-Gawad S, Fahmy H (2007) Drainage in Egypt: a story of determination, continuity, and success. Irrig Drain 56:S101–S111. https://doi.org/10.1002/ird.335
31. Abdel-Satar AM (2005) Water quality assessment of River Nile from Idfo to Cairo. Egypt J Aquat Res 31:200–223
32. MWRI, (Ministry of Water Resources and Irrigation) (2002) Survey of Nile system pollution sources. APRP-Water Policy Activity, Ministry of Water Resources and Irrigation (MWRI), EPIQ Report No. 64
33. Abdo MH (2004) Environmental studies on the River Nile at Damietta branch region. Egypt J Egypt Acad Soc Environ Dev Stud 5:85–104
34. NAWQAM (1998) Present status of water quality in Egypt. National Water Quality and availability management project (NAWQAM), National Water Research Centre, Canadian Executive Agency, Assessment Interim Report
35. NAWQAM (2003) Nile research institute data. National Water Quality and availability management project (NAWQAM), National Water Research Centre. Egypt
36. Wahaab RA, Badawy MI (2004) Water quality assessment of the River Nile system: an overview. Biomed Environ Sci 17:87–100
37. Elbana TA, Bakr N, Elbana M (2019) Reuse of treated wastewater in Egypt: challenges and opportunities. Handb Environ Chem 75:429–453. https://doi.org/10.1007/698_2017_46
38. El-Rafei S, El-Shawarby SI, Fahim FA (1987) Heavy metals in wastewater to the Nile. Desalination 67:355–362. https://doi.org/10.1016/0011-9164(87)90254-2
39. Ali MM, Soltan ME (1999) Heavy metals in aquatic macrophytes, water and hydrosoils from the river Nile. Egypt J Univ Arab Biol:99–115
40. Elsokkary IH, Müller G (1990) Assessment and speciation of chromium, nickel, lead and cadmium in the sediments of the River Nile. Egypt Sci Total Environ 97–98:455–463. https://doi.org/10.1016/0048-9697(90)90256-T
41. Gomaa MNE (1995) Recycling study of some heavy metals in the Egyptian aquatic ecosystem. Food Chem 54:297–303. https://doi.org/10.1016/0308-8146(95)00050-S
42. Mohamed MAM (1998) Environmental pollution of River Nile and drinking water by pesticides and heavy metals, Ph. D. thesis, Biochemistry Department, Cairo University, Egypt
43. Rashed MN (2001) Monitoring of environmental heavy metals in fish from Nasser Lake. Environ Int 27:27–33. https://doi.org/10.1016/S0160-4120(01)00050-2
44. Soltan ME, Awadallah RM (1995) Chemical survey on the River Nile water from Aswan into the outlet. J Environ Sci Heal Part A Environ Sci Eng Toxicol 30:1647–1658. https://doi.org/10.1080/10934529509376293
45. NBI (2005) Nile Basin water quality monitoring baseline report. Transboundary Environmental Action Project, Nile Basin Initiative
46. Younes HA, Mahmoud HM, Abdelrahman MM, Nassar HF (2019) Seasonal occurrence, removal efficiency and associated ecological risk assessment of three antibiotics in a municipal

wastewater treatment plant in Egypt. Environ Nanotechnol Monit Manag 12:100239. https://doi.org/10.1016/j.enmm.2019.100239
47. Vymazal J (2007) Removal of nutrients in various types of constructed wetlands. Sci Total Environ 380:48–65. https://doi.org/10.1016/j.scitotenv.2006.09.014
48. Abou-Elela SI, Hellal MS (2012) Municipal wastewater treatment using vertical flow constructed wetlands planted with *Canna*, *Phragmites* and *Cyperus*. Ecol Eng 47:209–213. https://doi.org/10.1016/j.ecoleng.2012.06.044
49. Zidan ARA, El-Gamal MM, Rashed AA, El-Hady Eid MAA (2015) Wastewater treatment in horizontal subsurface flow constructed wetlands using different media (setup stage). Water Sci 29:26–35. https://doi.org/10.1016/j.wsj.2015.02.003
50. Abou-Elela SI, Hellal MS, Elekhnawy MA (2019) Phytoremediation of municipal wastewater for reuse using three pilot-scale HFCW under different HLR, HRT, and vegetation: a case study from Egypt. Desalin Water Treat 140:80–90. https://doi.org/10.5004/dwt.2019.23362
51. Khalifa ME, Gaber Y, El-Reash A, Ahmed MI, Rizk FW (2020) Effect of media variation on the removal efficiency of pollutants from domestic wastewater in constructed wetland systems. Ecol Eng 143:105668. https://doi.org/10.1016/j.ecoleng.2019.105668
52. Abou-Elela SI, Golinelli G, El-Tabl AS, Hellal MS (2014) Treatment of municipal wastewater using horizontal flow constructed wetlands in Egypt. Water Sci Technol 69:38–47. https://doi.org/10.2166/wst.2013.530
53. Abdel-Shafy HI, El-Khateeb MA (2013) Integration of septic tank and constructed wetland for the treatment of wastewater in Egypt. Desalin Water Treat 51:3539–3546. https://doi.org/10.1080/19443994.2012.749585
54. Hamad MTMH (2020) Comparative study on the performance of *Typha latifolia* and *Cyperus Papyrus* on the removal of heavy metals and enteric bacteria from wastewater by surface constructed wetlands. Chemosphere 260:127551. https://doi.org/10.1016/j.chemosphere.2020.127551
55. Abdel-Shafy HI, El-Khateeb MA, Shehata M (2017) Blackwater treatment via combination of sedimentation tank and hybrid wetlands for unrestricted reuse in Egypt. Desalin Water Treat 71:145–151. https://doi.org/10.5004/dwt.2017.20538
56. El-Sheikh MA, Saleh HI, El-Quosy DE, Mahmoud AA (2010) Improving water quality in polluted drains with free water surface constructed wetlands. Ecol Eng 36:1478–1484. https://doi.org/10.1016/j.ecoleng.2010.06.030
57. Gaballah MS, Ismail K, Aboauge D, Ismail M, Sobhi M, Stefanakis AI (2021) Effect of design and operational parameters on nutrients and heavy metal removal in pilot floating treatment wetlands with *Eichhornia Crassipes* treating polluted lake water. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-12442-7
58. Gaballah MS, Ismail K, Beltagy A, Zein Eldin AM, Ismail MM (2019) Wastewater treatment potential of water lettuce (*Pistia stratiotes*) with modified engineering design. J Water Chem Technol 41:197–205. https://doi.org/10.3103/s1063455x1903010x
59. Sasaqi D, Setyono P (2019) Estimation of water losses through evapotranspiration of water hyacinth (*Eichhornia crassipes*). Caraka Tani J Sustain Agric 34:86–100
60. Iqbal J, Javed A, Baig MA (2019) Growth and nutrient removal efficiency of duckweed (*lemna minor*) from synthetic and dumpsite leachate under artificial and natural conditions. PLoS One 14:1–9. https://doi.org/10.1371/journal.pone.0221755
61. Alufasi R, Parawira W, Stefanakis AI, Lebea P, Chakauya E, Chingwaru W (2022) Environ Technol 43(7):949–961. https://doi.org/10.1080/09593330.2020.1811395
62. García-Ávila F, Patiño-Chávez J, Zhinín-Chimbo F, Donoso-Moscoso S, Flores del Pino L, Avilés-Añazco A (2019) Performance of *Phragmites Australis* and *Cyperus Papyrus* in the treatment of municipal wastewater by vertical flow subsurface constructed wetlands. Int Soil Water Conserv Res 7:286–296. https://doi.org/10.1016/j.iswcr.2019.04.001
63. Hwang JI, Li Z, Andreacchio N, Ordonez Hinz F, Wilson PC (2020) Potential use of floating treatment wetlands established with *Canna flaccida* for removing organic contaminants from surface water. Int J Phytoremediation 22:1304–1312. https://doi.org/10.1080/15226514.2020.1768511

64. Gholipour A, Stefanakis AI (2021) A full-scale anaerobic baffled reactor and hybrid constructed wetland for university dormitory wastewater treatment and reuse in an arid and warm climate. Ecol Eng 170:106360. S0925857421002159 106360. https://doi.org/10.1016/j.ecoleng.2021.106360
65. Sricoth T, Meeinkuirt W, Pichtel J, Taeprayoon P, Saengwilai P (2018) Synergistic phytoremediation of wastewater by two aquatic plants (*Typha angustifolia* and *Eichhornia crassipes*) and potential as biomass fuel. Environ Sci Pollut Res 25:5344–5358. https://doi.org/10.1007/s11356-017-0813-5