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Research article

Demonstration scale treatment of drainage canal water in the Nile Delta through a combination of facultative lagoons and hybrid constructed wetlands

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ABSTRACT

Drainage canal water (DCW), a mixture of Nile water, drainage water and municipal wastewater, is largely used for irrigation in the Nile Delta. Facultative lagoons (FL) and constructed wetlands (CWs) represent interesting options for DCW treatment before its agricultural re-use, but very few studies investigated their implementation in Egypt. This work aimed at developing at demonstration scale (250 m^3 d^{-1}) a FL + CW treatment train capable to turn DCW into an effluent reusable in agriculture. Three types of hybrid CWs were tested in parallel for 530 days. The combination of FL with a cascade hybrid CW, operated at a 200 L d^{-1} m^{-2} surface loading rate, led to medium-to-high removal efficiencies (suspended solids 90%, total nitrogen 84%, phosphate 80%, COD 67%, faecal coliforms 2.2 Log) and surface removal rates (COD 47.5 t y^{-1} ha^{-1}, total nitrogen 10.9 t y^{-1} ha^{-1}, faecal coliforms 1.5 • 10^{11} MPN y^{-1} ha^{-1}). The effluent, compliant with class C of EU 2020/741 regulation, is potentially reusable to irrigate numerous Egyptian crops. The results show that the combination of FLs with cascade hybrid CWs has a great potential for the treatment of DCW and low-strength municipal wastewater, with near-zero energy consumption, null consumption of chemicals and a land requirement varying between 1.1% and 1.5% of the agricultural land irrigated with the treated DCW.

1. Introduction

The canal network in the Nile Delta region of Egypt serves as a primary source of irrigation for agricultural fields in the area. While its main purpose is to transport Nile water to farmers, it also receives regular discharges of drainage water from agricultural fields, as well as occasional discharges of untreated or poorly treated domestic and industrial wastewater (Frascari et al., 2018; Hamad, 2020). This water, referred to as drainage canal water (DCW) in this paper, typically contains various pollutants such as organic matter, nutrients, suspended solids, pesticides, and pathogens. Given Egypt's significant water scarcity issues (Hamad, 2020; De Miguel et al., 2020; El-Khayat et al., 2022), promoting the safe reuse of DCW in agriculture is crucial (Khairy et al., 2022; Pinelli et al., 2020).

Therefore, it is imperative to develop proper treatment technologies to enhance the quality of DCW before its reuse in agriculture. Considering the agricultural context, such technology should be simple to construct and operate, cost-effective, and easily applicable at a decentralized level. Constructed wetlands (CWs) fully meet these requirements. CWs are human-made basins that leverage the natural functions of vegetation, soil, and microorganisms to treat various types of wastewater, including municipal wastewater (MWW), industrial

Abbreviations: CHCW, Cascade Hybrid CW; CW, Constructed Wetland; DCW, Drainage Canal Water; DO, Dissolved Oxygen; EC, Electrical Conductivity; FBCW, Floating Bed CW; FC, Faecal Coliforms; FL, Facultative Lagoon; FWSW, Free Water Surface Wetland; FWS CW, Free Water Surface CW; HFCW, Horizontal Flow CW; GBSW, Gravel Bed Subsurface Wetland; HRT, Hydraulic Retention Time; HSLR, Hydraulic Surface Loading Rate; HSSF CW, Horizontal Sub-Surface Flow CW; MWW, Municipal Wastewater; RY, Removal Yield; SHCW, Sequenced Hybrid CW; SRR, Surface Removal Rate; TC, Total Coliforms; TSS, Total Suspended Solids; VFCW, Vertical Flow CW; VSSF CW, Vertical Sub-Surface Flow CW.

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wastewater, and DCW (Lavrnić et al., 2020). In CWs, the filling materials, roots, stems, and litter of wetland vegetation provide surfaces for microbial attachment.

In comparison to conventional wastewater treatment plants, CWs have higher surface area requirements and lower removal efficiencies. However, they offer several advantages such as low operational and maintenance costs, minimal energy and chemical consumption, and the capability to handle variable hydraulic and organic loads (Liu et al., 2015; Nan et al., 2020, 2023; García-Herrero et al., 2022). These characteristics make CWs particularly suitable for isolated areas and developing countries like Egypt.

Various types of CWs have been developed, including free water surface (FWS) CWs, horizontal sub-surface flow (HSSF) CWs, vertical sub-surface flow (VSSF) CWs, and floating bed (FB) CWs (Benvenuti et al., 2018; Spangler et al., 2019; Lavrnić et al., 2018; Kaliakatsos et al., 2019). These types can be combined to create hybrid CWs, which can achieve higher removal efficiencies than single-stage systems. For instance, the removal of total nitrogen (TN) through nitrification/denitrification requires both aerobic and anaerobic conditions, which can be achieved through a combination of FWS or VSSF (mainly aerobic) and HSSF (mainly anaerobic) (Kadlec and Wallace, 2008).

Despite the suitability of CWs for treating DCW in the Nile Delta with the aim of reuse in irrigation, no full-scale CWs have been installed for DCW treatment in this region. Moreover, pilot-scale studies on CW implementation for DCW treatment in Egypt are exceedingly rare, predominantly limited to FWS CWs and lacking a specific focus on producing irrigation-quality water — a crucial aspect in an agriculturally intensive region like the Nile Delta (Hamad, 2020; Hendy et al., 2023; El-Refaie, 2010; Nasr and Ismail, 2015).

In addition, in the wider perspective to use CWs for the treatment of MWW and agricultural WW, the studies relative to the Egyptian and to the wider North African context focused on CWs characterized by high hydraulic retention times (HRT) (7–11 days) and consequently low hydraulic surface loading rates (HSLR) (100–150 L d^{-1} m^{-2}), whereas very few studies focused on the development of CW types featuring low HRTs and high HSLRs (El-Refaie, 2010; Nasr and Ismail, 2015). The resulting very large surfaces required represent an extremely limiting factor for large-scale CW implementation.

The general goal of this research was to assess at demonstration scale (250 m^3 d^{-1}) the implementation of three hybrid CW types in combination with a facultative lagoon (FL) for treating DCW and converting it into irrigation-quality water, adapting this technology to the specific context of the Egyptian Nile Delta and trying to reduce the amount of land required. In particular, the specific goals and the corresponding novelties are:

(i) determining the most effective hybrid CW type for DCW conversion into irrigation-quality water, among three types tested in parallel (cascade hybrid CW (CHCW), sequenced hybrid CW (SHCW), and floating bed CW (FBCW)), whereas the few previous studies relative to the use of CWs to treat DCW in the Egyptian context focused on FWS CWs (Hamad, 2020; El-Refaie, 2010; Nasr and Ismail, 2015);

(ii) assessing the effectiveness of the FL + hybrid CW combination with the specific purpose to turn DCW into irrigation-quality water according to Egyptian and international standards, whereas the previous studies did not specifically focus on water reuse for irrigation (Hamad, 2020; El-Refaie, 2010; Nasr and Ismail, 2015);

(iii) assessing the CW performances attainable at lower hydraulic retention times and higher hydraulic surface loading rates in comparison to those typically applied in CWs (El-Refaie, 2010; De Anda et al., 2018; Masi and Martinuzzi, 2007; Merino-Solís et al., 2015), in order to reduce the amount of land required and thus promote the implementation of CWs in the North African context.

In the specific context of drainage canal water treatment and reuse in the Nile Delta, hybrid CWs were considered the most appropriate CW type, due to several factors: i) the need to achieve high removal efficiencies in order to produce irrigation quality water; ii) the need to maintain high treatment efficiencies despite the high variability of DCW in terms of both flow rate and composition, due to the intermittent discharges of industrial wastewater; and iii) the importance to limit water losses resulting from evaporation and evapotranspiration, so as to maximize the amount of treated water available for irrigation. All these requirements could not be easily met by a single type of CW due to their structural limitations (Jiang and Chui, 2023). In particular, horizontal and vertical subsurface flow CWs are not the best choice for the treatment of variable flow rates (Lavrnić et al., 2020), notably in the presence of relevant TSS concentrations: indeed in these CWs, due to the lack of surface flow zones, peaks of flow rate and/or TSS can lead to clogging of the porous medium (Shi et al., 2024; Hua et al., 2014). Conversely, surface flow CWs often result in lower treatment efficiencies and higher water losses by evaporation, in comparison to hybrid and subsurface flow CWs (Jiang and Chui, 2023).

This work contributes to the achievement in Egypt of sustainable development goal 6 “Ensure availability and sustainable management of water and sanitation for all”.

2. Material and methods

2.1. Demonstration plant description

The plant, illustrated in Fig. 1, comprises the following units: a pump station responsible for extracting DCW from the Bahr El Baqar Drain; a 500 m^3 facultative lagoon (FL) (depth 2 m, surface 250 m^2); three 160 m^3 CWs (depth 0.8 m, length 20 m, width 10 m, surface 200 m^2), illustrated in Fig. 2, fed in parallel by the FL effluent. Each CW is divided into four 40 m^3 cells arranged sequentially, as described below. A Google Earth visualization of the plant is shown in Fig. S1, whereas some pictures of the CWs are reported in Fig. S2, Supplementary Material.

a. *Cascade Hybrid Constructed Wetland* (CHCW) (Fig. 2a) - It consists of a 0.4-m deep free water surface wetland (FWSW) on top of a 0.4-m gravel bed subsurface wetland (GBSW). Metal baffles were installed at the entrance, exit and intermediate points to direct water flow through the FWSW and GBSW cells, thus creating the treatment paths illustrated in Fig. 2a. Reeds were transplanted at 25 stem m^{-2} density on the gravel surface.
b. *Sequenced Hybrid Constructed Wetland* (SHCW) (Fig. 2b) - It consists of two 0.8-m deep FWSWs at the entrance and exit of the wetland cells, and 2 GBSW 0.8-m deep cells in an intermediate position. Metal baffles were installed to drive water flow through the FWSW and GBSW as shown in Fig. 2b. Reeds were transplanted at 25 stem m^{-2} density.
c. *Floating beds Constructed Wetland* (FBCW) (Fig. 2c) – It consists of a 20x10 $\times$ 0.8 m floating treatment wetland cell (FTW). Baffles were installed as in the other hybrid wetland cells in order to mimic water flow paths. Reed plants were planted on recycled floating foam mats of 1.0x0.5 $\times$ 0.05 m each.

Taking into account the 0.30 void fraction of the gravel, the water volume in the CWs resulted equal to 104 m^3 in the CHCW and SHCW, and 160 m^3 in the FBCW.

2.2. Plant operational conditions and drainage canal water characterization

After a 4-month start-up and plant adaptation phase, the demo plant was operated and monitored for 530 days, divided into 2 periods characterized by different operational conditions in the 3 CW types:

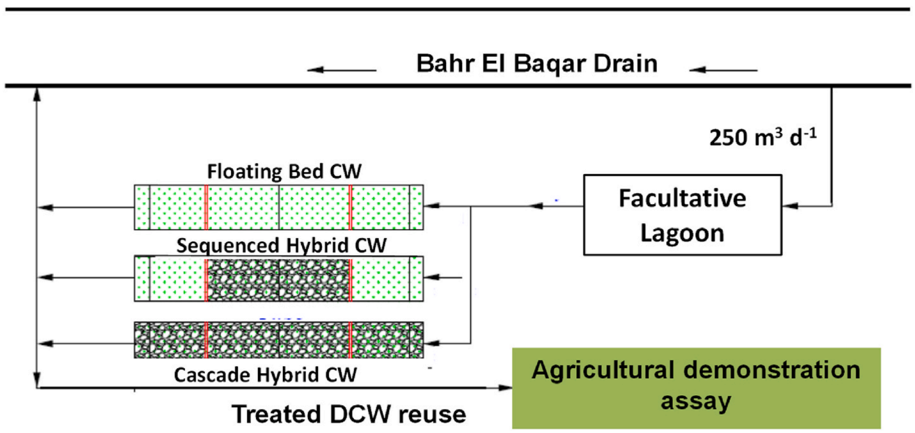

Fig. 1. Layout of the experimental demonstration plant.

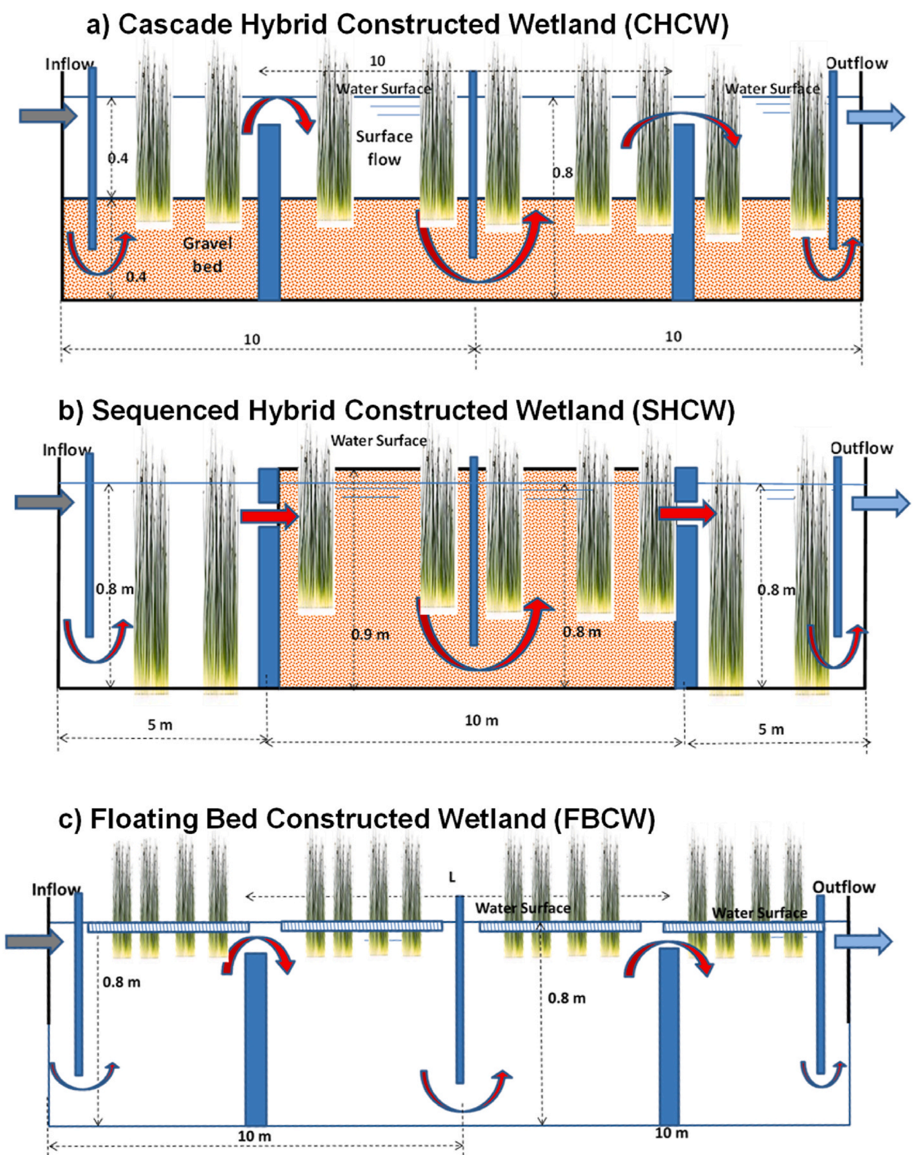

Fig. 2. Layout of the cascade hybrid constructed wetland (CHCW) (a), sequenced hybrid constructed wetland (SHCW) (b), and floating bed constructed wetland (FBCW) (c).

1. Period 1, from day 1 to day 165 (from January 1 to June 15). FL: flow rate 250 m^3 d^{-1}, surface loading rate 1000 L d^{-1} m^{-2}, HRT 2 d. Constructed wetlands: flow rate 50 m^3 d^{-1} each, surface loading rate 250 L d^{-1} m^{-2}, HRT 2.08 d (CHCW and SHCW) or 3.20 d (FBCW). During period 1, the inlet water temperature ranged from 14 °C in January to 26 °C in June.
2. Period 2, from day 166 to day 530 (1 year starting from June 16). FL: flow rate 250 m^3 d^{-1}, surface loading rate 1000 L d^{-1} m^{-2}, HRT 2 d. Constructed wetlands: flow rate 83.3 m^3 d^{-1} each, surface loading rate 417 L d^{-1} m^{-2}, HRT 1.25 d (CHCW and SHCW) or 1.92 d (FBCW). During period 2, the inlet water temperature ranged from 26 °C in June to 14 °C in January.

Indeed, in period 1 the CWs exhibited hydraulic surface loading rates (HSLRs) in the medium-high range and HRTs in the medium-low range, in comparison to those typical of CWs treating MWW and agricultural WW (El-Refaie, 2010; Masi and Martinuzzi, 2007; Merino-Solís et al., 2015; Dal Ferro et al., 2018). In period 2, an extra 66% increase in HSLR was implemented in the 3 CW types, with a corresponding decrease in HRT, to further reduce the land surface required to apply CWs at large scale for DCW treatment.

The average values of the main monitored parameters in the DCW fed to the pilot plant during the 1st and 2nd period are reported in Table 1. The influent DCW presents an intermediate quality between agricultural drainage water and municipal wastewater. For example, COD and BOD are high for Egyptian drainage water (Khairy et al., 2022; Assar et al., 2019) and closer to low-strength municipal wastewater (Rahman et al., 2020). TSS, TN and phosphate concentrations were higher than those typical of drainage water in Egypt (Khairy et al., 2022; Assar et al., 2019). On the other hand, while TSS concentration was similar to the ones observed in agricultural drainage water (Lavrnić et al., 2020), nutrients concentrations were higher and closer to low-medium strength wastewater (Rahman et al., 2020). Microbiological pollution was lower than the typical values of domestic wastewater (Guimarães et al., 2016).

2.3. Monitoring plan and analytical methods

Biological oxygen demand (BOD; 5 days, 20 °C), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN), ammonium (NH_4), phosphate, electrical conductivity (EC), total coliforms (TC), faecal coliforms (FC), lead, zinc, nickel, temperature, pH and dissolved oxygen were measured twice a month in the FL inlet, FL outlet (corresponding to the inlet of all CWs), in the intermediate sampling points located in each CW at 5, 10 and 15 m from the inlet, and in the outlet of each CW. In order to correctly assess the actual depletion yields, water samples were taken from each sampling point with a delay – in comparison to the sampling time at the FL inlet – equal to the hydraulic retention time (HRT) assessed from the FL inlet to each sampling point. Flow rate was measured twice a month at the FL inlet and at the inlet and outlet of each CW, by means of RIF600S ultrasound flow meters (Riels Instruments, Padova, Italy).

COD, TSS, TN, Zn, Ni and Pb were analysed by means of Hach-Lange cuvette tests. Ammonium and phosphate were analysed by Ion Chromatography as illustrated previously (Frascari et al., 2019; Pinelli et al., 2022). BOD, TC and FC were analysed according to the American Public Health Association methods (APHA, 2000). Temperature, pH, EC, DO were analysed with a Hanna HI9829 multiparameter.

2.4. Data analysis

Removal yields (RY) and surface removal rates (SRR), calculated for each monitored parameter from the measured concentrations and flow rates, were selected as performance parameters to compare the different CW types. They were calculated as follows:

Table 1
Pollutant concentrations during the 1st and 2nd operational periods in the inlet DCW and in the effluents of the three FL + CW combinations, and comparison with international and Egyptian wastewater reuse standards[a].

Parameter[b]	Unit	Period	DCW inlet conc.	DCW outlet concentrations[c,d]			Standards for WW reuse for irrigation		
				FL + CHCW	FL + SHCW	FL + FBCW	EU 741/2020[e]	ISO 16075[f]	Egyptian Law 92/2013[g]
COD	mg L^{-1}	1	113 ± 9	39 ± 3 a	41 ± 1 a	42 ± 3 a	–	–	50
		2	124 ± 4	53 ± 2 a	63 ± 3 b	67 ± 3 b			
BOD	mg L^{-1}	1	54 ± 3	**16 ± 1 a**	21 ± 1 b	23 ± 1 c	25	20	30
		2	63 ± 5	46 ± 2 a	47 ± 2 a	51 ± 2 b			
TSS	mg L^{-1}	1	137 ± 22	**13 ± 1 a**	**17 ± 2 b**	**24 ± 2 c**	35	25	–
		2	127 ± 8	48 ± 2 a	54 ± 4 b	58 ± 3 b			
TN	mg L^{-1}	1	20 ± 3	3.3 ± 0.6 a	3.5 ± 0.4 a	3.3 ± 0.3 a	–	–	15
		2	21 ± 8	9 ± 1 a	9 ± 1 a	9 ± 1 a			
NH_4^+	mg L^{-1}	1	11 ± 2	1.8 ± 0.2 a	1.1 ± 0.2 a	1.4 ± 0.5 a	–	–	–
		2	15 ± 4	3.3 ± 0.3 a	4.1 ± 0.2 b	4.2 ± 0.2 b			
PO_4^{3-}	mg L^{-1}	1	5.6 ± 0.7	1.1 ± 0.2 a	1.1 ± 0.2 a	1.1 ± 0.2 a	–	–	–
		2	4.4 ± 1.8	0.8 ± 0.1 a	0.9 ± 0.1 a	0.9 ± 0.1 a			
Zn	μg L^{-1}	1	220 ± 50	24 ± 1 a	23 ± 5 a	29 ± 6 a	–	–	–
		2	190 ± 40	14 ± 3 a	22 ± 4 b	38 ± 8 c			
Total coliforms	MPN 100 mL^{-1}	1	84000 ± 7000	2680 ± 580 a	2060 ± 290 a,b	1340 ± 350 b	–	–	5000
		2	81000 ± 11000	4630 ± 630 a	5500 ± 510 a,b	7200 ± 690 b			
Fecal coliforms	MPN 100 mL^{-1}	1	47040 ± 4940	**228 ± 75 a**	**370 ± 100 a**	**650 ± 180 b**	1000	1000	–
		2	49200 ± 4400	2630 ± 630 a	3600 ± 1600 a, b	4500 ± 410 b			

[a] For each parameter and each sampling point, 13 measurements were made during period 1, and 25 measurements were made during period 2.
[b] Pb and Ni resulted always below the detection limit, equal to 2 μg/L.
[c] The concentrations that comply with both the EU and ISO standards reported in the last 2 columns are highlighted in bold.
[d] The results of the ANOVA are reported with lowercase letters after the 95% confidence interval. For each parameter and period, different letters indicate a statistical difference between the tested treatment trains ($p < 0.05$).
[e] The reported water quality levels are relative to class C of the EU 741/2020 regulation (Irrigation of food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops; irrigation methods that avoid direct contact with the edible part of the crop).
[f] The reported water quality levels are relative to class B of the ISO 16075 standard (Irrigation of processed food crops and restricted urban irrigation).
[g] Art. 51 of Law 92/2013: water suitable to irrigate food-crops to be consumed after cooking, after 1:1 dilution with fresh high quality water.

$$RY_{i,CW_j} = 1 - \frac{Q_{OUT,CW_j} \bullet C_{i,OUT,CW_j}}{Q_{IN,CW_j} \bullet C_{i,IN,CW_j}} \quad (1)$$

$$SRR_{i,CW_j} = \frac{Q_{IN,CW_j} \bullet C_{i,IN,CW_j} - Q_{OUT,CW_j} \bullet C_{i,OUT,CW_j}}{S_{CW_j}} \quad (2)$$

where RY_{i,CW_j} (%) indicates the removal yield of pollutant i across CW j (CHCW, SHCW or FBCW), SRR_{i,CW_j} (kg y^{-1} ha^{-1}, or MPN y^{-1} ha^{-1} for coliforms) the surface removal rate of pollutant i across CW j, Q_{IN,CW_j} and Q_{OUT,CW_j} the flow rates measured at the inlet and outlet of CW j, S_{CW_j} the surface of CW j, C_{i,IN,CW_j} and C_{i,OUT,CW_j} the concentrations of pollutant i at the inlet and outlet of CW j. In order to calculate, for each monitored pollutant, average values of RY and SRR relative to each operational period, in Eqs. (1) and (2) the average values of C_{i,IN,CW_j} and C_{i,OUT,CW_j} relative to the last 3 months of each operational period - corresponding in both cases to the period April–June and to a roughly steady state condition - were utilized. This choice is further justified by the analysis of the correlation between temperature, removal yields and surface removal rates, illustrated in sections 3.2 and 3.3.

The removal yields relative to the facultative lagoon and to each FL + CW combination were calculated in an analogous way. For coliforms, the Log removal was calculated instead of the % removal. The choice to calculate RYs and SRRs on the basis of the mass flow rate of each pollutant at the inlet and outlet of each plant section allows to take into account evapotranspiration in the CWs.

In order to check whether the differences between the compositions of the effluents of the three systems were statistically significant, a one-way ANOVA test ($p < 0.05$) was applied to the main water quality parameters.

3. Results and discussion

3.1. Treatment performances of the facultative lagoon

The average DO in the FL effluent was equal to 4.9 ± 0.1 mg L^{-1}. DO gradually decreased with depth, ranging from 5.2 mg L^{-1} in the 0–20 cm zone to 2.9 mg L^{-1} in the 60–80 cm zone. This indicates that the upper part of the 2-m lagoon maintained sufficient DO levels for aerobic processes, confirming the facultative nature of the lagoon. DO was not measured below 80 cm.

Table 2 presents the average pollutant removals across the FL during the 1st and 2nd operational periods. The 2-day HRT, common to both operational periods, led in the FL to a TSS removal of about 50% and to a 50–60% Zn removal thanks to the sedimentation process. Apart from a notable phosphorus (P) removal rate during period 1 (53%), other pollutants were typically removed at rates ranging from 20 to 30%, and the FC removal varied in the 0.2–0.4 Log range. Removal of pathogens in lagoons varies widely, depending on several factors such as HRT, sunlight intensity, DO and TSS concentration, pH and temperature (Liu et al., 2018). In this study, the low HRT has probably contributed to the low disinfection observed in the FL, determining a short exposure of pathogens to different removal processes, such as sedimentation, predation and UV radiation. Additionally, as a result of the exponential decrease of radiation intensity, the 2-m water depth of the FL – higher than those typically implemented in these systems - could have reduced sunlight penetration and consequently pathogen inactivation (Wu et al., 2016).

Overall, the removal performances obtained in the FL are in line with those previously reported (Russo et al., 2019).

The FL contribution to the overall treatment performances of the FL + CW treatment trains was moderate but not negligible. The most beneficial effect was given by the removal of TSS, thereby decreasing the risk of clogging the CW porous media, as well as P and Zn.

3.2. Treatment performances of the three CWs in the first period, at medium-high hydraulic surface loading rate

The 1st operational period, that lasted from January 1 to June 15, featured in the CWs a medium-high HSLR (250 L d^{-1} m^{-2}) and low HRTs (2.08 d in the CHCW and SHCW, 3.20 d in the FBCW).

The concentration time profiles measured in the effluents of the 3 CWs are shown in Fig. 3.

It can be observed that, while for some pollutants the effluent concentrations were almost constant during the 165-day period 1, for others (notably TN, NH_4^+) the initial 30–90 days were characterized by a marked decrease in effluent concentration, followed by a rather constant trend during the last part of period 1.

To investigate the potential influence of temperature on observed removal efficiencies, the correlation between water temperature and removal yields for the main pollutants and the three FL + CW combinations was assessed during period 1 using the Spearman correlation coefficient (ρ_s), as detailed in Table S1, Supplementary Material. The correlation coefficients fell within the (−0.3; 0.3) interval, indicating a very weak correlation with temperature for all parameters and FL + CW combinations. Consequently, the calculation of average effluent concentrations (Table 1), removal efficiencies (Table 2), and surface removal rates (Fig. 4) was not conducted on a seasonal basis. Instead, these performances were based on data from the last 3 months of period 1 (April–June), which were deemed representative of the steady state achieved by the end of period 1. The observed gradual improvement in CW performance for certain pollutants during the initial months of period 1 is likely attributed to the growth of plant roots and rhizosphere microbial communities.

As shown in Table 2, the three CWs led to the highest removal yields

Table 2
Pollutant removal yields during the 1st and 2nd operational periods in the different treatment systems (Facultative Lagoon, CHCW, SHCW, FBCW). For the entire treatment trains (FL + CW), the highest removal yield relative to each pollutant is highlighted in bold.

Removal yields	Period	COD (%)	BOD (%)	TSS (%)	TN (%)	NH_4^+ (%)	PO_4^{3-} (%)	Zn (%)	TC (Log)	FC (Log)
Facultative Lagoon (FL)	1	20 ± 5	26 ± 3	54 ± 10	23 ± 4	27 ± 5	53 ± 5	60 ± 15	0.4 ± 0.1	0.3 ± 0.1
	2	23 ± 3	12 ± 1	44 ± 1	22 ± 1	15 ± 6	32 ± 6	49 ± 11	0.2 ± 0.1	0.3 ± 0.1
CHCW	1	46 ± 5	45 ± 4	36 ± 8	60 ± 5	57 ± 9	28 ± 4	36 ± 16	1.2 ± 0.0	1.9 ± 0.2
SHCW	1	44 ± 4	36 ± 4	33 ± 9	59 ± 5	62 ± 11	28 ± 4	37 ± 18	1.3 ± 0.1	1.7 ± 0.1
FBCW	1	44 ± 4	33 ± 3	29 ± 7	61 ± 3	60 ± 12	28 ± 7	32 ± 14	1.5 ± 0.2	1.4 ± 0.1
FL + CHCW	1	**67 ± 2**	**71 ± 1**	**90 ± 1**	**84 ± 3**	84 ± 2	80 ± 2	85 ± 7	1.5 ± 0.1	**2.2 ± 0.2**
FL + SHCW	1	65 ± 1	61 ± 1	87 ± 1	83 ± 1	**90 ± 4**	80 ± 3	**86 ± 4**	1.6 ± 0.1	2.0 ± 0.1
FL + FBCW	1	64 ± 2	57 ± 4	83 ± 3	83 ± 2	88 ± 4	**82 ± 2**	81 ± 10	**1.8 ± 0.1**	1.7 ± 0.1
CHCW	2	35 ± 5	21 ± 3	19 ± 1	8 ± 2	43 ± 3	30 ± 5	49 ± 12	0.9 ± 0.1	0.8 ± 0.2
SHCW	2	27 ± 5	18 ± 6	13 ± 1	13 ± 2	35 ± 7	24 ± 7	38 ± 13	0.9 ± 0.1	0.7 ± 0.2
FBCW	2	25 ± 3	16 ± 3	12 ± 1	13 ± 1	35 ± 7	25 ± 5	14 ± 9	0.8 ± 0.1	0.6 ± 0.1
FL + CHCW	2	**58 ± 1**	**34 ± 2**	**63 ± 1**	11 ± 1	**59 ± 3**	**62 ± 3**	**78 ± 10**	**1.2 ± 0.1**	**1.1 ± 0.1**
FL + SHCW	2	50 ± 2	30 ± 1	58 ± 1	15 ± 1	51 ± 5	56 ± 2	68 ± 5	1.1 ± 0.1	1.0 ± 0.1
FL + FBCW	2	48 ± 2	28 ± 1	56 ± 1	**16 ± 1**	51 ± 6	57 ± 1	44 ± 12	1.0 ± 0.1	0.9 ± 0.1

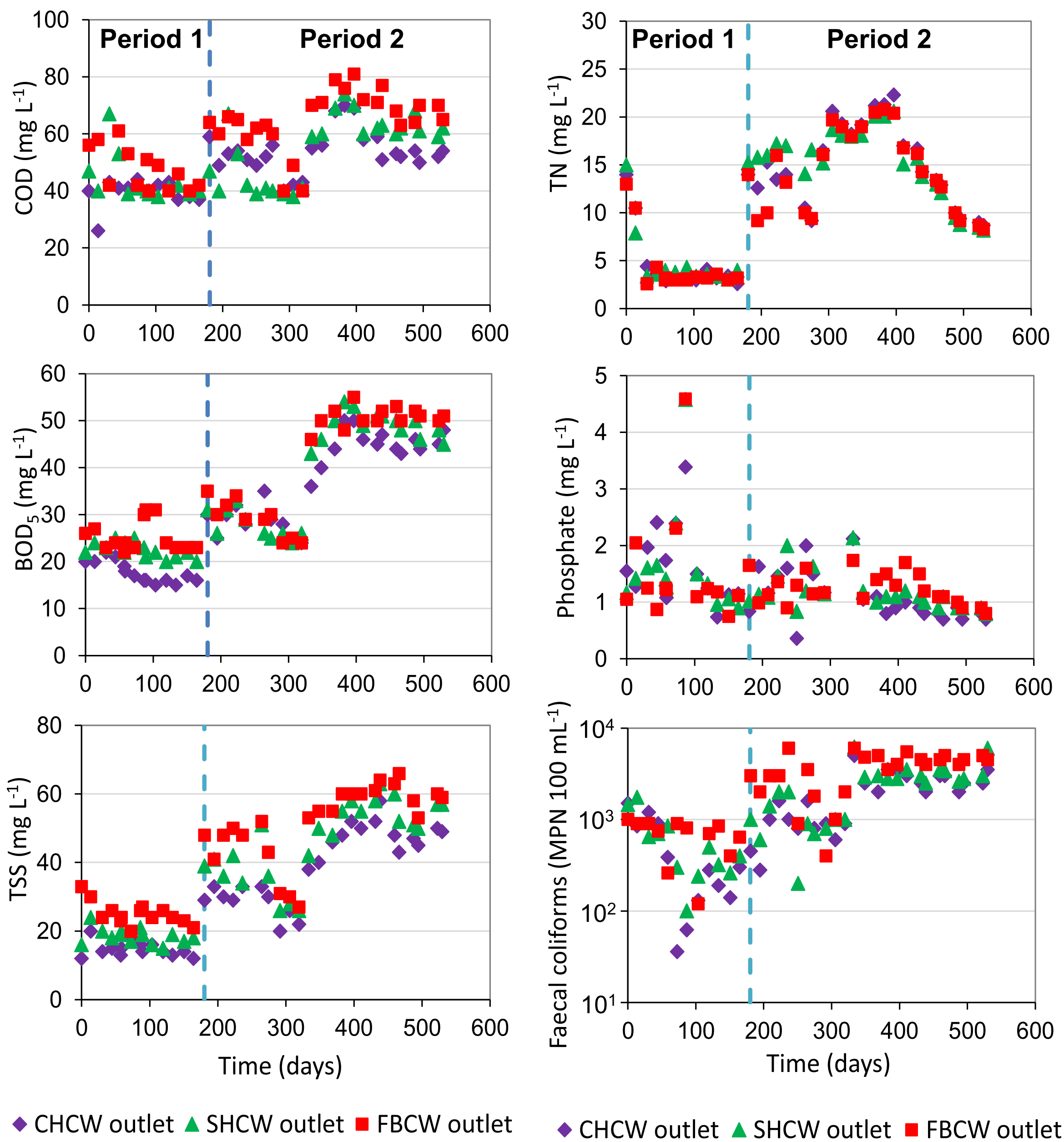

Fig. 3. Effluent concentrations of the three tested treatment trains during the first and second experimental period. The vertical dashed lines indicate the switch from the 1st to the 2nd period.

for TN and NH_4^+ (about 60%), followed by COD (44–46%), TSS and Zn (29–37%) and phosphate (28%). They also achieved a satisfactory disinfection efficiency, with a 1.4–1.9 Log removal of FC. The three FL + CW combinations led to very interesting performances, with removals in the 80–90% range for TSS, TN, NH_4^+, phosphate and Zn, and in the 57–71% range for BOD and COD. The FC Log disinfection efficiencies ranged between 1.7 and 2.2.

Overall, the performances of the three FL + CW combinations did not exhibit significant differences. However, analysis of the data presented in Table 2, where the highest removal yield for each monitored parameter is highlighted in bold, suggests that the FL + CHCW combination slightly outperformed the others, achieving the highest removal yield for COD, BOD, TSS and FC. In agreement with this, Fig. 4 shows that the CHCW featured higher surface removal rates in particular for BOD and TSS, whereas the removal rates relative to the other parameters were similar across the three CW types. This conclusion is confirmed by the data reported in Table 1, where the CW effluent concentrations are compared with 2 international standards relative to WW reuse for irrigation: class C of the EU 741/2020 regulation (irrigation of food crops consumed raw where the edible part is produced above ground, processed food crops and non-food crops; irrigation methods that avoid direct contact of the reclaimed water with the edible part of the crop) and class B of the ISO 16075 standard (irrigation of processed food crops and restricted urban irrigation). Table 1 shows that, during period 1, all the three FL + CW combinations allowed to comply with both standards relatively to TSS and FC, whereas only the FL + CHCW train complied with both standards relatively to BOD. The selection of these water quality classes is based on the rationale that class C of EU 741/2020 allows the irrigation of the vast majority of food crops, included several crops consumed raw, provided drip irrigation is used, whereas class B of ISO 16075 allows the irrigation of several crops largely produced in Egypt, such as rice, beans, wheat and cotton and tobacco.

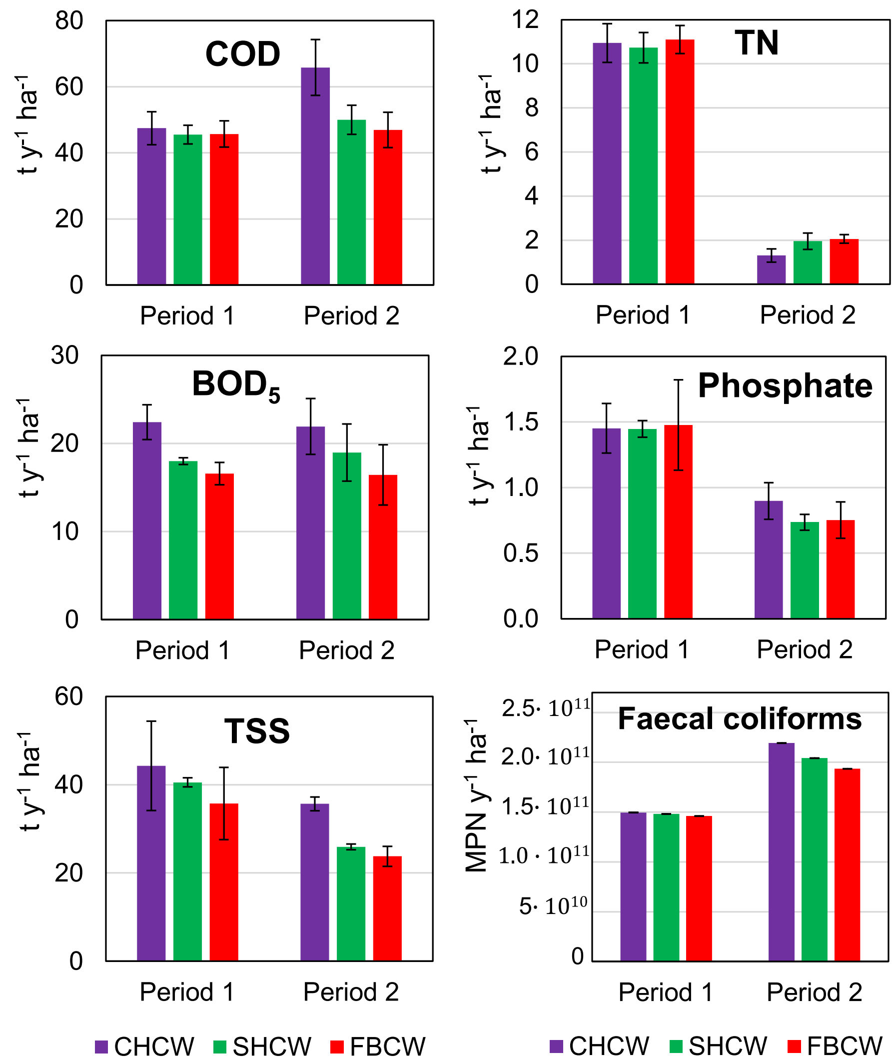

Fig. 4. Surface removal rates obtained in the three tested CW types during the first and second experimental period.

Table 1 includes also the comparison between the effluents of the 3 FL + CW combinations and Art. 51 of Egyptian Law 92/2013, setting the standard for water suitable to irrigate food-crops to be consumed after cooking, after 1:1 dilution with high-quality freshwater. During period 1, all the three FL + CW combinations allowed to comply with the Egyptian standard.

During period 1, the water loss across each CW resulted equal to 2% ± 0.2% in the CHCW, 1.0% ± 0.1% in the SHCW and 4.6% ± 0.5% in the FBCW. These results indicate that evapotranspiration and leakages through the CW bottom and side walls had a minor effect on the overall DCW flow rate.

3.3. Treatment performances of the three CWs in the second period, at high hydraulic surface loading rate

The 2nd operational period lasted 1 year starting from June 15, 2021. In the attempt to further reduce the land surface required to apply CWs at large scale for DCW treatment, this period featured in the CWs a 66% increase in HSLR (417 L d^{-1} m^{-2}), resulting in very low HRTs (1.25 d in the CHCW and SHCW, 1.92 d in the FBCW). In the comparison between the CW performances obtained in periods 1 and 2, it should be considered that the two periods were characterized by moderate variations of the average inlet concentrations, with 10–24% higher levels in period 2 for COD, BOD and FC, 25−64% lower levels in period 2 for nutrients (TN, NH4+, phosphate) and variations <10% for FC and TSS.

As for the correlation between temperature and removal yields during period 2, the Spearman correlation coefficient ρ_s resulted in the (−0.5; 0.3) for all parameters and FL + CW combinations, indicating a lack of correlation for these parameters, except for COD in the FL + CHCW train. In the latter case, ρ_s resulted equal to 0.51, indicating a low/moderate effect of temperature on COD removal. Based on this analysis and for consistency with the approach utilized for period 1, the calculation of average effluent concentrations (Table 1), removal yields (Table 2), and surface removal rates (Fig. 4) was based on data from the last 3 months of period 2 (April–June). No further seasonal elaborations were conducted.

The analysis of the CW surface removal rates (SRRs) (Fig. 4) shows that the increase in HSLR that characterized the shift from period 1 to period 2 was associated to an increase in SRR for FC (+32−47%) and secondarily for COD (+3−39%). For these parameters, it is reasonable to assume that the higher HSLR was partly compensated by the higher inlet concentrations that characterized period 2. Coherently, period 2 featured relevant decreases in SRR for TN (-81−88%), phosphate (-38−49%) and NH_4^+ (-10−33%), i.e. the pollutants whose inlet concentrations were lower during period 2. The TSS SRRs in period 2 were significantly lower than those of period 1 (-19−36%) despite the lack of variations in inlet concentrations. Lastly, the BOD SRRs resulted about equal during the 2 periods.

As a result of the above-described variations in inlet concentrations and SRRs, the shift from period 1 to 2 determined for all the monitored parameters a decrease in the % removals of all the FL + CW combinations (Table 2), with the most relevant decreases for BOD (that dropped to 28–34%), TSS (56–63%), TN (11–16%) and FC (0.9–1.1 Log removal). Coherently, during period 2 the effluents of all the FL + CW trains resulted non-compliant with all the international and Egyptian regulations for WW reuse in agriculture taken into consideration (Table 1).

Despite these variations in performances from period 1 to 2, the FL + CHCW combination resulted also in period 2 the best performing one in terms of both SRRs and % removals, as shown in Fig. 4 and Table 2. In order to validate statistically this conclusion, an ANOVA was applied to the effluent concentrations of the 3 FL + CW combinations reported in Table 1, for both periods 1 and 2. The results, shown in Table 1, indicate that for 6 parameter/period combinations, the FL + CHCW treatment train resulted in effluent concentrations statistically lower than those of the other 2 combinations ($p < 0.05$), confirming the effectiveness of the FL + CHCW solution.

The superior performance of the CHCW may be attributed to the presence of gravel in all four cells of this CW. In contrast, the SHCW only has gravel in the two intermediate cells, with floating plants and no gravel in the first and last cell, while the FBCW lacks gravel altogether. Gravel and similar filtering media support the growth of macrophytes and the formation of biofilm, facilitating a more effective synergy between roots and rhizosphere microbial communities. Additionally, the greater presence of anaerobic zones in cells with gravel can promote the development of aerobic/anaerobic processes, such as nitrification and denitrification.

In order to better investigate the impact of HSR and HSLR on the CW performances, thanks to the analysis performed in intermediate sections of each CW at 5, 10 and 15 m from the cell inlet, the concentrations of selected parameters measured in the 3 CWs were plotted versus HRT and HSLR for both operational periods. As a representative example, the plot of FC versus HRT is shown in Fig. 5, which clearly shows that i) with the exception of the FBCW during period 2, for all the CW types and for both periods the FC concentrations follow roughly the same negative exponential trend versus HRT, and ii) an HRT of at least 1.5 days is necessary in order to achieve the FC level of 1000 MPN 100 mL^{-1}, corresponding to class C of the EU 741/2020 regulation and class B of the ISO 16075 standard.

3.4. Discussion

The results illustrated in sections 3.1 and 3.2 indicate that, even if in the 2nd period (featuring high HSLR and low HRTs) the CWs led to

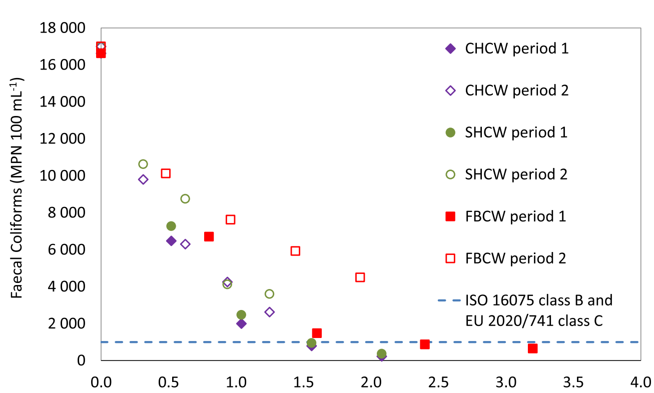

Fig. 5. Profiles of faecal coliforms (FC) versus HRT in the 3 CW types and in the 2 operational periods. The dashed line indicates the FC limit relative to class B of the ISO 16075 standard and class C of the EU 2020/741 regulation.

interesting performances in terms of SRRs, the operational conditions of period 1 (HSLR 250 L d^{-1} m^{-2}, HRT 2.08 d in the CHCW) resulted the optimal ones, in the perspective to convert a medium-strength DCW into a treated water useable for the irrigation of a large spectrum of crops. Therefore, the discussion object of this section is referred to the CW operational conditions and performances relative to period 1.

The HSLR applied to the CWs in period 1 (250 L d^{-1} m^{-2}) were high compared to other full-scale systems treating MWW. For example, among the highest values reported, Masi and Martinuzzi (2007) applied a 150–170 L d^{-1} m^{-2} HSLR for a hybrid HFCW-VFCW system, whereas De Anda et al. (De Anda et al., 2018) applied 22 L d^{-1} m^{-2} for a HFCW treating a UASB municipal effluent. The HSLR implemented in this work in period 1 is closer – even though still higher - to those typical of CW systems treating agricultural drainage water, such as Dal Ferro et al. (Dal Ferro et al., 2018) (230 L d^{-1} m^{-2} for a SFCW) or Kynkäänniemi et al. (2013) (164 L d^{-1} m^{-2} for a HFCW). Coherently with the high HSLR, the HRTs applied in period 1 to the three CWs (2.08–3.20 d) are low, in comparison to those typically implemented in CWs treating MWW or agricultural water, which are in the 3–15 d range (Masi and Martinuzzi, 2007; Merino-Solís et al., 2015; Dal Ferro et al., 2018).

Despite the high HSLR and low HRT, the three CWs tested in this work achieved surface removal rates (SRRs) higher than those typically reported for both MWW and agricultural drainage water. The COD removal rates, in the 45–65 t y^{-1} ha^{-1} range (Fig. 4), were higher in comparison with those previously reported for two CWs treating MWW in Egypt (24 and 35 t y^{-1} ha^{-1} for an HFCW and VFCW, respectively) (Abou-Elela et al., 2013) or for a vegetated ditch in Czech Republic (7 t y^{-1} ha^{-1}) (Vymazal and Dvořáková Březinová, 2018). Similarly, in terms of TSS SRRs (36–44 t y^{-1} ha^{-1}) the three CWs outperformed the typical values reported for CWs treating agricultural drainage water, which are in the 7–20 t y^{-1} ha^{-1} range (Lavrnić et al., 2020; Vymazal and Dvořáková Březinová, 2018). Likewise, the nutrient SRRs achieved in the three CWs (10.7–11 t y^{-1} ha^{-1} for TN, 1.45–1.48 t y^{-1} ha^{-1} for phsophate) were significantly higher than the worldwide average values reported for HFCWs (Vymazal and Kröpfelová, 2008) (0.11–0.38 t y^{-1} ha^{-1} for TN, 0.03–0.24 t y^{-1} ha^{-1} for phsophate). The very interesting performances achieved by the studied hybrid CWs, and in particular by the CHCW, can be ascribed: i) to the presence of both aerobic and anaerobic zones, promoting nitrogen nitrification/denitrification; ii) to the temperatures of the studied Egyptian demo plant (14–26 °C as water temperature), higher than those of the countries where most studies on CWs were performed, with the result of higher rates of bacterial activity and plant growth (Kadlec and Wallace, 2008); and iii) to the fact that hybrid CWs combine the benefits provided by the single CW types.

The total HSLR of the best performing treatment train tested in this work (FL + CHCW) is equal to 0.20 L d^{-1} m^{-2}, or 73 m^3 y^{-1} m^{-2}, considering both the FL and CW surfaces. Since the irrigation water requirements of typical Egyptian crops such as cotton, potatoes or sugar beet are in the 0.8–1.1 m^3 y^{-1} m^{-2} range (Brouwer and Haibloem, 1986), in the perspective to implement this technology at large scale in the Nile Delta, the amount of land required (and therefore subtracted to agriculture) for the production of irrigation-quality water varies in the 1.1–1.5% of the total agricultural land, which can be considered an acceptable fraction. Furthermore, it should be considered that 56% of the surface requested by the FL + CHCW combination is occupied by the FL, which provides a modest contribution to the overall removals achieved by this combination, except for TSS, P and heavy metals (Table 2). Future research should therefore investigate the performances of CHCWs in the absence of the FL pre-treatment, in the effort to increase the HSLR and thus decrease the amount of land required by this treatment technology.

4. Conclusions

A 250 m^3 d^{-1} demonstration plant of DCW treatment by means of a facultative lagoon followed by three types of hybrid CWs was conducted for 530 days, during two periods characterized by different values of HSLR (in the medium-high range) and HRT (medium-low range). The combination of lagooning and cascade hybrid CW, operated at 200 L d^{-1} m^{-2} total HSLR and 4.08 d total HRT, led to satisfactory treatment performances in terms of removal efficiencies (COD 67%, TSS 90%, TN 84%, phosphate 80%, Zn 85%, FC 2.2 Log reduction) and surface removal rates (COD 47.5 t y^{-1} ha^{-1}, TSS 44.3 t y^{-1} ha^{-1}, TN 10.9 t y^{-1} ha^{-1}, phosphate 1.5 t y^{-1} ha^{-1}, FC $1.5 \bullet 10^{11}$ MPN y^{-1} ha^{-1}). This combination led to an effluent compliant with class C of the EU 2020/741 regulation, class B of the ISO 16075 standard and art. 51 of Egyptian Law 92/2013, potentially reusable for the irrigation of a large range of typical Egyptian crops. Seasonal water temperature variations in the 11–28 °C range did not significantly influence the FL and CW performances. During the second operational period, a 66% increase in HSLR of the CHCW led to a decrease in the SRRs relative to TSS and nutrients.

Overall, the FL + CHCW combination showed a great potential for the treatment of drainage canal water, turning it into an irrigation-quality effluent compliant with national and international regulations, with a near-zero energy consumption (no aeration costs), a null consumption of chemicals and a land consumption equal to 1.1−1.5% of the agricultural land irrigated with the treated DCW. The large-scale implementation of this promising technology in the Nile Delta could lead i) to a marked improvement in the quality of irrigation water, reducing the risk of crop contamination and decreasing the pollutant load ultimately discharged into the Mediterranean, and ii) to a significant saving in the consumption of freshwater derived from the Nile River, thus reducing water stress in the Nile Delta. As the tested DCW is similar to a low-strength MWW, the proposed FL + CHCW combination represents a potentially promising solution also for the treatment of MWW. Further research is needed in order to optimize the implementation of the FL + CHCW combination for MWW treatment in the North African context.

CRediT authorship contribution statement

Dario Frascari: Writing – original draft, Supervision, Software, Data curation, Conceptualization. **Ahmed Rashed:** Methodology, Investigation, Conceptualization. **Elisa Girometti:** Writing – review & editing, Validation, Data curation. **Davide Pinelli:** Writing – review & editing, Software, Data curation. **Attilio Toscano:** Writing – review & editing. **Stevo Lavrnić:** Writing – review & editing, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.122663.

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