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Published Version:

Potential of constructed wetland treatment systems for agricultural wastewater reuse under the EU framework / Xi Nan; Stevo Lavrnić; Attilio Toscano. - In: JOURNAL OF ENVIRONMENTAL MANAGEMENT. - ISSN 0301-4797. - ELETTRONICO. - 275:(2020), pp. 111219.1-111219.14. [10.1016/j.jenvman.2020.111219]

Availability:

This version is available at: https://hdl.handle.net/11585/769769 since: 2021-07-28

Published:

DOI: http://doi.org/10.1016/j.jenvman.2020.111219

Journal of Environmental Management

Review

Potential of constructed wetland treatment systems for agricultural wastewater reuse under the EU framework

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A R T I C L E I N F O

Keywords:
Wastewater treatment
Constructed wetland
Agricultural wastewater reuse

A B S T R A C T

One of the solutions for the problems regarding increasing water scarcity and pollution of water resources can be wastewater reuse. Constructed wetlands (CWs) are a sustainable and cost-effective technology for wastewater treatment. If they are able to produce effluent of a needed quality, they can be a valuable addition for wastewater reuse schemes. This review studied 39 treatment systems based on CWs, and it assessed their characteristics and performance on pollutant removal. Moreover, their potential to reach the new European Union standards for agricultural wastewater reuse was evaluated. The results showed that the combination of CWs with additional technologies (e.g. UV treatment, anaerobic reactors) can further increase their performance and provide better removal efficiencies in comparison with conventional horizontal and vertical subsurface flow CWs. Particularly, hybrid systems showed a better removal of organic matter and bacterial indicators than single-stage CWs. For most of the systems considered, the concentrations of biochemical oxygen demand and total suspended solids in treated effluent were below the limits for agricultural reuse. However, that was often not the case with *Escherichia coli* and therefore it is recommended to add a disinfection unit to the systems in order to achieve the levels required in the case of agricultural reuse.

1. Introduction

Currently, water scarcity is becoming a worldwide risk (Mekonnen and Hoekstra, 2016). The severe pressure on water resources is mainly attributed to global population growth, expansion of irrigation agriculture, economic development and climate change (Gosling and Arnell, 2016; Hamadeh et al., 2014; Mekonnen and Hoekstra, 2016; Tao et al., 2017). In fact, existing natural freshwater resources seem to be inadequate to satisfy ever-increasing needs (Almuktar et al., 2018) and therefore imbalance between water demand and water supply (Ghaitidak and Yadav, 2013). Moreover, discharging untreated wastewater can harm different ecosystems (Lavrnić et al., 2018). On the other hand, treated wastewater can be considered as an alternative resource that can be used for different purposes (Barbagallo et al., 2012; Hamadeh et al., 2014; Tao et al., 2017). In this way, sustainable water and biogeochemical cycles can be achieved (Masi et al., 2018), which means that wastewater reclamation and reuse practice is expected to facilitate implementation of circular economy approach (Langergraber and Masi, 2018). Therefore, research on wastewater reclamation strategies is being carried out in order to address increasing demand for water resources and to prevent further deterioration of water quality (Almuktar et al., 2018; NAS, 2016).

Apart from conventional wastewater treatment technologies, nature-based solutions (NBSs) as sustainable measures (Eggermont et al., 2015) have been used worldwide for treating wastewater and improving its quality (Hamadeh et al., 2014). NBSs take advantage of the complex system of natural processes and features to achieve the environmental, social and economic goals (European Commission, 2015; Langergraber et al., 2020). One of the NBSs that can be used for this purpose are constructed wetlands (CWs), engineered ecological systems, that can treat wastewater through different natural processes influenced by the combined action of aquatic plants, soils and microorganisms (Hamadeh et al., 2014; Tao et al., 2017).

CWs are viewed as a cost-effective and sustainable option for wastewater treatment (Arden and Ma, 2018; ElZein et al., 2016; Lavrnić et al., 2020b; Lee et al., 2009). Their main advantages are good removal efficiency, simple and low cost construction, operation and maintenance, nutrient recycling, energy biomass production and esthetic values (Brix et al., 2011; Chen, 2011; Hamadeh et al., 2014; Lavrnić et al., 2020a; Liu et al., 2015; Molari et al., 2014; Rousseau et al., 2008).

CWs effluents can be reused in irrigation, gardening, flushing toilet, groundwater replenishment and other public and industrial uses (Angelakis and Snyder, 2015; Barbagallo et al., 2014; Dou et al., 2017; Rousseau et al., 2008).

However, CWs also have certain shortcomings. For example, for horizontal subsurface flow wetlands there is a certain risk of bed clogging, especially under high loading rates of organic matter and suspended solids (SS). It can later cause hydraulic malfunction and decrease overall treatment performance, even shorter lifespan (Aiello et al., 2016; Barbagallo et al., 2011; Jóźwiakowski et al., 2018; Kim et al., 2016; Ruiz et al., 2010). Moreover, nitrogen removal efficiency of CWs is sometimes limited due to insufficient conditions for denitrification and nitrification (Jóźwiakowski et al., 2018; Liu et al., 2015; Wu et al., 2014). Pathogen removal could be low due to the unsatisfactory performance of single-stage CW and the lack of disinfection treatment or other chemical agents (Andreo-Martínez et al., 2017; Toscano et al., 2015; Zurita and White, 2014). In addition, antibiotic resistance in CW is a new challenge (Russo et al., 2019b).

As one of the biggest consumers of freshwater resources in the world, agriculture needs additional water resources (e.g. treated wastewater) to ensure sufficient crop production (Lavrnić et al., 2017). However, wastewater treated by CWs cannot always satisfy the standards for safe reuse in agriculture (Arden and Ma, 2018; García et al., 2013; Jokerst et al., 2011; Lavrnić et al., 2017). In order to overcome issues related to wastewater treatment and reuse and to obtain effluents of high quality, it is recommended to combine CWs with additional technologies, e.g. adding appropriate disinfection measures (Arden and Ma, 2018), artificial aeration technologies or the anaerobic baffled reactor (ABR).

Therefore, the main objective of this paper is to provide an overview on the configuration, characteristics, as well as performance of domestic wastewater treatment systems based on CWs, including hybrid configurations and additional technologies, in order to assess their potential for wastewater reuse within the new EU framework (EU, 2020).

2. Materials and methods

This review focuses on pollutant removal by wastewater treatment systems based on CWs and the potential of their effluent to be reused in irrigation. The data were obtained through the search of Web of Science database using combinations of keywords “constructed wetland”, “domestic wastewater”, “wastewater treatment”, “wastewater reuse” and “water reuse” (Fig. 1). The retrieval coverage was from 2008 to 2019. According to the main objective of this review, 39 experimental research publications related to wastewater treatment systems based on CWs were selected to be discussed. It should be noted that some papers were excluded from the selection, due to lack of information on pollutant concentrations or removal rates, high similarity of contents (including double results) and low matching degree with points of the review. The flow chart of literature selection with detailed description is provided on Fig. 1.

The 39 articles analyzed cover 19 countries. Regular domestic wastewater (a mixture of kitchen, shower, toilet etc.) treatment is the main topic of 77% of the articles considered, while greywater (domestic wastewater from non-toilet sources) and blackwater (domestic wastewater from toilets) amount to 18% and 5%, respectively. Hybrid CWs or CWs combined with other systems are 64% of the total, while single-stage CWs are 36%. They were mostly of pilot-scale (51%), but full-scale (31%) and lab-scale studies (18%) were also well represented (Fig. 2a). Information about the CW scales was obtained from each research. The design of full-scale systems is often expected to be used directly without considering scale-up. On the other hand, pilot-scale ones are usually with the average area between 1 m^2 and 10 m^2 (Liu et al., 2009), and they are mainly studied to achieve the objectives of the issue identification, design optimization and reliability verification (Tao et al., 2017). Regarding experimental duration, 49% of the research studies lasted for more than one year, 33% were between six months and one year long, 10% were shorter than six months, while the remaining 8% did not provide a specific time (Fig. 2b). The systems considered were vegetated either with a single plant species or a mixture of various

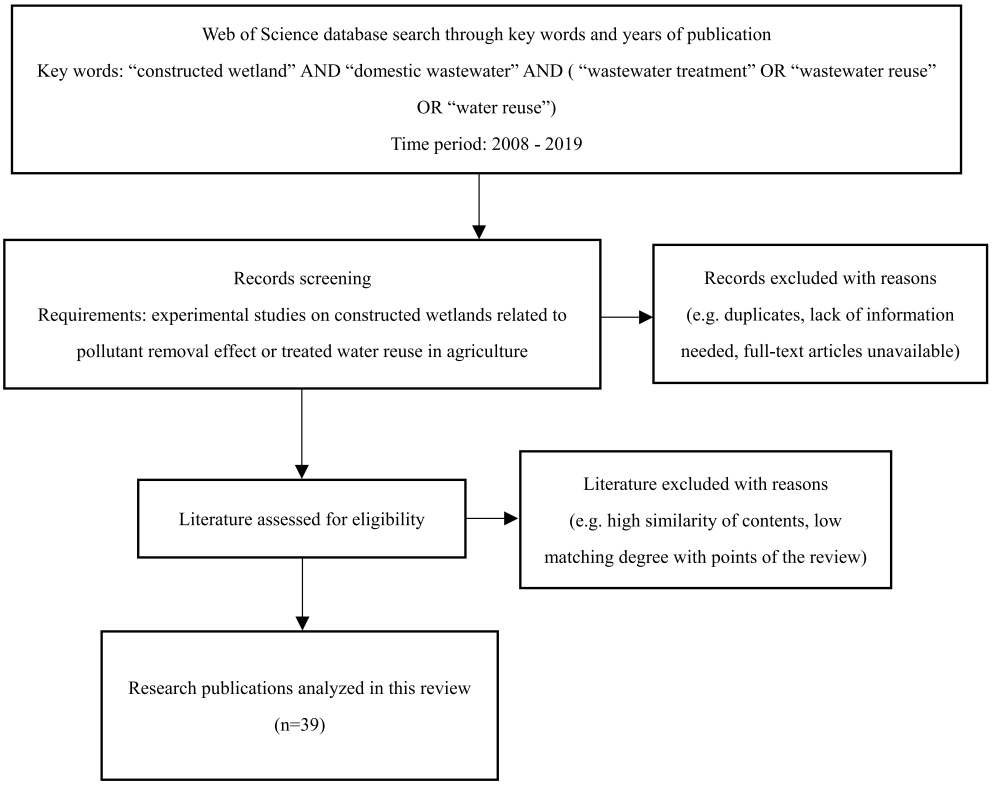

Fig. 1. Flow chart of the literature selection.

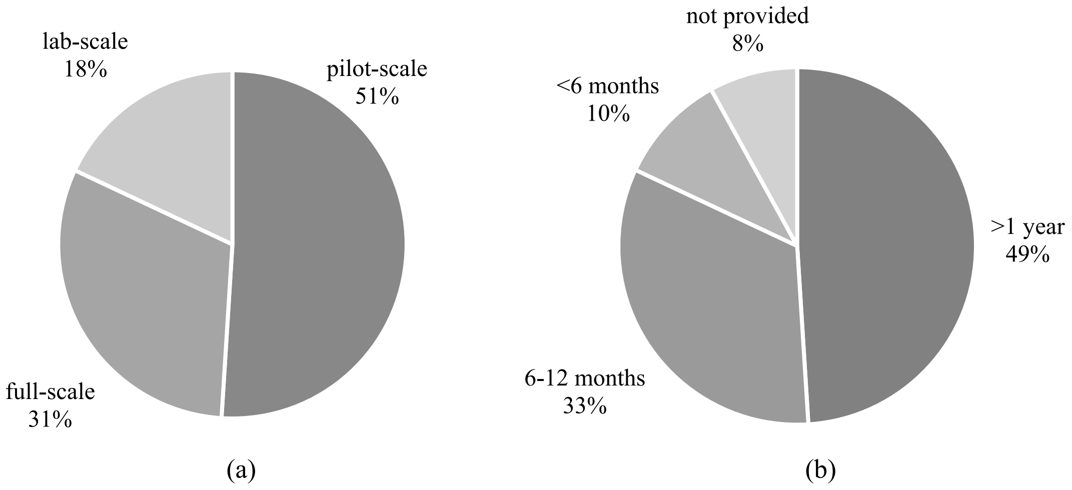

Fig. 2. Distribution of case studies based on (a) constructed wetland scales and (b) experimental duration.

species.

Table 1 lists the 39 selected experimental case studies. Each case study was given a number from 1 to 39, as reported in Table 1 (system No.), and that number was later used to refer to a particular case study in the following sections of the paper. The efficacy of these various wastewater treatment systems was analyzed and conformity of their effluents to reuse limits was evaluated. This research did not introduce studies on single free surface flow CWs, since not many cases suitable for this review were reported in the time frame considered. However, free surface flow CW were considered if combined with other technologies in a hybrid system. It was also noted that some studies in the hybrid system section (Table 1) tested more than one system, either with similar (No. 16, 17, 18, 20, 35 and 37) or different configurations (No. 27a, 27b, 36a and 36b).

In the case when the paper did not provide influent, effluent concentration or removal efficiency, the following equation was used to calculate the missing variable:

$$\frac{C_i - C_e}{C_i} \times 100 = E \tag{1}$$

Where Ci = influent concentration of a pollutant (mg L^{-1}), Ce = effluent concentration of a pollutant (mg L^{-1}), and E = removal efficiency of a pollutant in a system (%).

3. Single-stage CW

On the basis of wetland flow, CWs are classified into free water surface (FWS CW) and subsurface flow (SSF CW). SSF CWs can be subdivided into two specific types, horizontal (HSSF CW) and vertical (VSSF CW) one. Generally, SSF systems show a better performance than FWS ones, especially when hydraulic loading rate (HLR) is high (Liu et al., 2009). Certain modifications of the conventional CWs also yielded some novel technologies such as the green roof water recycling system CW (Avery et al., 2007) and the recirculating vertical flow CW (Gross et al., 2007). Improved systems are seen as an option to solve the drawbacks of conventional CWs. They can save land resources (Ramprasad et al., 2017), optimize the removal of organic matter and biogenic compounds (Sklarz et al., 2009; Xuan et al., 2009), decrease the possibility of human contact with wastewater (Sklarz et al., 2009) and the environmental risks of wastewater reuse (Travis et al., 2010), and at the same time can get better overall treatment effect (Ramprasad et al., 2017; Sklarz et al., 2009; Travis et al., 2010). Furthermore, CWs can be filled with different substrates and vegetated with aquatic plants (Chen, 2011; Herrera-Melián et al., 2010; Toscano et al., 2015), which were suggested to be able to improve pollutant removal (Arden and Ma, 2018; Liu et al., 2009).

3.1. Horizontal subsurface flow CW (HSSF CW)

Until now, many studies on HSSF CWs have been implemented and reported. More HSSF systems were operated in Europe and United States than VSSF CWs (Nivala et al., 2019), and showed reliable capacity for total suspended solids (TSS) and biochemical oxygen demand (BOD) removal (Lavrnić et al., 2017). However, it is worth noting that these systems may not ensure a stable and good removal efficiency of phosphorus, nitrogen and organics (Andreo-Martínez et al., 2017), as a result of a lack of metal ions (e.g. Ca, Mg, Fe and Al) in conventional substrates (Vohla et al., 2011) and a lack of dissolved oxygen (DO) in water (Vymazal, 2007).

The effect of evapotranspiration (ET) on the treatment efficiency has been presented in several studies. For example, in the west of Sicily, Italy, Tuttolomondo et al. (2016) carried out a two-year experiment on a pilot-scale HSSF CW system (containing three independent units) where one unit was planted with *Cyperus alternifolius*, one with *Typha latifolia* and the third was unplanted. The system was filled with silica quartz river gravel (a particle size of 20–30 mm) and operated at a HLR of 12 cm d^{-1}. The mean removal rates based on concentrations chemical oxygen demand (COD) and BOD_5 are shown in Table 2 (No. 1). ET, as a primary factor of the system water balance, had an influence on available treated water volume. The findings showed that the observed removal efficiency of BOD_5 and COD was negatively correlated with ET. Therefore, ET should be taken into consideration especially for arid areas when wastewater reuse in irrigation is the objective. Similarly, in Sicily, Toscano et al. (2015) applied pilot HSSF CWs for tertiary treatment of domestic wastewater from March to November 2012. The CWs were filled with volcanic gravel to a depth of 0.6 m. It was also reported that vegetation has affected water balance of systems leading to different ET values measured in planted and unplanted wetlands. Four were planted with macrophytes (*Vetiveria zizanoides*, *Miscanthus* x *giganteus*, *Arundo donax*, *Phragmites australis*, respectively) and the fifth one was unplanted. The authors indicated that the vegetated CWs were more effective in contaminants removal. The average removal efficiencies based on concentrations for planted CWs were 92.8% for TSS, 68.1% for COD and 61.3% for total nitrogen (TN), and they were greater than the ones of unplanted systems that were 89.4%, 55.4% and 43.1%, respectively. The best performance of pollutant removal was attained by the system planted with *Phragmites australis*, with efficiencies of 99.9% for *Escherichia coli* (*E. coli*), 88% for TSS, 63% for COD and 61% for TN (Table 2, No. 2), thus regarded as the most suitable plant species for wastewater treatment in this case.

Table 1
39 Selected case studies of wastewater treatment systems recorded in the literature from 2008 to 2019.

CW types	System No.	Experimental scale	Country	Influent	Experimental period	Vegetation	Reference
Single-stage CW							
HSSF	1	Pilot-scale	Italy	RDW	>1 year	*Cyperus alternifolius* L. (unit 1), *Typha latifolia* L. (unit 2), unplanted (unit 3)	Tuttolomondo et al. (2016)
	2	Pilot-scale	Italy	RDW	6–12 months	*Vetiveria zizanoides*, *Miscanthus* x *giganteus*, *Arundo donax*, *Phragmites australis*	Toscano et al. (2015)
	3	Pilot-scale	Spain	RDW	>1 year	*Phragmites australis*	Morató et al. (2014)
	4	Pilot-scale	Turkey	RDW	>1 year	*Cyperus*	Ayaz (2008)
	5	Full-scale	Poland	RDW	>1 year	*Salix viminalis* L.	Jóźwiakowski et al. (2018)
	6	Pilot-scale	Spain	RDW	6–12 months	*Phragmites australis*	Andreo-Martínez et al. (2017)
VSSF	7	Pilot-scale	Italy	RDW	>1 year	*Typha latifolia*, *Phragmites australis*	Morari and Giardini (2009)
	8	Pilot-scale	Egypt	RDW	>1 year	*Canna*, *Phragmites australis* and *Cyperus papyrus*	Abou-Elela and Hellal (2012)
	9	Pilot-scale	Greece	RDW	6–12 months	*Atriplex halimus*, *Juncus acutus* and *Sarcocornia perennis*, *Phragmites australis*	Fountoulakis et al. (2017)
	10	Lab-scale	UK	RDW	>1 year	*Phragmites australis*	Almuktar et al. (2017)
Improved system GROW	11	Pilot-scale	India	GW	>1 year	8 varieties of Indian native plant species	Ramprasad et al. (2017)
Improved system RVFCW	12	Lab-scale	Israel	GW	>1 year	*Juncus alpigenus* and *Cyperus haspen*	Sklarz et al. (2009)
	13	Lab-scale	Israel	GW	<6 months	*Hydrocotyle leucocephala* and *Cyperus papyrus*	Travis et al. (2010)
Improved system upflow subsurface CW using green sorption media	14	Pilot-scale	USA	GW	<6 months	*Juncus effusus* (cell 1), *Panicum hemitomon* (cell 2), *Zizaniopsis miliacea* (cell 3)	Xuan et al. (2009)
Hybrid systems							
VSSF-HSSF	15	Full-scale	South Korea	RDW	>1 year	*Phragmites australis* and *Phragmites japonica* (VF), *Miscanthus sacchariflorus*, *Carex dispalata*, *Juncus effusus*, and *Iris pseudacorus* (HF)	Kim et al. (2016)
Two VSSF-HSSFs in parallel[a]	16	Pilot-scale	Spain	RDW	6–12 months	*Phragmites australis* and *Scirpus* sp.	Herrera-Melián et al. (2010)
Four separate HSSF-VSSFs[b]	17	Pilot-scale	Iran	RDW	6–12 months	*Phragmites australis*, *Typha latifolia*, *Arundo donax*, unplanted	Haghshenas-Adarmanabadi et al. (2016)
HSSF-HSSFs, VSSF-VSSFs, VSSF-HSSFs[c]	18	Lab-scale	Colombia	RDW	Not provided	*Papyrus*	García et al. (2013)
FWS-SSF	19	Pilot-scale	USA	GW	6–12 months	*Typha latifolia* (FWS), *Scirpus acutus* (SSF)	Jokerst et al. (2011)
HSSF-VSSFs[d]	20	Lab-scale	Spain	RDW	>1 year	Common reed and *Papyrus* (HSSF), not provided (VSSF)	Herrera-Melián et al. (2018)
IVFCW-HSSF	21	Pilot-scale	China	RDW	6–12 months	*Canna indica* L. (down-flow VSSF), *Juncus effusus* L. (up-flow VSSF), *Scirpus validus* Vahl (HSSF)	He et al. (2018)
Saturated VSSF-free-drain VSSF-HSSF	22	Pilot-scale	Czech Republic	RDW	>1 year	*Phragmites australis* (saturated VSSF), *Phragmites australis* (free-drain VSSF), *Phalaris arundinacea* (HSSF)	Vymazal and Kröpfelová (2015)
VSSF-HSSF-FWS	23	Full-scale	Spain	RDW	Not provided	*Phragmites australis* (VSSF), *Phragmites australis* (HSSF), *Typha* spp., *Scirpus* spp., *Iris pseudacorus*, *Carex flacca*, *Cyperus rutundus* and *Juncus* spp. (FWS)	Ávila et al. (2015)
Settling cum equalization tank-UFDF sand filter-HSSF-charcoal filter-water hyacinth system	24	Full-scale	India	GW	6–12 months	*Canna indica*	Patil and Munavalli (2016)
BCO pretreatment-greenhouse-structured HSSF	25	Full-scale	China	RDW	>1 year	ornamental plants including *Hemerocallis lilioasphodelus* L., *Iris tectorum*, *Oxalis violacea*, *Sedum erythrostictum* Mig and *Hosta ensata*	Gao and Hu (2012)
Ice-block unit[e]-VSSF	26	Pilot-scale	Mongolia	GW	6–12 months	not provided	Uddin et al. (2016)
HSSF-lagooning	27a	Full-scale	Italy	RDW	6–12 months	*Phragmites australis*, *Typha latifolia*	Russo et al. (2019a)
HSSF-UV treatment	27b	Full-scale	Italy	RDW	6–12 months	*Phragmites australis*, *Typha latifolia*	Russo et al. (2019a)
RVFCW-UV disinfection	28	Lab-scale	Israel	RDW	>1 year	*Cyperus haspen*, *Juncus alpigenus* and *Hydrocotyle vulgaris* L.	Sklarz et al. (2013)
SSF-UV/TiO$_2$/O$_3$	29	Pilot-scale	Brazil	BW	>1 year	*Hymenachne grumosa*	Horn et al. (2014)
Anaerobic pretreatment-HSSF-VSSF	30	Pilot-scale	Turkey	RDW	<6 months	*Phragmites australis*	Ayaz et al. (2015)
HUSB reactor-VSSF-HSSF-FWS	31	Lab-scale	Spain	RDW	>1 year	*Phragmites australis*	Ávila et al. (2016)
OP-FWS-Cascade-FWS-SSF	32	Full-scale	China Taiwan	RDW	6–12 months	*Typha latifolia* and *Phragmites australis* (FWS), *Phragmites australis* (SSF)	Yeh et al. (2010)
FP-FWS-SSF	33	Full-scale	Spain	RDW	6–12 months	*Typha latifolia* (SF), *Salix atrocinerea* (SSF)	Reinoso et al. (2008)

(*continued on next page*)

Table 1 (*continued*)

CW types	System No.	Experimental scale	Country	Influent	Experimental period	Vegetation	Reference
Sedimentation tank-HSSF-VSSF	34	Pilot-scale	Egypt	BW	Not provided	*Phragmites*	Abdel-Shafy et al. (2017)
Combinations of HSSF, VSSF or stabilization pond[f]	35	Pilot-scale	Mexico	RDW	>1 year	*Zantedeschia aethiopica*, after 8 months (replaced with) *Canna indica* (HSSF), *Strelitzia reginae* (VSSF)	Zurita and Carreón-Álvarez (2015)
HSSF-biological pond-storage reservoir-sand and disk filters	36a	Full-scale	Italy	RDW	<6 months	*Phragmites australis*	Licciardello et al. (2018)
HSSF-sand and disk filters-UV treatment	36b	Full-scale	Italy	RDW	<6 months	*Phragmites australis*	Licciardello et al. (2018)
ABR-VSSF/HSSF-FWS[g]	37	Full-scale	Pakistan	RDW	6–12 months	*Typha latifolia*, *Phragmites australis* and vetiver grass (VSSF, HSSF), *Pistia stratiotes* (FWS)	Ali et al. (2018)
Two settling tanks in series-VSSF-a zeolite tank	38	Full-scale	Greece	RDW	>1 year	Unplanted (cell 1), *Phragmites australis* (cell 2)	Gikas and Tsihrintzis (2012)
A septic tank-an Imhoff tank-two parallel VSSFs-HSSF	39	Full-scale	Spain	RDW	>1 year	*Typha latifolia* (HSSF)	Vera et al. (2013)

HSSF = horizontal subsurface flow constructed wetland, VSSF = vertical subsurface flow constructed wetland, RDW = regular domestic wastewater, GW = greywater, BW = blackwater, GROW = green roof-top water recycling system, RVFCW = recirculating vertical flow constructed wetland, FWS = free water surface constructed wetland, SSF = subsurface flow constructed wetland, IVFCW = integrated vertical flow constructed wetland, UFDF = up-flow down-flow filter, BCO = bio-contact oxidation, UV = ultraviolet, HUSB = hydrolytic up-flow sludge blanket, OP = oxidation pond, FP = facultative pond, ABR = anaerobic baffled reactor.

[a] System 1: VSSF-HSSF both with lapilli, system 2: VSSF-HSSF both with gravel.

[b] System 1: *Phragmites* HSSF-*Phragmites* VSSF, system 2: *Typha* HSSF-*Typha* VSSF, system 3: *Arundo* HSSF-*Arundo* VSSF, system 4: unplanted HSSF-unplanted VSSF.

[c] System 1: HSSF-HSSF planted, system 2: HSSF-HSSF unplanted, system 3: VSSF-VSSF planted, system 4: VSSF-VSSF unplanted, system 5: VSSF-HSSF planted, system 6: VSSF-HSSF unplanted.

[d] System 1: Mulch-based HSSF-gravel-based VSSFs, system 2: Mulch-based HSSF-mulch-based VSSFs.

[e] The system functioned as the storage pond of frozen wastewater in winter and transferred to septic tanks for treating melted wastewater in summer.

[f] System 1: HSSF-stabilization pond, system 2: HSSF-VSSF, system 3: VSSF-HSSF

[g] System 1: ABR-Saturated VSSF-FWS, system 2: ABR-HSSF-FWS.

Table 2

The mean removal efficiency based on concentrations of main pollutants in single-stage systems analyzed.

System No.	HLR (cm d^{-1})	Removal efficiency (%)							
		Organic matter		Nutrients		Solids	Bacterial indicators		
		COD	BOD$_5$	TN	TP	TSS	*E. coli*	FC	TC
1	12	60.5	53.8	–	–	–	–	–	–
2	36	63	–	61	–	88	99.9	–	–
3	3.6	63.8	65	–	–	–	–	–	–
4	–	50	65	–	–	–	–	>94	>94
5	0.6	–	–	51.3	72.7	–	–	–	–
6	2.62	92.7	97.8	91.5	96.9	97.5	–	–	–
7	1.8–4	79	76.5	–	62.8	59.3	–	–	–
8	–	88	90	–	–	92	94–99.9	94–99.9	94–99.9
9	9.5	78.5	–	26.5	30	–	–	–	–
10[a]	–	–	–	–	–	–	–	–	–
11	1.94–3.75	92.5	90.8	91.7	87.9	91.6	–	91.4	–
12	–	84	95	–	–	90	–	–	–
13	–	–	99	–	–	95	–	–	–
14	–	–	–	75.4	94.9	–	–	–	–

[a] The research did not provide either removal efficiencies of main pollutants or influent concentrations, so the efficiency values could not be calculate.

Pollutant removal in HSSF CWs was reported to be related to seasonal factors. In Spain, Morató et al. (2014) evaluated the effect of design factors (water depth and gravel granulometry) on treatment efficiency of HSSF systems. The mean removal efficiencies of COD and BOD$_5$ were 63.8% and 65%, respectively (Table 2, No. 3). Seasonal variations affected removal of some bacterial groups - a higher removal of *E. coli*, total coliforms (TC) and *Clostridium* spores was achieved in summer, while for heterotrophic plate counts it was during winter. Ayaz (2008) also demonstrated the effect of seasonal changes on removal efficiency, since removals of BOD$_5$ and COD were greater during summer. Furthermore, the authors indicated that HSSF CWs were more effective for SS (80%), BOD$_5$ (65%) and COD (50%) removal in comparison with VSSF and FWS CWs. The mean removal efficiency of fecal coliforms (FC) and TC both amounted to more than 94% (Table 2, No. 4). The only exception was total organic carbon (TOC), which showed low removal efficiency (sometimes negative) in all wetlands due to the additional generation of organic carbon by planted vegetation. In addition, the case No.3, Morató et al. (2014), found that the application of fine substrates was beneficial to the removal of some pollutants. The system with the water depth of 0.27 m and the size of granular medium of 3.5 mm, was more effective for microbial removal in comparison with other systems (0.5 m water depth, 10 mm size of granular medium). Microbial removal was primarily attributed to mechanisms of filtration and sedimentation occurring near the inlet of HSSF CWs. A larger proportion of water volume that was in contact with root systems of the vegetation, beneficial to microbial reduction, may explain the removal effectiveness in the system with a fine substrate. Similarly, Jóźwiakowski et al. (2018) presented the dependency of substrates sorption capacity on the system age. They carried out a 14-year investigation on a HSSF wetland in Poland operated under a HLR of 0.6 cm d^{-1}. The 1.2 m deep system was filled with sand and *Salix viminalis* L. was planted in the humus layer distributed over the sand layer. It was observed that for TN and total phosphorus (TP) it was not possible to achieve a continuous and satisfactory removal in the long-term (14 years) (Table 2, No. 5). Lower TP removal during later period of the experiment could be explained by the fact that the sorption capacity of sand declined. Also, the HSSF system did not provide sufficient conditions for nitrification, which in turn negatively affected TN removal.

3.2. Vertical subsurface flow CW (VSSF CW)

VSSF CWs differ from horizontal ones mainly by flow direction. They have a greater oxygen transfer rate that is beneficial for nitrification and organic matter removal (Sklarz et al., 2009), and that is leading to a smaller surface area required in comparison to HSSF CWs (Herrera-Melián et al., 2018; Lavrnić et al., 2017). Several research studies have recently focused on them.

Different plant species were used to investigate the effect they have on treatment capacity of VSSF CWs. In Italy, two types of pilot-scale VSSF CWs planted with macrophytes *Typha latifolia* and *Phragmites australis,* respectively, were evaluated for two years by Morari and Giardini (2009). The systems were both filled with gravel (30–50 mm, 4–8 mm and 8–12 mm size of granular media) and topped with sand (effective size of 0.16 mm). The mean removal efficiency of parameters tested over two years is shown in Table 2 (No.7). It was also found that the systems performed much better in the second experimental year, especially regarding COD (>93%), BOD (>92%), N (>90%) and K (>86%) removal. These high removal rates were mainly due to the positive effect of plants - uptake of nutrients and providing a habitat for many decomposer microbial populations. Plant uptake contributed up to 75%–85% and 66%–75% of the annual mass removal of N and P, respectively. Furthermore, the authors attributed such a result to macrophytes that were completely established by the second year. However, the treatment efficiency did not differ for tested macrophyte species. Interestingly, Abou-Elela and Hellal (2012) in Egypt found different advantages of the macrophyte species. They conducted a pilot-scale VSSF CW experiment for two years with three species of macrophytes (*Canna*, *Phragmites australis* and *Cyperus papyrus*) in different sections of this wetland unit. The top 60 cm of the bed were filled with 10 mm gravel and the bottom 25 cm with 20 mm gravel. The different mean concentrations of pollutants accumulated in roots of *Canna*, *Phragmites australis* and *Cyperus papyrus* proved vegetation species could influence the removal rates of contaminants. It was further stated that *Cyperus papyrus* increased removal of heavy metals, TN and TP, while *Canna* was better for pathogen reduction. The average removal rates of TSS, BOD and COD were 92%, 90%, 88% (Table 2, No. 8), respectively.

Additionally, the application of halophytes and common reeds was compared by Fountoulakis et al. (2017). The authors reported the use of a VSSF system planted with halophytes, namely *Atriplex halimus*, *Juncus acutus* and *Sarcocornia perennis*, for treatment of primary treated domestic wastewater in Heraklion, Greece, and compared it with another VSSF CW planted with *Phragmites australis*. Both beds were filled with a 15 cm deep drainage layer of 20–40 mm gravel, a 10 cm deep transition layer with 8–20 mm gravel and a 55 cm deep main layer of 1–3 mm coarse sand, while HLR was 95 mm d^{-1}. The authors indicated that *Atriplex halimus* was better for salt accumulation (especially sodium ions), biomass production and pathogen removal. However, there was no significant difference on the removal efficiency of phosphorus and organic matter among CWs planted with halophytes and common reeds, except for a slightly lower TN removal rate achieved by the system planted with halophytes. The mean removal efficiency of all systems were 78.5% for COD, 26.5% for TN and 30% for TP (Table 2, No. 9).

In some experiments, various design parameters of VSSF CWs were also evaluated in order to obtain effluents with higher quality for irrigation purpose. For example, in the UK, Almuktar et al. (2017) adopted a completely randomized design when testing ten different VSSF CWs located at an aerated greenhouse. They were filled with pea gravel (a depth of 60 cm) differing in four parameters (aggregate diameter, loading rate, contact time, resting time) and operated for more than 4 years (June 2011 to September 2015). The authors assessed the effect of effluents obtained by different systems on chili irrigation. The high yields came from the chilies irrigated by the systems containing small aggregate diameters, with long resting and contact time, and under high inflow loading rates, providing more nutrients for irrigation and leading to substantial marketable profits.

3.3. Improved single-stage constructed wetlands

In recent years, increasing number of studies focused on improved constructed wetlands for wastewater treatment. In comparison with conventional single-stage CWs, these systems can enhance contaminant removal or occupy less surface area, due to changing or modifying their original design (e.g. placing them on a commonly unexploited space, application of recirculation or aeration) (Martínez et al., 2018; Ramprasad et al., 2017; Xuan et al., 2009).

For instance, based on HSSF CWs, the green roof-top water recycling system (GROW) CW was first established in the UK, and it was placed on the roof to save ground space. The system was constructed by interconnected weirs and channels, which were functioning as the beds for wastewater treatment. GROW was proposed as a viable alternative to treat greywater, addressing the limitation of land resource (Ramprasad et al., 2017). The system was piloted in India tropical conditions, from November 2013 to April 2015, planted with eight kinds of local common plants and filled with a 15 cm deep layer of mixed substrates, containing sand, brick bats and gravel (1:1:1). The results showed that overall removal rate of all tested parameters was very high, in particular COD (92.5%), BOD (90.8%), TSS (91.6%), TN (91.7%), TP (87.9%) and FC (91.4%) (Table 2, No. 11). The authors attributed the high removal of solids to the baffled CW configuration, which increased the flow path and improved filtration process. It was also concluded that 100 L day^{-1} was the most suitable flow rate for organics removal (BOD and COD). A flow rate higher than 100 L day^{-1} caused shorter hydraulic retention time (HRT) and lower pollutant removal. Moreover, seasonal conditions affected the system, attaining the greatest treatment efficiencies of pollutants (i.e. organics, nutrients and FC) in summer.

In Israel, the research related to the recirculating vertical flow constructed wetland (RVFCW) reported that recirculation was beneficial to organics abatement (Sklarz et al., 2009). In this study, Sklarz et al. (2009) monitored two RVFCW systems filled with the substrates (lime pebbles and plastic beads), and tested the treatment effectiveness when the beds were operated with or without an additional soil-plant component (a layer of peat vegetated with *Juncus alpigenus* and *Cyperus haspan* for a depth of 8 cm). They revealed that the both recirculating systems performed well, even the one without the soil-plant component, removing organics from wastewater with a high efficiency, namely 95% for BOD_5 and 84% COD on average, besides a 90% TSS removal (Table 2, No. 12). Similarly, in another 40-day study (Travis et al., 2010) on a lab-scale RVFCW planted with *Hydrocotyle leucocephala* and *Cyperus papyrus* and fed with domestic greywater, TSS removal was around 95% and in the case of BOD_5 it was about 99% (Table 2, No. 13).

Artificial aeration and innovative media were introduced into some CW systems to address a lack of oxygen and the unfavorable adsorption rates of conventional media. Andreo-Martínez et al. (2017) tested a HSSF wetland in Spain filled with blast furnace slags (BFS) and fed with artificially aerated municipal sewage, and found out that those changes produced higher quality effluent. The data demonstrated that the application of BFS and aeration optimized TP removal. Moreover, the average removal efficiency of turbidity (99.5 ± 0.3%), TSS (97.5 ± 1.3%) and TN (91.5 ± 5.3%) had also been improved due to the presence of aeration (Table 2, No. 6). Xuan et al. (2009) introduced green sorption media (recycled and natural materials) into upflow subsurface CWs and tested them for three months. It was found that TP and TN were effectively reduced by 94.9% and 75.4% (Table 2, No. 14) in the CWs.

Table 2 shows the mean removal efficiency based on concentrations of previously discussed 14 single-stage CW studies. Actually, the removal efficiency of pollutants can be assessed by two methods - using concentrations or mass loads for calculation. Values attained from the two methods were similar when ET was low, while obviously different under very high ET in summer (Tuttolomondo et al., 2016). High ET losses cause unsatisfactory residual concentration of pollutants, as they concentrate the elements in effluent, offsetting the effect of treatment (Morari and Giardini, 2009). Therefore, removal efficiency based on mass loads can be considered more accurate (Tuttolomondo et al., 2016). However, most researchers provided removal based on concentrations in their studies due to easier measurement of related parameters.

Among all the single-stage systems considered (Table 2), improved systems GROW and RVFCW displayed the greatest overall removal efficiency, beyond 90% for the most of contaminants measured (Table 2, Nos. 11–13). According to Table 2, the majority of VSSF and HSSF CWs reached a good efficiency in solids removal. Generally, VSSF systems (Table 2, Nos. 7–10) showed better effect on organic matter removal in comparison with HSSF ones (Table 2, Nos. 1–5). One exception was the improved HSSF system (Table 2, No. 6), which also showed greater capacity of nutrients removal compared to other HSSF and VSSF CWs. Regarding bacterial indicators, the HSSF systems No. 2, 4 and the VSSF system No. 8 (Table 2) removed them most effectively. The observed abatement higher than 94% could be related to a longer HRT (Ayaz, 2008), or favorable seasonal conditions and oxygen concentration in the VSSF CW, that provided aerobic environment unfavorable for coliforms survival (Abou-Elela and Hellal, 2012). It was revealed that the removal of organics and solids was also high in the system No. 8 (Table 2). Settleable organics could be eliminated through filtration and deposition, while the high removal of organic compounds can be explained by the fact that this system provided both oxygen and a more favorable habitat for microorganisms due to the presence of various plants. Moreover, the diversity of roots increased HRT, which was beneficial for pollutant removal (Abou-Elela and Hellal, 2012).

4. Hybrid systems

In order to improve pollutant treatment capacity and attain higher quality effluent, some researchers designed hybrid systems by combining different types of CWs or combining CWs with other technologies, making use of their respective advantages (Ávila et al., 2015; Haghshenas-Adarmanabadi et al., 2016; Ramprasad and Philip, 2018; Zurita and White, 2014).

4.1. Hybrid constructed wetlands

The most widely used hybrid CW system is the combination of two subsurface flow CWs - horizontal and vertical one (Ramprasad et al., 2017). For example, in South Korea, Kim et al. (2016) carried out a full-scale experiment on VSSF-HSSF CWs from 2002 to 2013. The VSSF system was planted with *Phragmites australis* and *Phragmites japonica*, while the HSSF CW was planted with *Miscanthus sacchariflorus*, *Carex dispalata*, *Juncus effusus* and *Iris pseudacorus*. Both of them were filled with coarse sand. The study revealed that the hybrid system had a stable TN removal in the whole 12-year operation period, with the average removal rate of 71.8% (Table 3, No. 15). In general, the VSSF CW had better removal efficiency of TN than the HSSF CW. It can be explained by the fact that HSSF CWs cannot satisfy the needs of denitrification/nitrification for a complete anaerobic/anoxic condition, as already reported by Jóźwiakowski et al. (2018) (see section 3.1). On the other hand, VSSF CWs can provide aerobic conditions that are essential to the nitrification process. It was also reported that TN removal efficiency was associated with the factors like season (greater removal rates in summer), operating stage (greater removal rates during the middle stage of

Table 3
The mean overall removal efficiency based on concentrations of main pollutants in hybrid systems analyzed.

System No.	HLR (cm d^{-1})	Removal efficiency (%)							
		Organic matter		Nutrients		Solids	Bacterial indicators		
		COD	BOD_5	TN	TP	TSS	*E. coli*	FC	TC
15	4.5–22.7	–	–	71.8	–	–	–	–	–
16	3.7–7.9	82	89	–	–	–	–	99.9	–
17	5.3	79	84	–	43–97	78	–	99	–
18	10	>90	>90	>90	–	>85	99.984	–	99.987
19	1.3–3.4	–	80.5	74.8	66.3	–	–	–	–
20	–	82	97	–	–	99	–	99.8	–
21	15–24	59	–	57.7	82.8	–	–	–	–
22	3.8–61.1	83.8	92.5	79.9	30	96	–	–	–
23	4.4	89	99	94	47	98	99.999	–	–
24	1.5–9.3	70	–	–	–	–	–	–	–
25	–	85	–	–	36.5	–	–	–	–
26	–	98–100	–	–	–	97	98	–	–
27a	–	28.26	19.23	50.93	11.86	22	99.937	–	99.899
27b	–	–	–	–	–	–	>99.99	–	99.996
28	–	85.5	96.8	29.5	7	90	99.999	–	–
29	–	62.1	88.7	–	63.4	–	–	–	–
30	11.1–21.9	94.3	91.9	–	–	97	–	–	–
31	27	82	93	–	–	96	–	–	–
32	–	48	81	65	–	–	–	–	–
33	–	–	–	–	–	–	99.33	–	97.12
34	–	98.5	98	–	–	97.4	–	–	–
35	6.8–14.5	–	–	–	–	–	99.94	–	99.5
36a	–	69.02	68.01	–	–	90.15	99.99	–	–
36b	–	76.48	80.43	–	–	90.87	99.999	–	–
37	–	73.6	76.2	–	–	82	–	–	–
38	–	94.9	95.8	–	67.3	96	–	–	99.97
39	–	89	93	61	47	98	–	–	–

When the research tested more than one hybrid system (No. 16, 17, 18, 20, 35 and 37), the one with the best overall removal efficiencies was reported in this table. The study (No. 26) provided only the maximum removal rates.

operation, between 2006 and 2009) and nitrogen load. Similarly, another study in USA reported the effect of seasonal variation. Jokerst et al. (2011) operated a pilot-scale FWS-SSF hybrid CW in a semi-arid, temperate climate for one year. The FWS and SSF beds were planted with *Typha latifolia* and *Scirpus acutus*, respectively. The FWS CW was filled with amended soil (a mixture of 50% sandy-loam soil and 50% sphagnum peat) up to a depth of 0.9 m, while the SSF CW was filled with about 15 mm-diameter granite stone. It was shown that, except during winter, the average removal efficiency based on mass loads for BOD_5, TN and TP was as high as 92%, 85% and 78%, respectively. However, the treatment effect seemed to decrease in winter season. The mean yearly removal efficiency based on concentrations was given in Table 3 (No. 19). The authors also reported that TSS removal was probably negatively affected by a considerable algal growth in the FWS bed during warm spring months.

Plant species present in CW systems generally had a positive impact on wastewater treatment. For example, in Iran, Haghshenas-Adarmanabadi et al. (2016) evaluated four pilot HSSF-VSSF CWs from September 2013 to August 2014, three of them planted with different vegetation types and the last one unplanted. It was found that the hybrid systems can abate the main contaminants with high removal rates. The best removal efficiency was obtained in *Phragmites* hybrid CW, 84% for BOD_5, 79% for COD, 78% for TSS, 99% for FC, 43–97% for TP (Table 3, No. 17). The authors indicated that the planted CWs performed significantly better than the unplanted CW for TP reduction. It can be attributed to plant uptake and sequestration in microbial biomass. Additionally, it was noteworthy that the combination HSSF-VSSF CWs was highly effective for optimizing the removal of main pollutants except for nitrates, since they can be produced by ammonium nitrification in the VSSF stages.

Herrera-Melián et al. (2010) tested two pilot VSSF-HSSF systems filled with gravel and lapilli (a very porous volcanic sediment) for eight months in Spain. Generally, the removal efficiency of COD, FC and NH_4^+-N was not significantly different between the two systems. However, the lapilli system always had a significantly higher BOD_5 removal than the gravel one. This better performance on BOD_5 removal could be attributed to the application of lapilli particles with higher porosity and smaller diameter, thus leading to greater removal during the treatment processes (e.g. filtration, sedimentation and BOD_5 degradation). Between the two systems tested, considering all the parameters, the lapilli-based hybrid CWs performed better at high HLR, with the removal of 82% for COD, 89% for BOD_5 and 99.9% for FC (Table 3, No. 16).

Similarly, in Herrera-Melián et al. (2018), the reason why the mulch-based VSSF CWs performed better than the gravel-based ones was also related to small particle size of the medium used. In this case, the authors tested two hybrid systems in Spain, i) mulch-based HSSF followed by gravel-based VSSFs, ii) mulch-based HSSF followed by mulch-based VSSFs, under different feeding modes (continuous and intermittent). The greatest removal of various pollutants (82% for COD, 97% for BOD_5, 99% for TSS, 99.8% for FC) was provided by the second hybrid system, the combination of HSSF and mulch-based VSSFs, under the continuous feeding mode (Table 3, No. 20). The greater performance of mulch-based VSSFs can be attributed to the characteristics of mulch (e.g. compressibility and small particle size). Small particle size provided several benefits, longer HRT, better water distribution on the reactor surface and greater retention of pollutants (e.g. TSS, turbidity). Also, the authors argued that the intermittent feeding mode could have caused a shorter HRT compared to the continuous one, thus the lower removal efficiency. Conversely, the application of larger size media may lead to unsatisfactory removal efficiency of some pollutants.

In China, He et al. (2018) tested for nine months a system consisting of a down-flow VSSF CW, an up-flow VSSF CW and a HSSF CW. The results showed that COD removal was negatively affected by the application of large diameter media. Since the media could not have provided sufficient surface area for biofilm growth, microbial activities were limited and unsatisfactory COD removal efficiency was obtained. Despite this, the media decreased the possibility of clogging in the system. The highest nitrification and denitrification intensity of the media was in the down-flow VSSF bed and the HSSF bed, respectively, which may be associated with the abundance of nitrifying and denitrifying bacteria in these wetlands. During the experimental period the removal rates of COD, TP, TN and NH_4^+-N reached 59%, 82.8%, 57.7% and 79.2% on average, respectively (Table 3, No. 21). In Colombia, García et al. (2013) reported the high performance of a series of two-stage CWs in pathogen removal. These systems differed by the feeding modes, the order or combination of CWs (i.e. VSSF, HSSF) and the vegetation conditions. The detailed description can be found in Table 1 (No. 18). It was shown that the type of planted VSSF-HSSF combination can reduce 99.984% *E. coli*, 99.987% TC and 90.741% Helminth eggs. In addition, this system had the best nitrogen removal (>90%) of all, also providing high removal rates of organics and solids (>90% for both BOD_5 and COD, >85% for TSS) (Table 3, No. 18). It statistically displayed that vegetation probably contributed a lot to the reduction of nutrients and *E. coli*.

Among the hybrid systems considered, two of them achieved especially high removal efficiencies. In Czech Republic, a three-stage hybrid CW comprising of a saturated VSSF CW, a free-drain VSSF CW and a HSSF CW, was investigated by Vymazal and Kröpfelová (2015) for nineteen months. They reported good removal efficiency of the hybrid system - 92.5% for BOD_5, 96% for TSS, 88.8% for NH_4–N, 83.8% for COD and 79.9% for TN (Table 3, No. 22). A full-scale research (Ávila et al., 2015) also demonstrated the superb overall pollutant abatement capacity of the hybrid system (Table 3, No. 23), even for some emerging pollutants (more than 80% removal, e.g. analgesic and anti-inflammatory drugs, personal care products). The high removal of different pollutants in hybrid systems was related to warmer period of the year and the synergy of removal mechanisms (e.g. nitrification, denitrification, biodegradation and sorption) (Ávila et al., 2015; Vymazal and Kröpfelová, 2015).

4.2. CWs combined with additional technologies

Some studies have focused on adding different technologies to the existing CWs, such as filtration, ultraviolet (UV) treatment, etc. These physical, chemical or biological technologies were applied to improve wastewater treatment, especially for some pollutants like turbidity or microbial indicators (Patil and Munavalli, 2016; Russo et al., 2019a; Toscano et al., 2013).

In Sakharale, India, a tropical zone, Patil and Munavalli (2016) reported a three-stage treatment system, containing preliminary treatment, HSSF CW treatment and a post treatment. Pretreatment was done by a settling cum equalization tank and an up-flow down-flow filter (UFDF), and could significantly decrease the turbidity while also partially removing COD. The post treatment included a vertical flow charcoal filter and water hyacinth system, further improving the quality of final effluent to fulfill the outflow requirements, the removal effects mainly attributed to the role of adsorption and plant uptake. The overall removal rates of the system were 70% for COD, 70% for total kjeldahl nitrogen and 85% for pathogens (Table 3, No. 24).

In Heilongjiang, China, Gao and Hu (2012) combined bio-contact oxidation (BCO) technology with a greenhouse-structured HSSF CW. The utilization of double solar panels in the greenhouse provided a stable temperature for treating wastewater, and effectively improved pollutant removal rates especially during winter season. The overall removal efficiency of the parameters evaluated in the combined system was 85.01% (COD), 70.98% (NH_3–N), 36.48% (TP) (Table 3, No. 25). The BCO treatment was responsible for 74.6% and 85.4% of the total removal of COD and NH_3–N, respectively, while the wetland contributed to 59% of the total TP removal.

In Ulaanbaatar, Mongolia, an 'ice-block unit' consisting of a storage tank, septic tanks, a VSSF CW and a collecting tank showed a great potential for application in cold climates. It stored greywater throughout freezing period in an ice-block, and then melted and treated it during warm months. The removal rates of main pollutants (e.g. COD, NH_4^+, TSS, *E. coli*) ranged from 87% to 100% (Uddin et al., 2016) (Table 3, No. 26).

In Italy, Russo et al. (2019a) tested a full-scale HSSF CW combined with a UV unit for one year. The findings indicated that the whole system was highly efficient in removal of microbial indicators such as *E. coli*, somatic coliphages and *Clostridium perfringens* spores (Table 3, No. 27b). Similarly, Sklarz et al. (2013) proved the effectiveness of UV light disinfection treatment through agricultural reuse experiments, since there was no *E. coli* detected in the soil irrigated with the treated wastewater. Moreover, after the integrated treatment of the sedimentation tank, RVFCW, the filter and the UV disinfection unit, wastewater achieved a large decrease in the concentrations of BOD_5, COD, TSS and *E. coli* (Table 3, No. 28). Also, Horn et al. (2014) concluded that the combination of photocatalytic ozonation ($UV/TiO_2/O_3$) technologies and SSF CWs was capable of improving disinfection efficacy of the system. It effectively removed microbial contaminants and the microbial load under the detection limit. Furthermore, it eliminated 88.7% of BOD_5, 62.1% of COD and 63.4% of TP (Table 3, No. 29). However, it was observed that due to the effects of physical sorption and chemisorption, the ramp of $UV/TiO_2/O_3$ reactor reached saturation after 4 h of operation.

In Turkey, Ayaz et al. (2015) reported a three-stage hybrid pilot system built in a small community, consisting of anaerobic pretreatment, a HSSF CW and a VSSF CW. The pretreatment, an ABR and an upflow anaerobic sludge bed (UASB) reactor running in parallel, partially removed organic matter and SS. The combined system removed 90% of nitrogen and 95% of organic matter on average. The mean removal rates of pollutants BOD_5, COD and TSS are shown in Table 3 (No. 30). The authors stated that the combination of HSSF and VSSF CW optimized the removal of organics and SS, effectively reduced phosphorus and stimulated nitrification in the VSSF. In general, it showed greater performance than a single CW and effluent recirculation could also increase the removal of organics and TN (Sklarz et al., 2009).

Likewise, the study provided by Ávila et al. (2016) proved that an experimental integrated system containing an anaerobic reactor was a good alternative for wastewater treatment in small communities, particularly in warm climate zones. The system consisted of two alternating VSSF CWs, a HSSF CW and a FWS CW operating in series, following an anaerobic reactor - hydrolytic up-flow sludge blanket (HUSB). The results showed the system was able to effectively reduce BOD_5 (93% removal), TSS (96% removal), COD (82% removal) and NH_4–N (75% removal), whereas it did not perform well in PO_4–P (11%) and SO_4^{2-} (10%) removal (Table 3, No. 31). Another application of HUSB reactor in Spain showed that it did not perform as well as a conventional settler before HSSF CWs (Pedescoll et al., 2011).

Yeh et al. (2010) carried out an experiment on the system made up of an oxidation pond, two FWS CWs with a cascade between them and a SSF CW operating in series. The findings (Table 3, No. 32) showed the system removed 81% of BOD and 48% of COD on average, mainly owing to microbial degradation. TN removal of 65% was primarily attributed to nitrification and denitrification occurring in the treatment processes.

Reinoso et al. (2008) operated a facultative pond (FP) followed by a FWS and a SSF system for 10 months in Spain and the results revealed that FP was more effective in bacterial removal (e.g. TC, *E. coli*), while the SSF CW had the robust capacity for removing protozoan pathogens and coliphages. It was observed that 99.33% of *E. coli* and 97.12% of TC were removed on average (Table 3, No. 33).

In Egypt, Abdel-Shafy et al. (2017) tested a pilot system including a sedimentation tank, a HSSF CW and a VSSF CW running in series, for blackwater treatment. The hybrid system was proven to be capable of treating wastewater under high hydraulic and organic loads, with the removal efficiency of 98.5%, 98%, 97.4%, for COD, BOD and TSS, respectively (Table 3, No. 34). Furthermore, it was found that the large surface area and low velocity of the integrated system (HSSF and VSSF CWs) principally helped to improve the effluent quality. However, a disadvantage of the system was exactly its high surface requirement.

In Greece, a three-stage hybrid system consisting of two settling tanks in series, a VSSF CW and a zeolite tank, was operated for 40 months. The overall removal efficiency was satisfactory for BOD (95.8%), COD (94.9%), TSS (96%) and TC (99.97%) (Table 3, No. 38). It was observed that organics removal was mostly attributed to the septic tanks. Finally, the zeolite tank further enhanced the treatment performance, since the relatively large pore size of zeolite were favorable for the adsorption of organics. The high removal of TC was achieved mainly by sedimentation and filtration in the septic tanks and the CW, respectively. It was also reported that plants played a significant role in removal of organics and nutrients (except for TSS and TC). Moreover, their growth and movement may be beneficial for preventing clogging (Gikas and Tsihrintzis, 2012). Similarly, delaying or preventing system clogging can also be achieved by the application of larger size media (He et al., 2018), the setup of pretreatment (e.g. a HUSB reactor, a UFDF sand filter), adjustment of treatment operation and system structure (e.g. intermittent discharge, upflow structure of CWs) (Pedescoll et al., 2011; Vera et al., 2013), as well as the application of earthworms or a low organic loading rate (Lavrnić et al., 2019; Zapater-Pereyra et al., 2016).

Vera et al. (2013) reported a system composed of a septic tank and an Imhoff tank in series as pretreatment, and two parallel VSSFs followed by a HSSF as secondary treatment. It was found that the overall removal rates were 98% for TSS, 93% for BOD_5, 89% for COD, 61% for TN and 47% for TP (Table 3, No. 39). Although the removal efficiency of each stage affected by several factors (e.g. seasonal change and influent quality) was different, overall performance was relatively stable during the experimental period of 2 years.

4.3. *Comparison of various hybrid systems*

While section 4.1 analyzed the treatment capacity of hybrid CWs, and section 4.2 discussed the performance of additional technologies combined with CWs, this section will focus on the comparison of hybrid systems operated simultaneously and within the same environment. These studies allowed to assess the contribution of each treatment stage and to evaluate the impact of different designs on overall pollutant removal efficiencies.

In Mexico, Zurita and Carreón-Álvarez (2015) reported on the application of three integrated systems running for two years, namely HSSF+stabilization pond (SP), HSSF+VSSF and VSSF+HSSF systems. During the first year, it was observed the HSSF+VSSF and VSSF+HSSF systems showed the best efficacy of TC removal (2.2 log units) and *E. coli* removal (3.8 log units), respectively. During the second year, both HSSF+VSSF and VSSF+HSSF, performed well in TC and *E. coli* removal, ranging from 2.34 to 2.44, 3.44 to 3.74 log units, respectively. Both performances were significantly better than HSSF+SP system. As a result, HSSF+VSSF system was the most effective for *E. coli* (99.94%) and TC (99.5%) removal during the two-year experimental period (Table 3, No. 35).

Multistage hybrid systems were also utilized in some research. For instance, Licciardello et al. (2018) evaluated two systems with similar costs. The main difference between them was whether UV disinfection was used. One system was comprised of a HSSF CW, a biological pond, a storage reservoir followed by sand and disk filters, while the other one was made up of a HSSF CW, sand and disk filters and UV treatment, both of them operating in series. It was found that the system containing UV treatment was more effective. The removal efficiencies achieved were 76.48%, 80.43% and 90.87% for COD, BOD_5 and TSS, respectively. Moreover, *E. coli* reduced by 5.49 log units, mostly owing to the UV disinfection (Table 3, No. 36b).

According to Ali et al. (2018), the two full-scale systems tested in Pakistan were both influenced by seasonal factors. The system I was made up of an ABR, a saturated VSSF CW and a FWS CW and the system II consisted of an ABR, a HSSF CW and a FWS CW. They achieved greater removal efficiency in summer, similar with several findings in the experiments on single or hybrid CWs (Ayaz, 2008; Kim et al., 2016; Ramprasad et al., 2017). Generally, the system I provided higher overall removal rates of COD (73.6%), BOD_5 (76.2%) and NH_4–N (52.8%). The exception was TSS removal (82%), that was slightly lower than the values of the system II (91%) (Table 3, No. 37). The difference of removal efficiency between the two systems was mainly caused by the use of HSSF or VSSF CW as the secondary treatment. It was also found that the first stage treatment (ABR) of both systems predominantly contributed to solids removal and organics degradation.

Table 3 shows the overall pollutant removal efficiency of hybrid systems from 25 studies previously discussed. These integrated systems showed nearly complete removal of bacterial indicators and quite a good effectiveness in TSS abatement (>85% for most systems), except for the system HSSF-lagooning (Table 3, No. 27a). In comparison with single-stage CWs (Table 2), they had a better overall performance in organics reduction. These high removal rates can be explained by the combination of technologies in hybrid systems that contributed to a greater overall removal efficiency (Ayaz et al., 2015; Gikas and Tsihrintzis, 2012). However, in terms of nutrients removal, the hybrid systems showed large differences, i.e. TN and TP values ranging from 29.5% (Table 3, No. 28) to 94% (Table 3, No. 23) and from 7% (Table 3, No. 28) to 82.8% (Table 3, No. 21), respectively. Low TP removal observed in a few studies could be attributed to the limited sorption of some substrates applied (e.g. crushed rock), and to the fact that no additional measures were used for enhancing TP removal (Vymazal and Kröpfelová, 2015). Interestingly, there was one system HSSF-lagooning (Table 3, No. 27a) that showed low removal efficiencies for most pollutants, although a majority of hybrid systems performed well. It can be attributed to the fact that the algae growth and decomposition in the lagooning unit contributed to the increase of TSS, BOD_5 and COD concentrations. Besides, the lagooning unit was not able to further reduce nutrients (TN and TP), due to the anaerobic decomposition of algae.

5. Wastewater reuse in agriculture

Wastewater reuse can not only alleviate water scarcity, but it can also relieve pressure on conventional wastewater treatment plants (Ghaitidak and Yadav, 2013). Treated wastewater offers a more sustainable and constant supply in comparison with natural resources, especially when seasonal and climate changes are considered (Zhang and Shen, 2019). Moreover, treated wastewater is rich in inorganic elements and organic compounds that can increase the yield of crops, while reducing the use of fertilizers (Castro et al., 2011). Similar findings were also made by Almuktar et al. (2017), who concluded that nutrients recycled from wastewater resulted in greater weight and dimension of chilies, as previously discussed in section 3.2.

Nevertheless, wastewater could negatively affect irrigated soil and plants, thereby posing a potential threat to the environment and human health. Travis et al. (2010) argued that hydrophobicity development of soil can be a result of the application of raw wastewater directly in irrigation. It can also cause heavy metals accumulation as reported by Gola et al. (2016) and shallow groundwater pollution (Zhang and Shen, 2019). However, using proper wastewater treatment before irrigation can effectively prevent changes in soil properties and diminish environmental risks (Sklarz et al., 2013). Further information on the impact of wastewater reuse on soil and crops can be found in Al-Isawi et al. (2016); Almuktar et al. (2017) and Sklarz et al. (2013).

5.1. EU standards on wastewater reuse for agricultural purposes

Currently, more and more attention is given to wastewater treatment and reuse. Treated wastewater was reused for crop irrigation in many areas of the world (Licata et al., 2017). Specific standards for the use of reclaimed water in agriculture already exist, including those in developed countries (e.g. United States, Israel, Italy, Spain), developing countries (e.g. Egypt, Pakistan, Turkey, Iran, Mexico, Thailand, Colombia) and even some international institutions such as the World Health Organization (WHO). The two major influences on wastewater reuse standards, the WHO and the United States Environmental Protection Agency (USEPA) had an impact on the establishment of standards in several countries (e.g. Spain, France) (Jeong et al., 2016). The European Commission laid down its own regulation on minimum requirements for water reuse (EU, 2020), which were characterized by detailed classification limits based on crop types and irrigation methods (Table 4). WHO (2006) set microbe limits for wastewater reuse in agriculture in order to reduce the human health risk. USEPA (2012) is considered as a very strict standard with low adoption possibilities in developing countries, due to the issues of expensive cost and treatment technologies (Jeong et al., 2016). Interestingly, WHO and EU both proposed different limits according to irrigation methods and crop types, and USEPA (2012) laid down similar thresholds for BOD and TSS as the EU (2020).

Table 5 shows main pollutant concentrations in effluent from 39 studies analyzed in this review. According to the new European criteria, parameters BOD_5, TSS and *E. coli* are classified into different levels corresponding to different agricultural purposes. It can be seen that a majority of studies presented here achieved Class B, C and D (25 mg L^{-1}) for BOD_5 concentration in effluent, that was suitable for irrigation of certain crop types (e.g. industrial, energy, and seeded crops, processed food crops and non-food crops) under any method (Table 4). Furthermore, the better BOD_5 removals were exhibited by the improved single-stage CWs - GROW and RVFCW (Table 5, No. 11, 13) and several multistage hybrid systems (Table 5, No. 22, 23, 28, 32, 36b), which met the strictest standard of irrigation reuse (Class A). As expected, most treatment systems showed good performance on TSS removal leading to low effluent concentrations, except for two hybrid systems (Table 5, No. 27a, 37) exceeding the range of the guideline. The high TSS concentration in research No. 27a can be attributed to algae growth in the lagooning unit. The similar finding was also observed by Jokerst et al. (2011) as reported in section 4.1. Regarding *E. coli*, four studies (Table 5, No. 6, 27b, 33, 36b) met Class A (10 cfu 100 mL^{-1}) of the irrigation limits. Those results can be explained mainly by the positive effects of artificial aeration (Andreo-Martínez et al., 2017), UV treatment (Licciardello et al., 2018; Russo et al., 2019a) and the combination of different treatment systems (Reinoso et al., 2008). However, not many studies can achieve satisfactory *E. coli* removal without the application of disinfection measures or other chemical agents (Andreo-Martínez et al., 2017). Moreover, several researchers indicated that in order to

Table 4
The European guidelines on pollutants threshold values of reclaimed water for agricultural irrigation (EU, 2020).

Pollutants	Reclaimed water quality class			
	Class A	Class B	Class C	Class D
E. coli (cfu 100 mL^{-1})	10	100	1000	10000
BOD_5 (mg L^{-1})	10	25	25	25
TSS (mg L^{-1})	10	35	35	35

Class A: All food crops, including root crops consumed raw and food crops where the edible portion is in direct contact with reclaimed water. Irrigation method: All irrigation methods allowed.

Class B: Food crops consumed raw where the edible portion is produced above ground and is not in direct contact with reclaimed water, processed food crops, non-food crops including crops to feed milk- or meat-producing animals. Irrigation method: All irrigation methods allowed.

Class C: Crop category applicable is the same as Class B. Irrigation method: Drip irrigation or other irrigation method that avoids direct contact with the edible part of the crop.

Class D: Industrial, energy, and seeded crops. Irrigation method: All irrigation methods allowed.

Table 5
The mean effluent concentration of tested main pollutants of analyzed systems and the class level for agricultural purpose of treated wastewater according to parameters BOD_5, TSS and *E. coli* referring to the guidelines of EU (2020).

System No.	Effluent concentration								
Parameters required by EU (2020)						Other parameters			
	E. coli (cfu 100 mL^{-1} unless stated otherwise)	Class	BOD_5 (mg L^{-1})	Class	TSS (mg L^{-1})	Class	COD (mg L^{-1})	TN (mg L^{-1})	TP (mg L^{-1})
1	–	–	12.2	B, C, D	–	–	21.1	–	–
2	–	–	–	–	7.4	A	28.6	10.8	–
3	–	–	49	None	–	–	61.5	–	–
4	–	–	3.9	A	–	–	16.5	–	–
5	–	–	21.7	B, C, D	29.7	B, C, D	57.8	32.9	6.1
6	~0	A	16.5	B, C, D	<20	B, C, D	100.3	16.1	1
7	–	–	–	–	–	–	–	–	–
8	1.1×10^3 MPN 100 mL^{-1}	–	13.2	B, C, D	8.5	A	30.6	–	0.4–2
9	2.3 log MPN 100 mL^{-1}	–	–	–	–	–	48	62	7
10	–	–	19.1	B, C, D	7.1	A	51	–	–
11	–	–	<10	A	–	–	<20	–	0.8–1.4
12	–	–	–	–	–	–	–	–	–
13	–	–	1.2	A	8.5	A	38	0.5	7.9
14	–	–	–	–	–	–	–	11.2	0.35
15	–	–	–	–	–	–	–	10.8	–
16	–	–	16.2	B, C, D	–	–	79.46	–	–
17	–	–	14.4–96	B, C, D	21.34–127.6	B, C, D	42–336	–	–
18	1×10^3	C	<11.2	A, B	–	–	<33.9	–	–
19	–	–	16.8	B, C, D	8.2	A	–	3.4	1.4
20	–	–	17	B, C, D	–	–	99	–	–
21	–	–	–	–	–	–	62.3	8	0.1
22	–	–	7.7	A	2.6	A	39	6.5	2.8
23	<40	B	4	A	3	A	43	2.2	3.1
24	–	–	46	None	–	–	58	–	–
25	–	–	–	–	–	–	22.4	–	2.1
26	9.2×10^4	None	–	–	2.5–11.2	A, B, C, D	0–19.2	–	–
27a	1.8 log	B	21	B, C, D	39	None	33	10.6	5.2
27b	<1 log	A	–	–	–	–	–	–	–
28	–	–	5	A	8.9	A	25	25.3	6.5
29	–	–	25.3	None	–	–	100.8	–	3.1
30	–	–	11	B, C, D	5.6	A	28.4	26.2	–
31	–	–	21	B, C, D	8	A	73	–	–
32	–	–	3.2	A	–	–	8.8	4	–
33	3.23	A	–	–	–	–	–	–	–
34	–	–	18	B, C, D	7.6	A	18	–	8.9
35	1.11×10^3 MPN 100 mL^{-1}	–	–	–	4.1–4.6	A	35–56.9	58.6–111.6	5.5–12.2
36a	34	B	10.3	B, C, D	8.3	A	24.1	–	4.6
36b	1.6	A	6.3	A	7.7	A	18.3	–	4.8
37	–	–	30	None	84	None	47	–	–
38	–	–	20.2	B, C, D	14.9	B, C, D	48.9	–	2.9
39	–	–	48.8	None	8.46	A	138.3	45.2	8

In the studies (No. 16, 17, 18, 20, 35 and 37) when the research tested more than one hybrid system, the one with the least pollutants concentrations was reported in this table.

improve effluent quality and reach the recommended criteria for agricultural reuse, at least two stages of wastewater treatment in hybrid systems are required for pathogens removal (Toscano et al., 2015; Zurita and White, 2014). In terms of COD and TN, effluent concentrations varied considerably among various systems (Table 5). As concluded in section 3.3, artificial aeration and recirculation treatment can improve the removal of nutrients and organics, respectively. Furthermore, as reported in section 4.2, plants could also be beneficial for removing both pollutants.

6. Discussion on main findings

With respect to the performance of single-stage CWs, it was observed that VSSF CWs had greater efficiency in organic matter removal than HSSF CWs, as the design of VSSF systems provided higher oxygen concentration needed for aerobic degradation of organic matter (Abou-Elela and Hellal, 2012). Nutrient removal rates of the systems varied widely. The best performing system was that of Andreo-Martínez et al. (2017), probably due to the adoption of influent aeration, long HRT and the use of BFS as substrate. As for microbiological indicators, the systems that showed better performance were those with longer HRT (Ayaz, 2008) and elevated oxygen concentration (Abou-Elela and Hellal, 2012). Additionally, most single-stage CWs reached high efficiency (around 90%) for solids removal. It was concluded that the improved systems GROW and RVFCW had better treatment effects than conventional HSSF and VSSF CWs. Continuous recirculation can improve organics abatement (Sklarz et al., 2009), while the aeration can help to reduce the concentrations of nutrients, turbidity, TSS and organics (Andreo-Martínez et al., 2017; Sklarz et al., 2009).

The hybrid systems performed well in microbial and TSS removal. In terms of nutrients, the performance of hybrid systems differed greatly (similarly to single CWs), with TN and TP removal ranging from 29.5% to 94% and from 7% to 82.8%, respectively. However, they usually showed better overall organics removal rates than single-stage CWs, due to the integration of various technologies and the combination of different types of CWs (Ayaz et al., 2015; García et al., 2013; Gikas and

Tsihrintzis, 2012). For example, the application of anaerobic reactors optimized the removal of SS and organic matter (Ayaz et al., 2015; Ávila et al., 2016), while the use of UV treatment increased microbial removals (Horn et al., 2014; Russo et al., 2019a; Sklarz et al., 2013).

In addition, seasonal variation was shown to affect pollutant removal (organics, microbes and nutrients) and the greatest efficiency was usually achieved in summer (Ali et al., 2018; Ayaz, 2008; Kim et al., 2016; Morató et al., 2014; Ramprasad et al., 2017). The presence of plants had contradictory effects. They could be beneficial for removal of organics, nitrogen and phosphorus, especially after they were fully established (Abou-Elela and Hellal, 2012; Garca et al., 2013; Gikas and Tsihrintzis, 2012; Haghshenas-Adarmanabadi et al., 2016; Morari and Giardini, 2009; Toscano et al., 2015). However, it was noted that they could also have negative effects on treatment performance due to greater ET values (Toscano et al., 2015), increased concentration of TSS and organics and limited nutrients removal due to algae growth (Jokerst et al., 2011; Russo et al., 2019a). Furthermore, it was unclear whether single plant species had a different effect on pollutant removal rates (Fountoulakis et al., 2017; Morari and Giardini, 2009). Regarding the substrate type, it has been demonstrated that the ones with higher porosity, small media size and good compressibility were more likely to achieve high removal efficiency (Gikas and Tsihrintzis, 2012; Herrera-Melián et al., 2018; Herrera-Melián et al., 2010).

The reuse potential of effluent coming from the 39 treatment systems is largely different. Their effluent quality was within a wide range, and it could not always meet the new European standards for agricultural reuse. Both improved single-stage CWs and multistage hybrid systems generally had better possibilities to produce effluents with lower BOD_5 concentration (class A) than single-stage CWs. Also, hybrid systems showed better overall performance in TSS removal, but *E. coli* concentration could not always be reduced to the level needed for agricultural reuse without the application of specific disinfection measures (Andreo-Martnez et al., 2017). Therefore, additional technologies and treatment steps should be introduced before irrigation in order to decrease the environmental and public health risks (Sklarz et al., 2013).

7. Conclusions

Constructed wetlands are recognized as an effective and inexpensive technology for wastewater treatment. This review analyzed recent experimental studies on single-stage CWs and hybrid systems, that tested different scales, influent strengths, plant species, etc. According to the 39 studies considered, it can be concluded that improved single-stage CWs generally had better removal performances than conventional CWs. The multiple-stage treatment systems (e.g. hybrid CWs), and in particular the combination of additional technologies (e.g. UV treatment, anaerobic reactors) with CWs, were able to further increase and optimize overall removals. The effluent quality of the systems considered was also compared against the new European guidelines for water reuse in agriculture, in order to evaluate the possibility of wastewater treatment systems based on CWs to be used as an additional water source for irrigation. Treated effluents coming from hybrid systems and improved single-stage CWs had greater potential to meet these limits.

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.

Acknowledgements

The authors are grateful for the support from the program of China Scholarship Council (No. 201803250059). This study was carried out within the project “Safe and Sustainable Solutions for the Integrated Use of Non-Conventional Water Resources in the Mediterranean Agricultural Sector (FIT4REUSE)” which has received funding from the Partnership on Research and Innovation in the Mediterranean Area (PRIMA) under grant agreement No 1823. PRIMA is supported by the European Union’s Horizon 2020 research and innovation program. This research was also funded by the Italian Ministry of University and Research (MUR) as part of the PNR 2015–2020 Funding Program within the research project ARS01_00637 “Energie per l’Ambiente TARANTO” (“TARANTO”) approved with Decree n. 2055 dated 02/08/2018.

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