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Floating Wetlands for Sustainable Drainage Wastewater Treatment

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Abstract: The preservation of water resources in modern urbanized society is a major concern. In this study, a floating constructed wetland (FWT) pilot plant was designed and constructed for the treatment of a polluted wastewater drain. A series of experiments were run continuously for a year in pilot-scale FWTs in a semi-arid area located in Egypt's Delta. Four aquatic plant species (*Eichhornia*, *Ceratophyllum*, *Pistia stratiotes*, and *Nymphaea lotus*) were used to assess the performance of FWTs for pollutant removals, such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), electrical conductivity (EC), and total dissolved solids (TDS), from drainage wastewater to reuse the treated effluent in irrigation practices. The FWT systems were fed drainage tainted water on a weekly basis, and the concentrations and removal efficiency were assessed in the experiments. The average reduction in BOD, COD, TSS, TDS, TN, EC, and TP were 76–86%, 61–80%, 87–95%, 36.6–44.1%, 70–97%, 37–44%, and 83–96%, respectively. ANOVA with Post-HOC *t*-tests show that the *Eichhornia*, *Pistia stratiotes*, and *Nymphaea lotus* have the highest BOD and COD removal performance, whereas *Pistia stratiotes* and *Nymphaea lotus* have the highest TN and TP removal performance. In all cases, the *Nymphaea lotus* performed well in terms of pollutant removal. In addition, a design procedure for a FWT systems is presented. For wastewater treatment, FWT systems have proven to be a low-cost, long-term option.

Keywords: constructed floating wetlands; macrophytes; drainage wastewater treatment; irrigation practices

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1. Introduction

Egypt experiences a semi-arid climate with adequate solar radiation all year long with low precipitation, high evapotranspiration rates, and limited water resources [1]. The main water resource in Egypt is the Nile river, which contributes 55.5 km^3/year, the agriculture sector is the biggest freshwater consumer (about 80% of the Nile water) [2]. Population increases, urbanization, and intensification of industry and agriculture have all contributed to the steady degradation of water quality in aquatic habitats over the last few decades, mostly through wastewater generation and outflow [3]. Non-point source agrochemical pollution has become a major concern, and there is a growing need for cost-effective and environmentally friendly treatment technologies for agriculturally polluted water [4]. Currently, Egypt is facing a severe water shortage due to a progressive reduction in available surface water supplies, which has a negative impact on agricultural production throughout the country [5]. As a result, it is imperative that every feasible resource should be explored in order to improve the management of water resources throughout Egypt. Agricultural drains accumulate massive amounts of pollution mixtures (raw, treated, or partially treated effluent). The effluent from these drains is discharged into the Nile, Nile branches, coastal lakes, and the Mediterranean Sea. Agriculture drainage water reuse in Egypt is planned and controlled by the Egyptian Ministry of Water Resources and Irrigation (MWRI) and involves collecting agricultural drainage water in main drains channels and mixing it with Nile freshwater in mixing pump stations. Agricultural drainage water in branch drains, before it is discharged into a contaminated main drain, can be used for direct irrigation if the water is of suitable quality and the Ministry of Water Resources and Irrigation (MWRI) has given their authorization [2,3]. Farmers that reuse agriculture drainage water without first obtaining permission from the MWRI are engaging in unofficial reuse. The agricultural drains Bahr Elbaqar, El-Gharbia, Tillia, and Edku receive treated and untreated wastewater from the Egyptian Delta's eastern, western, and middle regions, respectively (Figure 1). Many studies have been conducted to determine whether the wastewater carried by these drains is suitable for irrigation and to analyze its environmental impact on natural lakes (EL-Manzala and Edko) (Figure 1). The key finding was that pre-treatment of water is required [6]. According to the Future-National Water Plan for Egypt 2017–2037 [3], reclaimed water from these drains would be used to construct a future horizontal extension of 96,600 hectares.

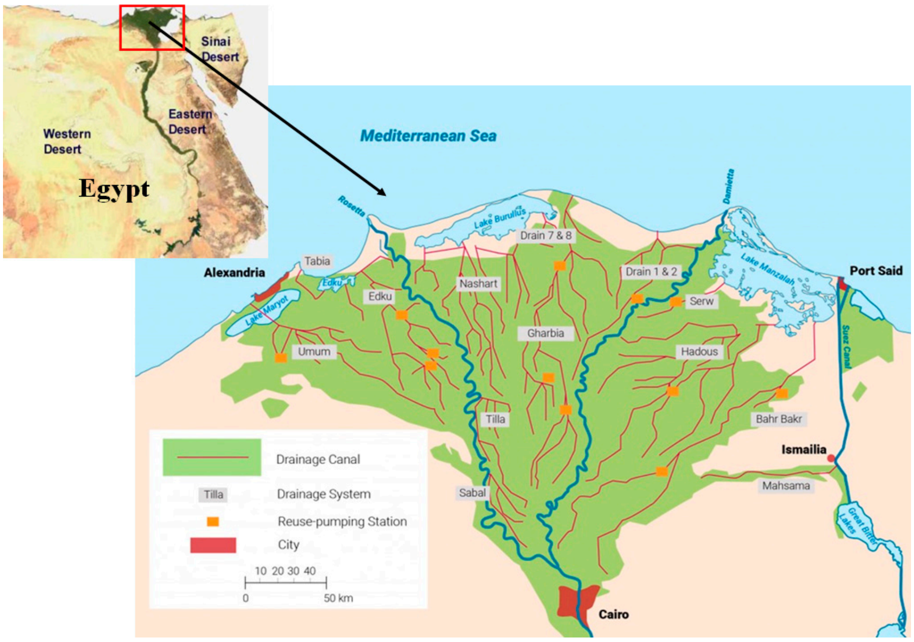

Figure 1. Drainage network in Delta [6].

Egypt's urbanization has put more strain on the country's domestic central wastewater treatment systems. Currently, the total collected wastewater was about 5 km^3, with total treated wastewater (TWW) accounting for 80% of the total collected wastewater. The recycled TWW is currently being reused about 3 km^3. TWW has the potential to provide up to 5 km^3 to Egypt's water resources. Treated wastewater is now mostly used for irrigation of green spaces (landscape development) and irrigation of non-food agriculture [6]. Recently, MWRI opened a big wastewater treatment plant to benefit from sewage water of 2 km^3/year from Bahr Elbaqar drain, instead of renting it in Lake Manzala, to reclaim 168 thousand hectares at the east of the Suez Canal via Elsalam Syphon under the Suez Canal. The total cost of this plant is 1 million USD, indicating a cost of 0.5 USD per m^3 of treated wastewater, which is considered a high cost.

One of the most cost-effective and efficient methods for the supply of irrigation water is wastewater treatment. Wastewater from the municipal sector is released into freshwater bodies such as rivers and streams, causing surface water quality to deteriorate [2,6]. Furthermore, seepage from unlined wastewater pipes can pollute groundwater [7]. Water bodies have become places for the dumping of domestic and industrial wastewater that requires suitable treatment throughout time [8,9]. Wastewater treatment is essential before being disposed in water, since it contains nutrients, heavy metals, and other contaminants to freshwater bodies [10,11]. Because wastewater contains a sufficient amount of nutrients, it can be used for bio-fertigation of agricultural crops following proper treatment. One of the alternative irrigation methods is to use wastewater for agricultural output [12,13]. Water scarcity and wastewater disposal are both addressed when wastewater is reused as bio-fertigation. Biological treatment options, such as activated sludge processes and tricking filters, are secondary treatment options that require a high cost for construction. Several natural systems, such as natural ponds and wetlands, aid in the controlled, ecologically friendly, and cost-effective treatment of wastewater. Because of their ease of use and maintenance, these systems are very efficient [14]. Constructed wetland is a well-known wastewater treatment technique that protects the environment. Surface flow constructed wetland systems and subsurface flow constructed wetland systems are the two most common forms of created wetland systems. These systems use soil and aquatic plants to remove toxins from wastewater [15]. The field-scale floating constructed wetlands used in Pakistan [16] efficiently attenuated a considerable fraction of various organic and inorganic pollutants for a cost of 0.0026 USD/m^3 of wastewater. Several physical, chemical, biological, and biochemical processes are used in a designed wetland system to remove containments from wastewater [14,17]. Floating wetland systems are made up of emergent vegetation growing on a buoyant infrastructure that floats on the surface of the water. The upper sections of the vegetation grow and stay mostly above the waterline, while the roots descend down into the water column, forming a large root system below the waterline. As a result, the vegetation grows hydroponically, taking nutrients directly from the water column [18]. The system's performance depends on the establishment of a large and dense root system. Biofilm forms on the roots and rhizomes, and the system acts as a natural filter while physical and biochemical processes occur [19,20]. Many floating plants, such as *Cyperus papyrus*, *Typha angustifolia*, *Cyperus alternifolius*, *Eichhornia*, *Ceratophyllum*, *Pistia stratiotes*, *and Nymphaea lotus*, can be utilized to remove pollutants in a wetland, however, plant selection criteria are dependent on the environment, wastewater type, and nutrients to be removed [21–25]. The goal of this research was to develop a design and construction approach for FWTs to treat polluted wastewater in agriculture drains in Egypt's Delta for reuse in irrigation practices. To attain this goal, (i) the prior work on deteriorated water resources along with the numerical results of FWT removal efficiency in the drainage network of Egypt's Delta was evaluated, (ii) an experiment was conducted to monitor and evaluate the performance of emergent plants *Eichhornia*, *Ceratophyllum*, *Pistia stratiotes*, *and Nymphaea lotus* plants in a floating wetland system to remove the water, including pollutants BOD, COD, TSS, TN, TDS, and TP, in drainage wastewater near some polluted drains in Damietta, Egypt's eastern Delta.

2. Materials and Methods

2.1. Setup and Experimental Work

An experimental FWT was established at New Damietta city near the studied drain from July 2020 to July 2021 (1 year). Four common types of floating plants were selected (*Eichhornia*, *Ceratophyllum*, *Pistia stratiotes*, and *Nymphaea lotus*) to be used in the experiment with a minimum of three duplicates (n = 3) per each macrophyte type. The influent water tanks were raised 50 cm above the FWT mesocosms, while the effluent was kept 50 cm below the FWT mesocosms (Figure 2). The drainage wastewater was pumped into the various influent storage buckets once a week at a rate of 1.5 L/day. The volume of the effluent buckets was 15 L, while the volume of the influence and wetland buckets was 25 L (30 cm diameter and 35 cm height) (30 cm diameter and 25 cm height). Every week, water samples from the influent and effluent were taken according to [26] and analyzed in the Faculty of Science lab, Damietta University, for the water quality parameters temperature, pH, TDS, TSS, BOD, COD, TN, and TP were measured. Figure 3 shows the *Eichhornia*, *Ceratophyllum*, *Pistia stratiotes*, and *Nymphaea lotus* plants' roots growing, which play the main role in pollutant removal.

Figure 2. Experimental floating wetland setup, (**A**) *Eichhornia*, (**B**) *Ceratophyllum*, (**C**) *Pistia stratiotes*, and (**D**) *Nymphaea lotus*.


(**a**) (**b**)
(**c**) (**d**)

Figure 3. Growing roots in the FWTs (**a**) *Eichhornia*, (**b**) *Ceratophyllum*, (**c**) *Pistia stratiotes*, and (**d**) *Nymphaea lotus* plants.

MS Excel 2019 was utilized to determine the statistical analysis for the measured inflow and outflow pollutants' concentrations. The statistically measured influent water quality parameters for the analyzed agriculture drain wastewater quality parameters are shown in Table 1.

Table 1. Statistical measured influent water quality parameters for studied Drain during July 2020 to July 2021.

Water Quality Parameters	Number of Samples	Maximum Value	Minimum Value	Average	Standard Deviation	Egypt Decrees Limits [27,28]
Temperature (°C)	33	30	17	23	4	>7
pH	33	8.8	7	7.5	0.4	6–9
EC (µs/cm)	33	2900	1500	2067	435.4	<3000
TDS (mg/L)	33	1850	1006	1286	204.9	<2000
BOD (mg/L)	33	190	75	112	29	<50
COD (mg/L)	33	380	115	217	71	-
TSS (mg/L)	33	310	120	207	47.6	-
TN (mg/L)	33	38	13	22	6.3	-
TP (mg/L)	33	6.2	1.5	4	1.3	-

EC, electrical conductivity; TDS, total dissolved solids; BOD, biochemical oxygen demand; COD, chemical oxygen demand; TSS, total suspended solids; TN, total nitrogen; and TP, total phosphorus.

2.2. Hydrological Wetland Balance

In dry and semi-arid conditions, Kadlec and Wallace [14] compute the wetland water balance.

For a surface flow constructed wetland as:

$$Q_{in} + R = Q_{out} + Q_{evap} + Q_{inf} + \Delta Q \tag{1}$$

where: Q_{in} is the inlet flow (m^3/day), R is the precipitation volume flow (m^3/day), Q_{out} is the outlet flow (m^3/day), Q_{evap} is the evapotranspiration (m^3/day), Q_{inf} is the infiltration flow (m^3/day), and ΔQ is the change in flow (m^3/day). The Q_{evap} is controlled by the reference evapotranspiration (ETo), which is a key component in the hydrologic balance of wetlands in dry and semi-arid climates. The FAO-CROPWAT 8 model and its connected CLIMWAT 2 model were used to determine the ETo of *Alfalfa* vegetation (vegetation of height 0.5 m) in this study, FAO [29]. The CROPWAT 8.0 is an FAO-developed decision-support computer tool that uses rainfall, soil, crop, and climate data to calculate ETo based on the FAO Penman-Monteith equation [30,31] by Allen et al. [32], crop water requirement, net irrigation water requirement, and irrigation schedule. Meteorological data is retrieved from the CLIMWAT 2.0 model, which includes seven long-term monthly climate characteristics as well as the location's coordinates and height. Monthly maximum and lowest temperatures (°C), wind speed (km/h), mean relative humidity (%), sunlight hours, rainfall data (mm), and effective rainfall data (mm) are the variables. In this study, the climate data for the Mansoura station, latitude 31.05° N and longitude 31.38° E, is approximately 50 kilometers from the studied drain. Table 2 summarizes the monthly average climate parameters in Mansoura station from 2010 to 2020.

Table 2. Monthly average climate parameters in Mansoura station during 2010 to 2020.

	Mansoura Station, Egypt		Latitude 31.05°		Longitude 31.38° E		Altitude 30 m	
Month	Minimum Temperature (°C)	Maximum Temperature (°C)	Relative Humidity (%)	Wind (Km/day)	Suns-hine Hours	Solar Radiation (MJ/m^2/day)	Rainfall (mm)	ETo (mm/day)
January	7.0	19.5	67	112	6.2	11.4	10.0	1.82
February	7.5	20.5	59	121	6.9	14.2	8.0	2.43
March	9.3	23.2	61	147	7.8	18.1	6.0	3.32
April	12.0	27.1	50	130	8.7	21.6	3.0	4.39
May	15.6	33.2	44	130	9.6	24.1	4.0	5.64
June	18.6	33.6	54	130	10.8	26.1	1.0	5.99
July	20.5	32.6	61	112	10.5	25.5	0.0	5.61
August	20.5	33.5	63	112	10.2	24.2	0.0	5.38
September	19.0	32.5	60	95	9.4	21.0	0.0	4.54
October	17.1	28.7	59	86	8.5	16.9	5.0	3.34
November	14.0	25.8	62	95	7.3	13.0	6.0	2.47
December	9.2	21.2	63	95	5.9	10.5	11.0	1.83
Average	14.2	27.6	59	114	8.5	18.9	54	3.90

2.3. FWT Design Procedure

A design methodology and a construction approach for the proposed floating wetland in the studied drain were developed for the removal of TSS, BOD, COD, TN, and TP. The influent wastewater flow rate (Q) was 2000 m^3/day at winter temperature (Tw) 7 °C, summer temperature (Ts) 33.6 °C, and average temperature 20.9 °C (Table 2), water depth (y) 0.75 m (Figure 4 shows the agriculture drain cross-section).

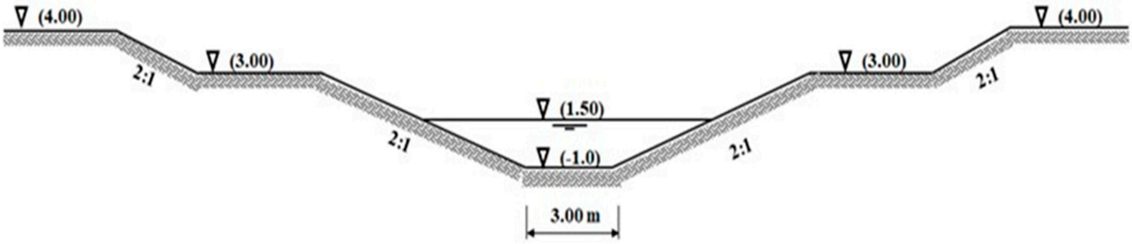

Figure 4. Studied drain cross-section.

The average values of BOD, COD, TSS, TN, and TP concentration of the studied wastewater were 121 mg/L, 220 mg/L, 207 mg/L, 22 mg/L, and 4 mg/L, respectively, which will be taken into account in the current design. A floating constructed wetland will be planted with *Nymphaea lotus* plants. In a well operating wetland system, the effluent concentration should be lower than the permissible concentrations suggested by the Executive Regulation of Law 48/1982 or Egypt Decree 92/2013 [27,28]. The maximum BOD concentration allowed in wastewater is 50 mg/L. Due to the huge rectangularity ratio of the suggested FWT, the first order P-k-C* model or relaxed tanks in series derived by Kadlec and Wallace [14] was utilized to determine the surface area of the BOD, COD, TN, TP, and TSS.

$$\frac{C_o - C^*}{C_i - C^*} = \left(1 + \frac{K_T}{XR}\right)^{-X} \tag{2}$$

$$K_T = K_{20}\theta^{T-20} \tag{3}$$

where: C_o is the effluent concentration of pollutant BOD, COD, TSS, TN, and TP in mg/L; C_i is the influent concentration of pollutant BOD, COD, TSS, TN, and TP in mg/L; C^* is the background pollutant concentration mg/L; K_T is the reaction rate constant in (m/day); X is the number of equal sized and completely mixed and connected in series (tanks); K_{20} is the removal rate constant at 20 °C (m/day); θ is the dimensionless temperature coefficient, and T is wetland temperature (°C); and R is the hydraulic loading rate in (m/day) defined by:

$$R = \frac{\mathrm{Q}}{\mathrm{A}} \tag{4}$$

$$\mathrm{HRT} = \frac{\mathrm{V}}{\mathrm{Q}} = \frac{\mathrm{A\ y\ N}}{\mathrm{Q}} = \frac{\mathrm{yN}}{R} \tag{5}$$

where Q is the design flow rate (m^3/day), assumed constant; A is the mean surface area of the FWT system (m^2); V is the system volume (m^3); y is the flow depth (m); N is the fractional porosity, which expresses the space available for the water to flow through the media, roots and other solids in the FWT system. Background concentrations in surface flow wetlands for C^* and K_T values will be derived from an empirical relationship based on a curve fitting to existing data sets for the wetland project, which will be equal to concentrations obtained from a similar in-stream wetland project conducted east of the Nile Delta [33]. The TSS, BOD, and COD background values were 5 mg/L, 2 mg/L, and 10 mg/L, respectively [33]. In addition, the corresponding removal rate temperature-dependent constants (K_T) for complete mixing flow models and the related K_{20} are 0.813, 0.489, and 0.54 for TSS, BOD, and COD respectively [34]. Figure 5 shows the flow chart for the design technique for the proposed FWT.

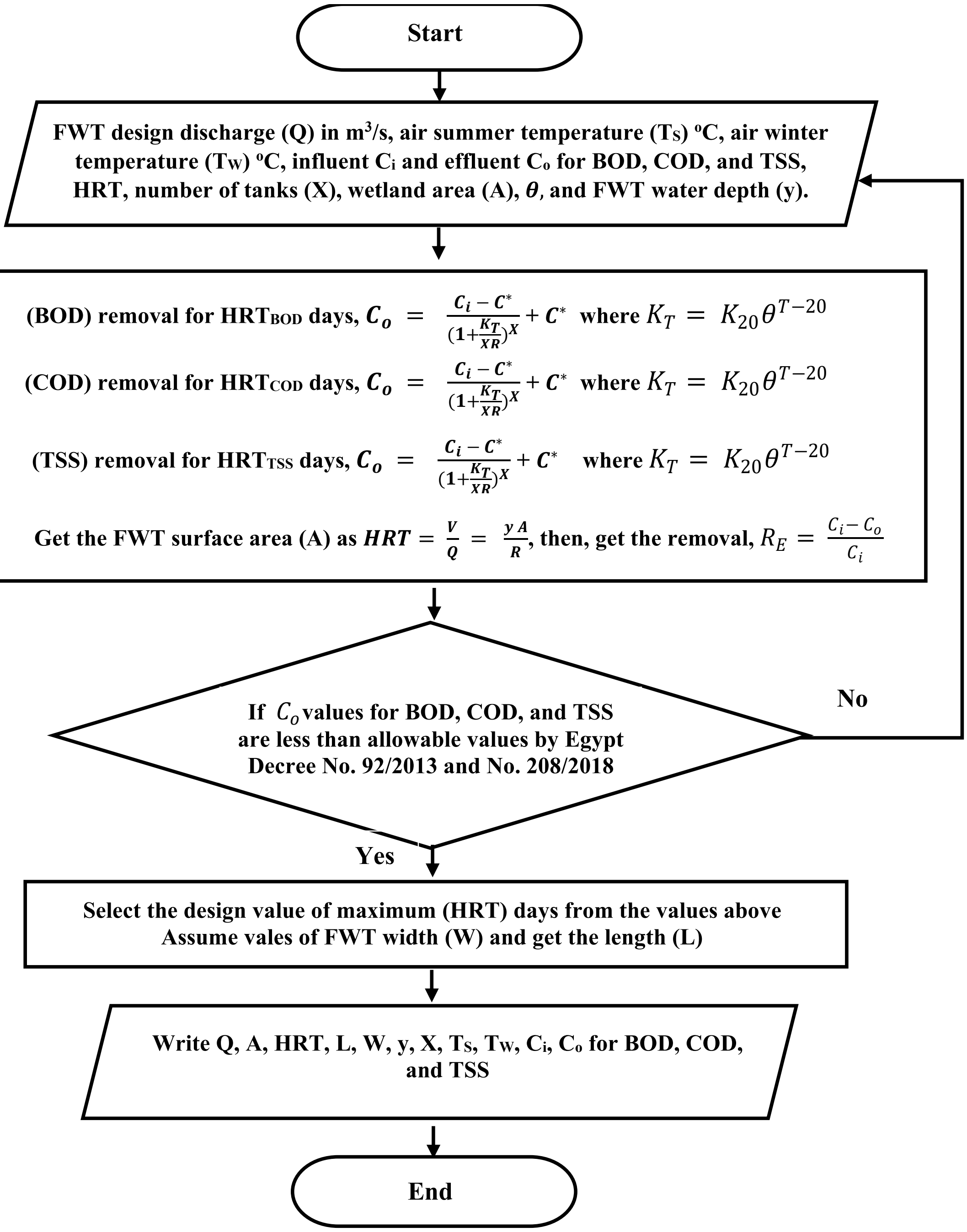

Figure 5. Design flow chart for the FWT system.

2.4. Pollutant's Removal Efficiency

The FWT treatment efficiency (R_E) is given as:

$$R_E = \frac{C_i - C_o}{C_i} \tag{6}$$

where, C_o is outlet pollutant concentration and C_i is the inlet influent pollutant concentration.

3. Results and Discussion

3.1. Pollutants Removal Efficiencies

Table 3 summarizes the removal rate (mean ± standard deviation) (%) for the BOD, COD, TN, TP, TDS, and EC removal for the different floating wetlands (FWTs), *Eichhornia*, *Ceratophyllum*, *Pistia stratiotes*, and *Nymphaea lotus* (plants A, B, C, and D respectively). Figure A1 shows the measured influent and effluent pH concentration for *Eichhornia*, *Ceratophyllum*, *Pistia stratiotes*, and *Nymphaea lotus*), all are within the allowable limits according to the Egyptian's regulation for the protection of the Nile River and its waterways from pollution [27,28]. The measured influent and effluent electrical conductivity (EC) concentration for *Eichhornia*, *Ceratophyllum*, *Pistia stratiotes*, and *Nymphaea lotus* (Figure A2) shows a reduction of 37–44%. *Pistia stratiotes* and *Eichhornia* achieved the highest EC reduction of 44 ± 10.6% and 42 ± 10.3%. Figure A3 illustrates the measured TDS concentrations in the influent and effluent, which are within the Egyptian regulatory limits. For *Pistia stratiotes* and *Eichhornia*, the highest TDS removals were 44.6% and 42.3%, respectively. Figure A4 shows the measured influent and effluent TSS concentrations for the four FWTs, *Eichhornia* and *Nymphaea lotus*, indicating the highest reduction of TSS 95 ± 2.8% and 94 ± 2.6% respectively.

Table 3. Comparison of mean BOD, COD, TN, TP, TDS, and EC removal for the different floating wetlands (FWTs).

FWTs	Removal Rate (Mean ± Standard Deviation) (%)						
	BOD	COD	TN	TP	TDS	TSS	EC
(A) *Eichhornia*	86 ± 5.8 a	80 ± 7.3 a	70 ± 19.8 a	86 ± 10.2 a	42.3 ± 10.4 a	95 ± 2.8 a	42 ± 10.3 b
(B) *Ceratophyllum*	76 ± 6.4 b	61 ± 17 b	70 ± 13.7 a	83 ± 11 a	36.6 ± 12.2 a	87 ± 4.6 b	37 ± 12.1 b
(C) *Pistia stratiotes*	82 ± 7.7 a	78 ± 7.6 a	97 ± 2.1 b	89 ± 8.4 a	44.1 ± 10.8 a	91 ± 4.1 c	44 ± 10.6 b
(D) *Nymphaea lotus*	84 ± 6.3 a	79 ± 9.5 a	97 ± 1.5 b	96 ± 7.4 b	39.7 ± 12 a	94 ± 2.6 a	40 ± 11.8 b

The same letter refers to no significant difference observed on $p = 0.05$ level according to ANOVA with Post-Hoc t-tests.

Figures A5 and A6 show the measured influent and effluent BOD and COD concentration for *Eichhornia*, *Ceratophyllum*, *Pistia stratiotes*, and *Nymphaea lotus* (plants A, B, C, and D respectively). The biological oxygen demand (BOD) in the influent ranged from 75 to 190 mg/L, with removal effectiveness of 76 to 86%, resulting in a considerable drop in BOD levels. For BOD, there were significant disparities between the FWTs. COD levels in the influent ranged from 96 to 380 mg/L, with removal effectiveness of 61 to 80%. There were significant variances in COD removal among all FWTs. The BOD/COD ratio in the final FWT readings in our investigation ranged from 0.79 to 0.31, with *Eichhornia* and *Nymphaea lotus* being the most efficient of all the FWTs. ANOVA: single factor was carried out for FTs BOD, COD, TN, TSS, and TP removal efficiency, which indicates p-values less than 0.05, and also a significant difference was recorded. In addition, ANOVA with Post-HOC t-tests indicate a similarity of BOD and COD removal efficiency for *Eichhornia* and *Pistia stratiotes*, *Eichhornia* and *Nymphaea lotus*, and *Pistia stratiotes* and *Nymphaea lotus* were detected. Also, a similarity in TN removal efficiency for *Eichhornia* and *Ceratophyllum*, *Pistia stratiotes*, and *Nymphaea lotus* were detected. Also, a similarity in TSS removal efficiency for *Eichhornia* and *Nymphaea lotus*. Therefore, ANOVA with Post-HOC t-tests shows that *Eichhornia*, *Pistia stratiotes*, and *Nymphaea lotus* have the highest BOD and COD removal efficiency, whereas *Pistia stratiotes* and *Nymphaea lotus* have the highest TN and TP removal efficiency.

Figures A7 and A8 show the measured influent and effluent TN and TP concentration for *Eichhornia*, *Ceratophyllum*, *Pistia stratiotes*, and *Nymphaea lotus.* In the main influent, TN concentrations ranged from 13 to 38 mg/L. TN removal efficiency ranged from 70 to 97% in the FWTs. *Pistia stratiotes* (plant C) and *Nymphaea lotus* (plant D) achieved the highest TN removal efficiency (Table 3). In all the cases the Nymphaea lotus performed well in terms of pollutant removal. During the summer season (June to August), changes in air and water temperature have a major impact on the reduction of pollutant concentrations for the species. The effect of temperature on the removal efficiency of the pollutants was tested by constructing a correlation matrix for the water quality parameters, including pH, temperature, EC, TDS, TSS, BOD, TN, and TP. Table 4 summarizes the correlation matrix for effluent water parameters for *Nymphaea lotus*. A moderate positive correlation between temperature, BOD, and COD was detected. In addition, a weak positive correlation between temperature, TN, and TP was detected. While the correlation between the temperature, TDS, and TSS indicated a weak positive relationship. Therefore, a higher removal performance was aided by high temperatures, especially in the summer season in June, July, and August (Table 2).

Table 4. Correlation matrix for effluent water parameters concentration for *Nymphaea lotus* FWT.

	Nymphaea lotus								
	pH	**Temperature °C**	**BOD (mg/L)**	**COD (mg/L)**	**TDS (mg/L)**	**TSS (mg/L)**	**TN (mg/L)**	**TP (mg/L)**	**EC (µs/cm)**
pH	1								
Temperature °C	−0.27	1							
BOD (mg/L)	−0.10	0.59	1						
COD (mg/L)	0.00	0.51	0.67	1					
TDS (mg/L)	−0.09	0.45	0.31	0.40	1				
TSS (mg/L)	0.16	−0.17	−0.21	0.02	0.32	1			
TN (mg/L)	0.13	0.38	0.31	0.14	0.37	−0.06	1		
TP (mg/L)	−0.02	0.22	0.46	0.12	0.15	−0.13	0.17	1	
EC (µs/cm)	−0.01	0.40	0.37	0.20	0.14	−0.28	0.50	0.16	1

BOD and COD removal efficiency results, compared to previous studies, show the same ranges as, according to [34], COD in synthetic wastewater treated with FWTs which was reduced by 58% in China. The removal values were also within the range reported by [35], who found a reduction in COD content of 33–68% for FWT receiving combined sewer overflow in Belgium. According to [36], in Sri Lanka, there was a reduction of 48.5–76.1% in BOD in domestic wastewater treated using FWTs. During the summer season (June to August), changes in the air and water temperature have a major impact on the reduction of BOD and COD concentrations for the species (Figures A5 and A6) [4]. For the TN, according to [37], in Uganda, there was a reduction of 90.4% of TN in primary treated sewage treated using FWTs.

In China, ref. [38] reported a TN removal of 36.9 in the treatment of river water using FWT. Total phosphorus concentration in primary influent ranged between 1.5 and 6.2 mg/L. The FWTs had a TN removal range of 83–96%. The removal efficiency of TP was found to be highest for *Pistia stratiotes* (plant C) and *Nymphaea lotus* (plant D) (Table 3).

According to [39], in China, a reduction of 87.1% of TP in eutrophic pool water was treated using FWTs, and also in China, ref. [40] reported a TP removal of 61.8% in treating a secondary effluent using FWT. In addition, ref. [25] studied the removal of nutrients and pesticides by constructing floating wetlands on a pilot scale using duckweed and water hyacinth, they reported a TN removal range from 27.4% to 83.6%. The minimum temperature during the summer season was 15.6–20.5 °C, while the maximum temperature was 33.2–33.5 °C. Furthermore, sunshine hours ranged from 9.6 to 10.8 h, and solar radiation ranged from 24.1–26.1 MJ/m^2/day (Table 2), indicating that the conditions were favorable for tertiary treatment of open water channels.

Bacterial cells are destroyed by a combination of high temperature and ultraviolet (UV) radiation, which destroys the cell membrane [4,41]. The treated sewage met fecal coliform levels of fewer than 14 MPN 100/mL after 6 h, according to USEPA criteria [42]. This disinfection will aid in increasing the oxygen content of treated water while also allowing the sun to eliminate pathogenic pollutants as well as the rest of the BOD and COD.

3.2. Proposing FWT Design and Construction for the Studied Drain

Input data for the tanks in the series model include the influent wastewater flow rate (Q) of 2000 m^3/day, winter temperature (Tw) 7 °C, summer temperature (Ts) 33.6 °C, average temperature 20.9 °C (Table 2), water depth (y) 0.75 m, and influent pollutant concentrations for BOD, COD, and TSS were 112 mg/L, 217 mg/L, and 207 mg/L, respectively.

In addition, the background concentrations C^* for BOD, COD, and TSS in the wetland were 2 mg/L, 10 mg/L, and 5 mg/L respectively. The influent pollutants concentrations of 0.986, 0.981, and 0.982 m/year for BOD, COD, and TSS, respectively were used to be the removal rate constants K_{20} at 20 °C with Two-days hydraulic retention time (HRT), and four connected tanks in the series (X = 4). Using spread MS Excel sheet to solve Equations (2) and (3) to calculate effluent concentrations (Co) for BOD, COD, and TSS, for different HRT, to meet permissible limits of effluent pollutant concentration according to the Egypt Decree [37,38] as shown in Figure 6. Therefore, it is selected HRT = 2.5 days indicated area of 10,000 m^2 (four cells each one of 357 m long and width of 7 m) and effluent concentrations (Co) for BOD, TSS, and COD are 12 mg/L, 24 mg/L, and 30 mg/L respectively. The expected pollutant removal efficiency for BOD, TSS, and COD are 89.3%, 88.4%, and 86.2%, respectively. Comparing computed BOD removal efficiency to experimental removal efficiency for *Nymphaea lotus* (84%), an increase of 6.3% was noticed. The computed COD removal efficiency was increased by 9.1%, as compared to experimental removal efficiencies of *Nymphaea lotus* (79%). Furthermore, the computed TSS removal efficiencies for *Nymphaea lotus* plants (94%) showed a drop of 6%, when compared to the experimental removal efficiencies. In addition, the expected TN and TP removal efficiencies based on the experimental results were 97% and 96% for *Nymphaea lotus. Nymphaea lotus* plants should be installed in buoyant rafts produced from polyethylene-based roof insulation rolls that should be used in the construction of the proposed FWTs. The roll was 1.8 m long, 1.2 m wide, and 0.025 m thick, with a mat unit area of 2.2 m^2. To allow for eventual vegetation, fourteen holes (diameter of 10 cm) were made at an equal spacing in each mat unit (Figure 7a). The holes were filled with coconut shavings, and the mats were linked with bamboo lining tied together by a wire to create eight floating islands. The mats were coated with up to 3 cm of dirt, sand, and gravel to shield the sheet from solar ultraviolet radiation. Each mat weighed 3.6 kg and could support up to 300 kg of weight. The FWT system was installed in one month by a team of ten persons. The projected FWT distribution along the drain is depicted in Figure 7b,c.

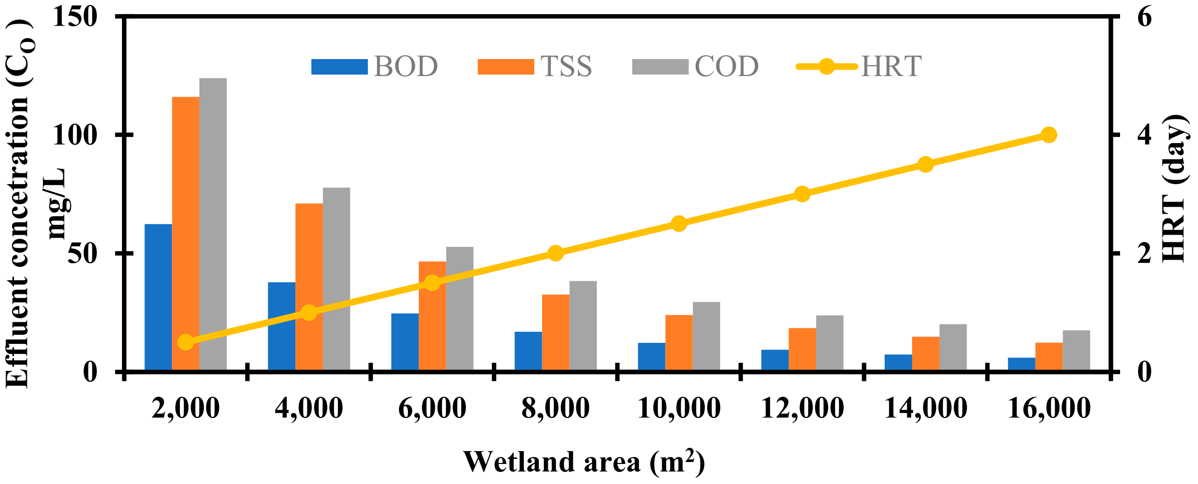

Figure 6. Floating wetland area and effluent concentration removal relationship.

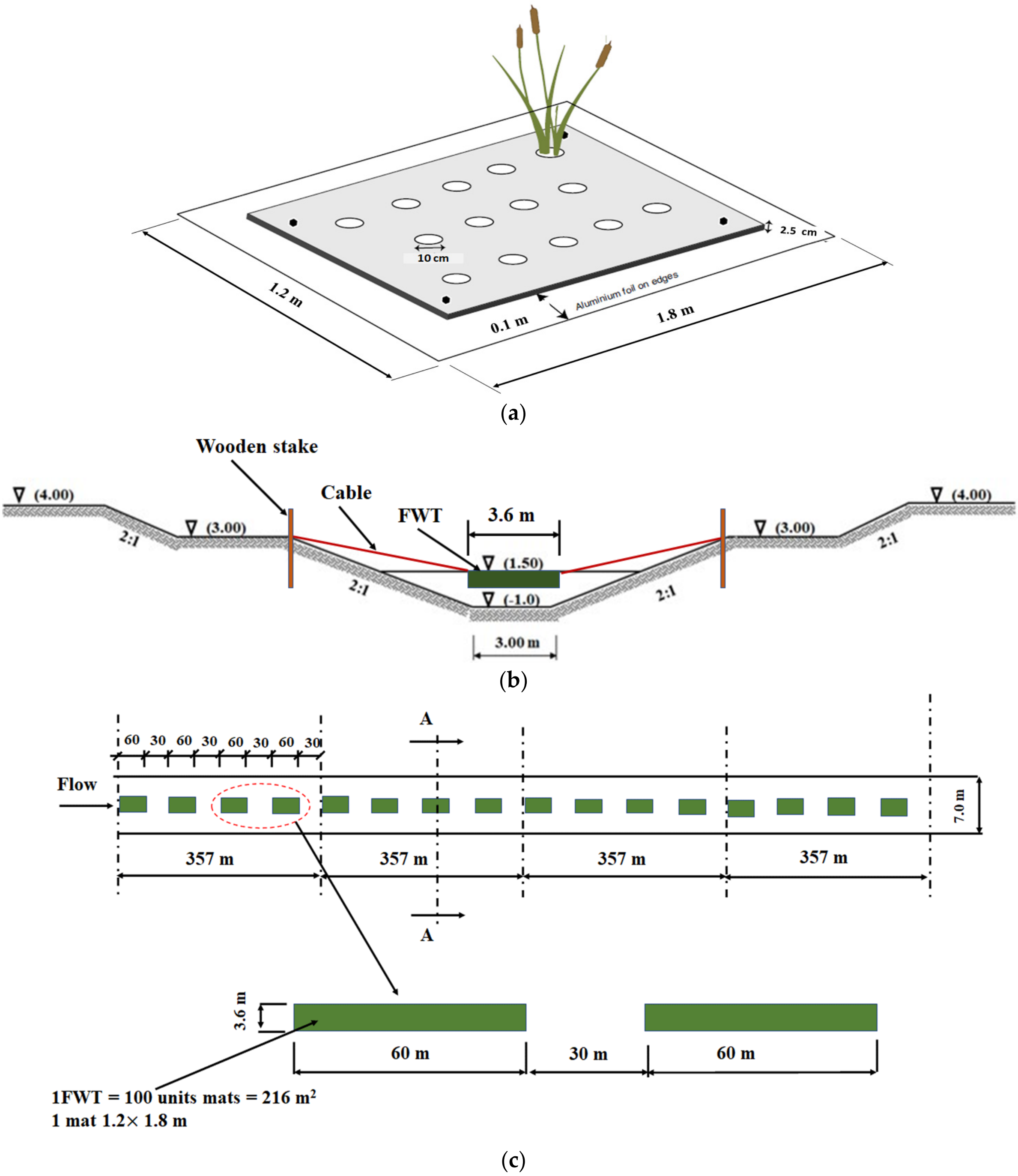

Figure 7. FWTs distribution along the drain, (**a**) FWTs dimension details composed of the buoyant rafts produced from polyethylene, (**b**) Cross-section A-A, and (**c**) Plan.

3.3. Wetland Hydrology

Table 2 summarizes the output of the CROPWAT 8 model for monthly average climatic parameters at Mansoura station, Egypt, from 2010 to 2020. The ETo ranged from 1.82–5.99 mm/day with an average of 3.9 mm/day, while the annual rainfall is 54 mm. As a result, the study region has a semiarid climate, with low rainfall values relative to the ETo, which has an impact on wetland hydrology. A sounding rod is used to estimate the cross-section water depth and velocity to determine the monthly average influent discharge for the drain. As a result, the flow rate ranged from (2950 to 38,003) m^3/d. The drain soil is clay with an average infiltration rate of 0.5 mm/h. As a consequence, Equation (1) was used to compute the suggested FWT hydrological balance for 10,000 m^2 water surface area, and the results are described in Table 5. The minimum and maximum effluent discharges were 2777.6 and 37,761.7 m^3/d, respectively. These suggest a water depth of 1.0 m to 2.0 m in a wetland. As a result, the wetland will not dry out during the year.

Table 5. Monthly wetland water balance (FWT area = 10,000 m^2).

Month	Q_{in} (m^3/day)	Rainfall (mm)	ETo (mm/day)	Infiltration Discharge (m^3/day)	Q Rainfall (m^3/day)	Q ETo (m^3/day)	Q_{out} (m^3/day)	Water Losses Ratio (%)
January	2950	10	1.82	187.5	33.3	18.2	2777.6	5.8
February	3000	8	2.43	187.5	26.7	24.3	2814.8	6.2
March	12,643	6	3.32	187.5	20.0	33.2	12,442.3	1.6
April	16,229	3	4.39	187.5	10.0	43.9	16,007.6	1.4
May	12,479	4	5.64	187.5	13.3	56.4	12,248.4	1.8
June	19,337	1	5.99	187.5	3.3	59.9	19,092.9	1.3
July	36,188	0	5.61	187.5	0.0	56.1	35,944.4	0.7
August	38,003	0	5.38	187.5	0.0	53.8	37,761.7	0.6
September	33,467	0	4.54	187.5	0.0	45.4	33,234.1	0.7
October	19,959	5	3.34	187.5	16.7	33.4	19,754.7	1.0
November	9577	6	2.47	187.5	20.0	24.7	9384.8	2.0
December	7813	11	1.83	187.5	36.7	18.3	7643.8	2.2

4. Conclusions

FWT treatment systems are a cost-effective and efficient treatment solution. Over a one-year period from July 2020 to July 2021, the efficiency of four different constructed floating wetlands pilot-scale systems (*Eichhornia*, *Ceratophyllum*, *Pistia stratiotes*, and *Nymphaea lotus*) in the removal of BOD, COD, TSS, TN, TP, EC, and TDS were compared to an unplanted system, indicating very promising results. The average reduction in BOD, COD, TSS, TDS, TN, EC, and TP were 76–86%, 61–80%, 87–95%, 36.6–44.1%, 70–97%, 37–44%, and 83–96%, respectively. The maximum BOD and COD removal performance is found in *Eichhornia*, *Pistia stratiotes*, and *Nymphaea lotus*, while the highest TN and TP removal performance is found in *Pistia stratiotes* and *Nymphaea lotus*. The ANOVA and Post-HOC *t*-tests revealed that *Nymphaea lotus* performed well in terms of pollutant removal in all the cases. The results of the design and construction of a FWT planted by *Nymphaea lotus* in a drain h a discharge of 2000 m^3/day, and a FWT hydraulic retention time of 2.5 days indicated an area of 10,000 m^2 (four FWT cells each 357 m × 7 m). Under the Mediterranean geoclimatic conditions reported in this paper, the investigated systems have the ability to decontaminate drainage wastewater, making them a viable and low-cost solution for farmers to reuse the treated water in irrigation.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

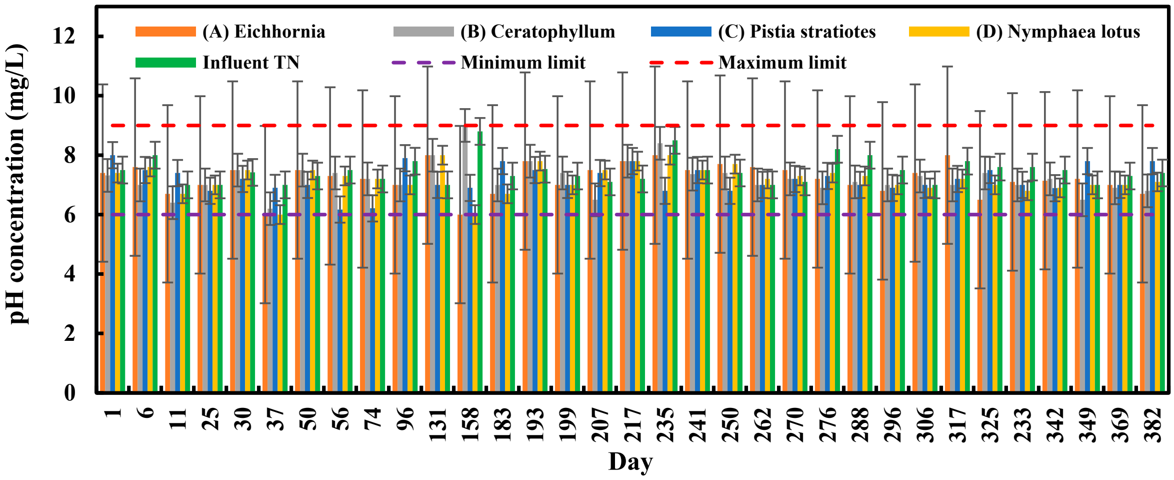

Figure A1. Measured influent and effluent pH concentration for (**A**) *Eichhornia*, (**B**) *Ceratophyllum*, (**C**) *Pistia stratiotes*, and (**D**) *Nymphaea lotus*.

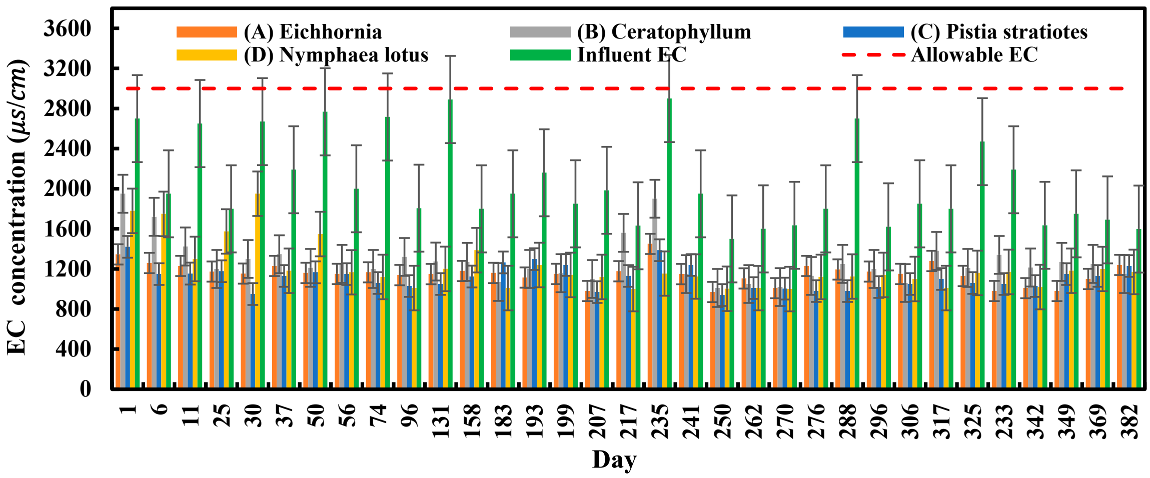

Figure A2. Measured influent and effluent EC concentration for (**A**) *Eichhornia*, (**B**) *Ceratophyllum*, (**C**) *Pistia stratiotes*, and (**D**) *Nymphaea lotus*.

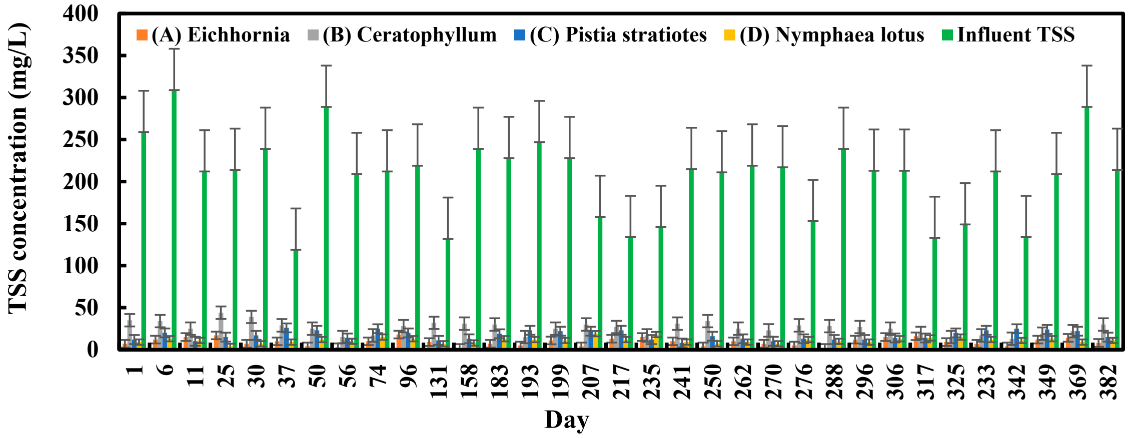

Figure A3. Measured influent and effluent TSS concentration for (**A**) *Eichhornia*, (**B**) *Ceratophyllum*, (**C**) *Pistia stratiotes*, and (**D**) *Nymphaea lotus*.

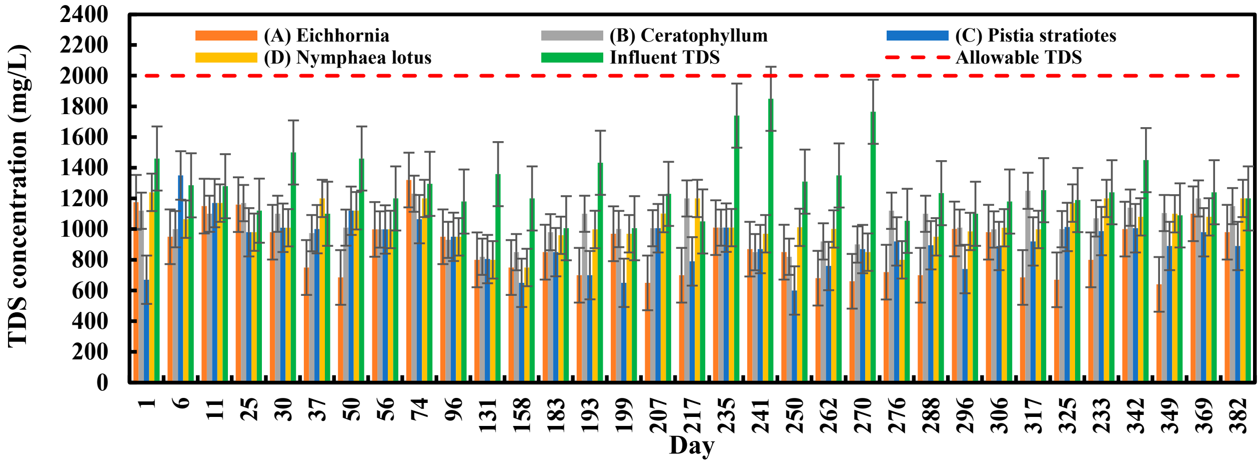

Figure A4. Measured influent and effluent TDS concentration for (**A**) *Eichhornia*, (**B**) *Ceratophyllum*, (**C**) *Pistia stratiotes*, and (**D**) *Nymphaea lotus*.

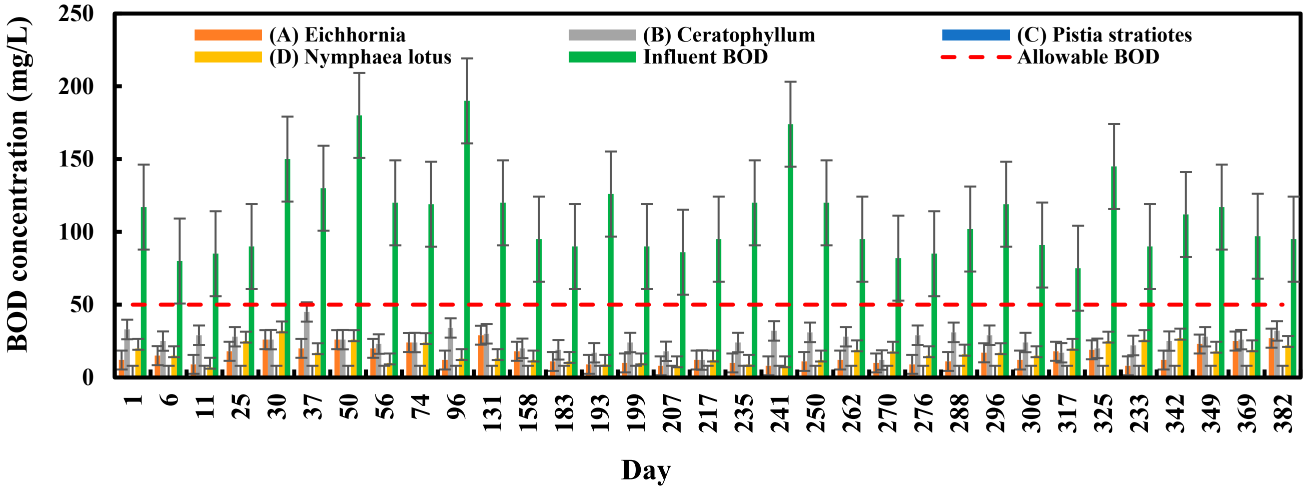

Figure A5. Measured influent and effluent BOD concentration for (**A**) *Eichhornia*, (**B**) *Ceratophyllum*, (**C**) *Pistia stratiotes*, and (**D**) *Nymphaea lotus*.

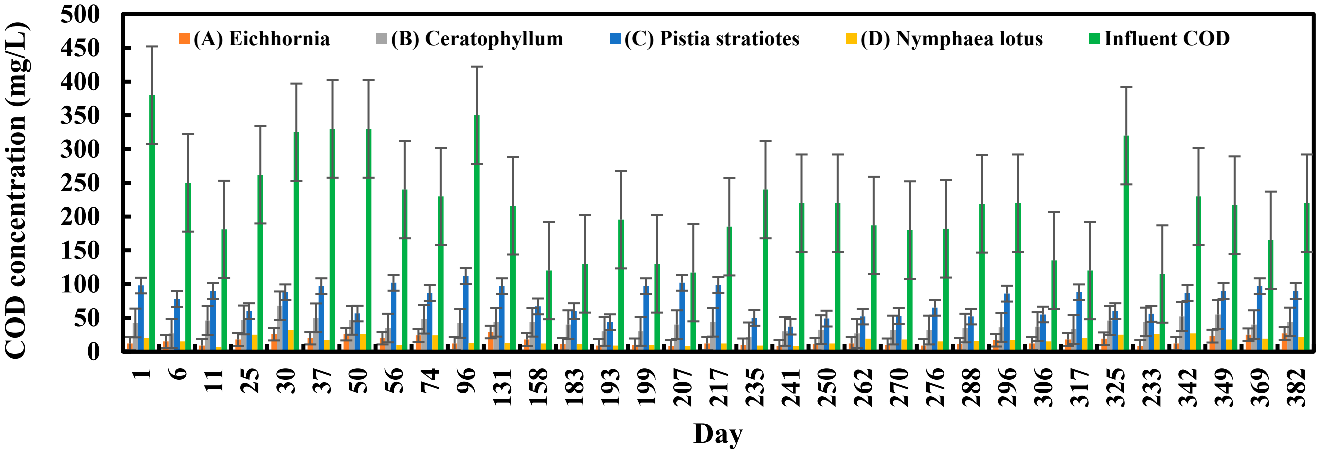

Figure A6. Measured influent and effluent COD concentration for (**A**) *Eichhornia*, (**B**) *Ceratophyllum*, (**C**) *Pistia stratiotes*, and (**D**) *Nymphaea lotus*.

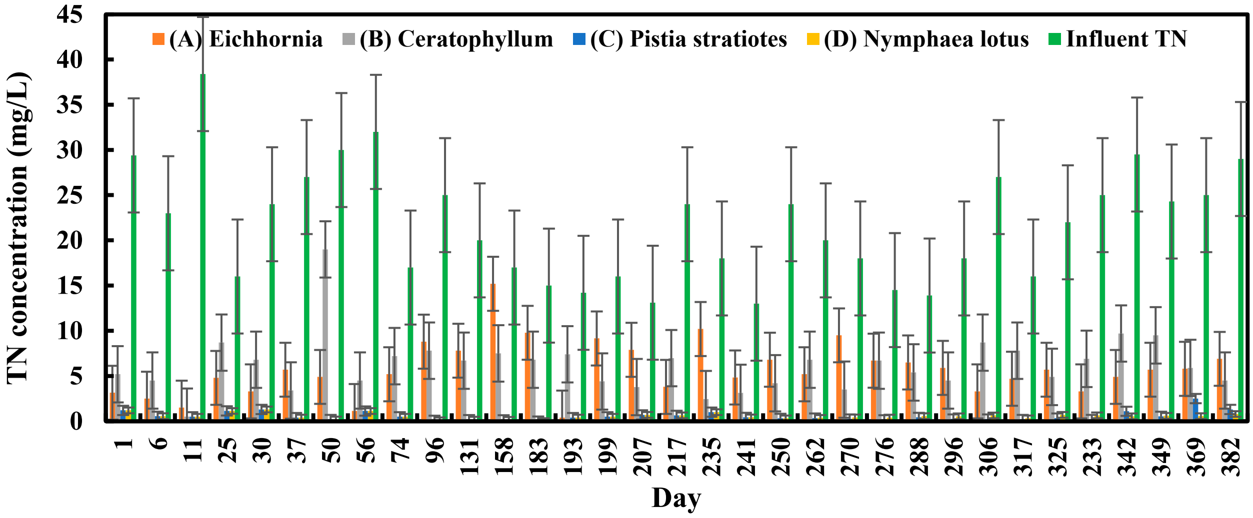

Figure A7. Measured influent and effluent TN concentration for (**A**) *Eichhornia*, (**B**) *Ceratophyllum*, (**C**) *Pistia stratiotes*, and (**D**) *Nymphaea lotus*.

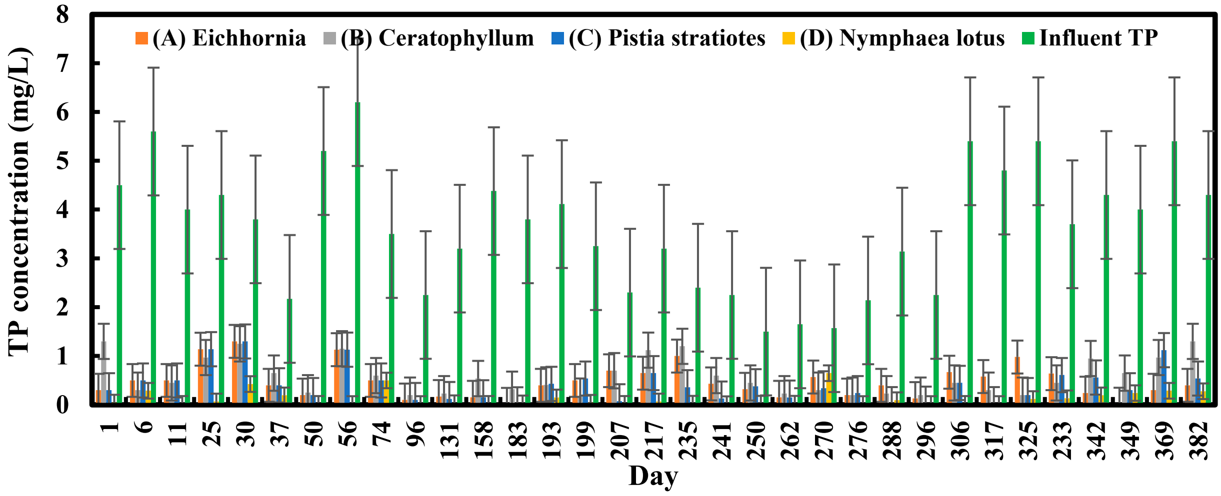

Figure A8. Measured influent and effluent TP concentration for (**A**) *Eichhornia*, (**B**) *Ceratophyllum*, (**C**) *Pistia stratiotes*, and (**D**) *Nymphaea lotus*.

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