Journal of Environmental Management 187 (2017) 560–570

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Review

Overview of the state of the art of constructed wetlands for decentralized wastewater management in Brazil

A.I. Machado [a, *], M. Beretta [b], R. Fragoso [c], E. Duarte [c]

[a] Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017, Lisboa, Portugal
[b] Departamento de Engenharia Ambiental, Universidade Federal da Bahia, Escola Politécnica, Rua Aristides Novis, 02 Federação, 40210-630, Salvador, BA, Brazil
[c] LEAF, Linking Landscape, Environment, Agriculture and Food, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017, Lisboa, Portugal

ARTICLE INFO

Article history:
Received 27 August 2016
Received in revised form
3 November 2016
Accepted 7 November 2016
Available online 16 November 2016

Keywords:
Constructed wetlands
Macrophytes
Nutrients
Organic matter
Support matrix
Wastewater treatment

ABSTRACT

Conventional wastewater treatment plants (WWTPs) commonly require large capital investments as well as operation and maintenance costs. Constructed wetlands (CWs) appear as a cost-effective treatment, since they can remove a broad range of contaminants by a combination of physical, chemical and biological processes with a low cost. Therefore, CWs can be successfully applied for decentralized wastewater treatment in regions with low population density and/or with large land availability as Brazil. The present work provides a review of thirty nine studies developed on CWs implemented in Brazil to remove wastewater contaminants. Brazil current sanitation data is also considered to evaluate the potential role of CWs as decentralized wastewater treatment. Performance of CWs was evaluated according to (i) type of wetland system, (ii) different support matrix (iii) vegetation species and (iv) removal efficiency of chemical oxygen demand (COD), biological oxygen demand (BOD_5), nitrogen (N), and phosphorus (P). The reviewed CWs in overall presented good efficiencies, whereas H-CWs achieved the highest removals for P, while the higher results for N were attained on VF-CW and for COD and BOD_5 on HF-CW. Therefore, was concluded that CWs are an interesting solution for decentralized wastewater treatment in Brazil since it has warm temperatures, extensive radiation hours and available land. Additionally, the low percentage of population with access to the sewage network in the North and Northeast regions makes these systems especially suitable. Hence, the further implementation of CW is encouraged by the authors in regions with similar characteristics as Brazil.

Contents

1. Introduction 561
2. Methodology 562
   2.1. Sanitation data in Brazil 562
   2.2. Studies selection 562
   2.3. Data analysis and procedure 562
3. Results and discussion 562
   3.1. Current sanitation scenario in Brazil 562
   3.2. Constructed wetland systems in Brazil 563
   3.3. Contaminants and organic loads removals 564
      3.3.1. Effect of the support matrix 564
      3.3.2. Effect of the macrophytes 565
      3.3.3. Effect of system design 566
4. Conclusion 567

* Corresponding author.
E-mail address: isabellmachado@gmail.com (A.I. Machado).

http://dx.doi.org/10.1016/j.jenvman.2016.11.015
0301-4797/

Acknowledgement 568
References 568
Further reading 570

1. Introduction

Water pollution has always been an important concern since it directly affects human health. Wastewater treatment plants (WWTPs) while effective systems to remove pollutants, commonly require large capital investments as well as operation and maintenance costs. Constructed wetlands (CWs) appear as a cost-effective treatment, since they can remove a broad range of contaminants by applying a combination of physical, chemical and biological process (Matamoros et al., 2005) and at the same time presenting low cost. Additionally, compared to conventional WWTPs they have a lower visual impact and lead to the production of smaller quantities of sewage sludge (Vymazal and Kröpfelová, 2008). These systems are particularly interesting to treat wastewater from small and rural communities that are isolated from the main municipality's sewage system, because they can operate with low energy consumption and do not need highly qualified operators (Vymazal and Kröpfelová, 2008). CWs are a land intensive treatment process, where the ratio of square meters per person will depend of the CWs type and design (Verlicchi et al., 2013). Therefore, CWs can be successfully applied in countries with low population density and/or with large land availability (Arias and Brown, 2009) as it is the case of Brazil.

CWs have conventionally been classified according to the used macrophytes type and water flow regime (Vymazal and Kröpfelová, 2008; Vymazal, 2007). They can be divided by flow regime in free water surface flow CW (FWS-CW) and subsurface flow CW (SSF-CW), where the later can be subdivided in vertical subsurface flow CW (VF-CW) and horizontal subsurface flow CW (HF-CW). These systems can be coupled, being designated as hybrid constructed wetland systems (H-CW). FWS-CWs can be further classified by dominant macrophyte type as free-floating plants, floating-leaved plants, emergent plants, or submerged plants (Vymazal and Kröpfelová, 2008).

Removal efficiencies in CWs will mostly depend on the hydraulic conductivity of the support matrix, type and amount of microorganisms, oxygen supply for the microorganisms, the substrate chemical characteristics (Saeed and Sun, 2012), as well as the region climate and latitude (Zhang et al., 2015). Temperature can play an important role on the CWs treatment performance, especially between FWS and SSF systems. SSF-CWs show a better insulation capacity being less sensitive to temperatures fluctuations. In contrast, FWS-CWs are more sensitive to solar radiation that can promote higher degradation rates. Furthermore, these systems are particularly effective in regions with warmer climate, as well as in regions with high light radiation to enhance plant growth (Kyambadde et al., 2004). Kivaisi (2001) reports that disease vectors, hazardous animals invasion and odours are important factors to take into account on the type of CW to be selected, especially in developing tropical regions. SSF-CWs will be less prone to insect infestation and odours compared to the open FWS-CWs, a key aspect for nearby population health. However, in terms of lifetime, FWS-CWs have a longer lifespan when compared to SSF-CWs, especially because of the support matrix clogging, one of the main limiting factors of these systems (Saeed and Sun, 2012).

The main difference between the two types of subsurface flow systems is related to the area requirements. HF-CWs have a much higher area demand when compared to VF-CWs, 5 m^2 PE^{-1} and 1–3 m^2 PE^{-1} (PE-person equivalent) respectively. Nevertheless, HF-CWs with the higher area requirement also allows these systems to have a higher flow distance, and hence, more removal potential, compared with VF-CWs. Another main difference is associated to the system feeding, that while HF-CWs are usually used with a continuous flow, the VF-CWs are fed by intermittent pulses (Vymazal, 2011). The later will allow the renovation of oxygen in the support matrix, enhancing the nitrification processes while continuous flow in the HF-CWs will allow the denitrification.

CW can be used as an effective treatment for a wide range of wastewaters: domestic (Fountoulakis et al., 2009; Paulo et al., 2013), municipal (Ávila et al., 2010), industrial (Vymazal, 2014) and agricultural runoff (Vymazal and Březinová, 2015). Likewise, several studies report that CW can also achieve a good efficiency to treat urban stormwater (Schmitt et al., 2015), polluted rivers (Borges et al., 2008; Jia et al., 2014) and reservoirs (Gomes et al., 2014).

CWs are complex systems where their efficiency depends of several variables: inlet contaminants concentrations, the presence of the bacteria in the rhizosphere and physicochemical characteristics such as the hydraulic loading, pH, redox conditions, temperature (Kadlec and Wallace, 2009). To optimize the performance of this treatment system is necessary to take into account variables such as climate conditions (Maine et al., 2007), CW design and selected support matrix, inlet quality and load, as well as the operating conditions (Brix et al., 2011; Saeed and Sun, 2012; Sezerino et al., 2015). Another key factor is to achieve a balance between the CW components macrophytes/microorganisms (Brisson and Chazarence, 2009; Song et al., 2009).

CW components selection is dependent of multiple factors. Several different types of substrates can be used as support matrix in CWs (Dordio and Carvalho, 2013; Vohla et al., 2011). The more common material used in CW are gravel, sand or a mixture of both. These materials are usually selected since they have a combination of high hydraulic conductivity with low prices (Dordio and Carvalho, 2013). According to Brix (1994) wetland aquatic plant have an important role in CW by adding oxygen to the system, improving the media filtration capacity, lowering the clogging formation prospective on HF-CW, increasing the potential area for microorganism growth, stabilize the beds surface, as well as helping to reduce the bed frosting in the cold seasons. Additionally, as part as CW maintenance these plants can be harvest and used for fertilisers or animal feeds. They are highly rich in nutrients and provided that they are without toxic levels of metal and emergent contaminants, is a further economic advantage of these systems. The work Verma and Suthar (2014) that used *Lemna gibba* to polish an urban wastewater, conclude that is was feasible to use the harvest plant for animal feed, being material with high protein and carbohydrate percentage.

These systems as a water pollution treatment have been used in Europe (Haberl et al., 2003) and North America (Vymazal, 2010) for a long time. In the last decades, studies on the application and sustainability of CWs in developing countries started to appear, due to their low cost operation requirements (Zhang et al., 2015) or in countries as China due to the fast increase of water pollution (Zhang et al., 2009). Zhang et al. (2015) report that CWs have a great potential to be implemented in tropical and subtropical regions due to their warmer climate. Furthermore, as Von Sperling and Chemicharo (2005) refer, several of the countries with warm climate are also associated with low Gross National Income (GNI) *per capita*. Recently, some research starts to appear in these countries showing the potential of CWs as low cost water treatment. Examples are the works of Zurita and Carreón-Álvarez (2015), Bustillo-Lecompte et al. (2016), Marrugo-Negrete et al. (2017) and García-García et al. (2016) in Latin America; Kansiime et al. (2005) and Mburu et al. (2013) in Africa; Saeed et al. (2012) and Weragoda et al. (2012) in South Asia and Greenway (2005) in North Australia.

The present work provides a review of the studies developed on CWs implemented in Brazil, to remove wastewater contaminants. Brazil current sanitation data is also considered to evaluate the potential role of CWs as decentralized wastewater treatment. The emphasis of this review is to assess the effect of CW support matrix, macrophyte and flow design types on the removal efficiency of chemical oxygen demand (COD), and biological oxygen demand (BOD_5), nitrogen (N), phosphorus (P), since they are the main target contaminants studied to evaluate CW's performance in Brazil.

2. Methodology

2.1. Sanitation data in Brazil

Sewage system network and treatment data was obtained from the annual report "Diagnóstico dos Serviços de Água e Esgotos" (SNIS, 2014). This document provides the most recent information on Brazil's sanitation based on data collected from 72.4% of the total municipalities covering 92.5% of the urban population. The same report also states that in 2014, Brazil had a total of 202 799 518 inhabitants from which 84.5% lived in urban areas. Values of urban inhabitants with access to sewage network and ratio of treated sewage by sewage produced from the different regions of Brazil were obtained from the Table 11 of the previous referred document.

2.2. Studies selection

The information compiled in this survey was based on thirty nine articles reviewed to assess the use of wetland treatment system to remove water pollutants in Brazil, ranging from 1999 up to 2015. The majority of the articles are from scientific international journals, although seven of the articles are from Brazilian Journals (written in Portuguese) and two are part of conferences proceedings (one presented in the 24th *Congresso Brasileiro de Engenharia Sanitária e Ambiental* and the other in the 3rd *International Faecal Sludge Management)*. These reviewed articles were selected taking in account that the featured CW was vegetated and/or comprise a support matrix. Therefore, polishing lagoons or SF-CW without vegetation or comprehensive description of their support matrices were treated as an exception since it does not encompass the main target variables to be screened in the present work.

The four types of CWs, HF-CW, VF-CW, H-CW and SF-CW, were examined in detail. The information collected is summarized in Table 1, including type of influent (source and treatment), CW design and dimensions, CW operational characteristics (flow rate and hydraulic retention time – HRT), as well as their geographic distribution.

2.3. Data analysis and procedure

All provided data from the reviewed studies were obtained and compiled (CW localization, design and dimensions, influent characteristics, type of support matrix and plants used, as well as removal efficiencies). In the reviewed works, pollutant load is expressed using different parameters, therefore, data was grouped in 5 main categories to facilitate comparison: Nitrogen (N), Phosphorus (P), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD_5) and "Others". N group includes the following forms: nitrates, nitrites, ammonia, ammonium, organic nitrogen and total kjeldahl nitrogen. P group comprise both total phosphorous and phosphates. Both COD and BOD_5 stand alone in different groups since they are the most common parameters in the reviewed studies and not always assessed together. The group referred as "Others" encompass the less common parameters (metals, carbon, chlorides, silicon and total phenolic compounds), being only referred in the present review when is evaluated the removal performance of a CW according to the features of their support matrix or the selected plant.

In order to have a valid comparison, the data from the different studies was harmonized to achieve uniformity among the study variables. Averaged values were calculated when replicates treatments were included. Negative removal efficiency values were assumed as zero, reporting that way null removal efficiency for the contaminant.

3. Results and discussion

3.1. Current sanitation scenario in Brazil

Brazil is divided in five regions: North (N); Northeast (NE); Central-west (CWE); Southeast (SE), and South (S) (Fig. 1a). In 2014, 56.5% of Brazil's urban population had access to sewer network being distributed unevenly through the country (Fig. 1b). N region had an extremely low ratio of 10%, where regarding NE, CWE, and S regions these values range between 31 and 53%. SE region which in turn include large metropolitan areas as São Paulo and Rio de Janeiro, presented the highest value of 83%. Related to treated sewage, the regions showed more similar values, reaching the maximum values for SE and CWE where 46% of their sewage produced was treated (Fig. 1c). N region, once more had the lowest value with 14%.

The funding required for continuing building wastewater infrastructures to cover sanitation services in all country is economically infeasible. To address this problem, other infrastructure regional models should be evaluated. Thus, the CWs can be an attractive option, especially in isolated communities where this

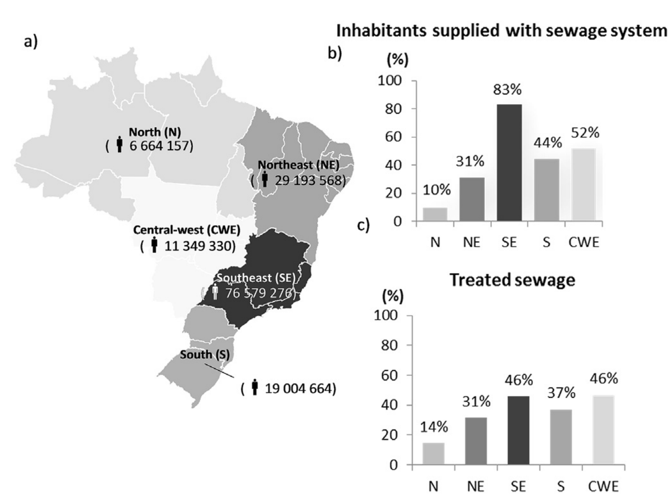

Fig. 1. Brazil 2014 statistics, by regions: Urban population (a), ratio of urban inhabitants with access to sewage network (b) and ratio of treated sewage by sewage produced (c).

service is more challenging to provide sanitation facilities.

3.2. Constructed wetland systems in Brazil

In Brazil the first studies on the use of CWs to treat water pollution were published in the 80's (Salati et al., 1999). However, only in the last decade they have been studied more intensely along the country (Table 1). This recent attention is showed on the review study Sezerino et al., 2015, where the design parameters on HFCW from Brazilian studies were discussed. These works are mainly from academic research projects, covering trials developed on mesocosm prototypes to full-scale systems. Subsurface flow designs are the most common type of CW studied, and only few works evaluate the potential of H-CW (Borges et al., 2008; Fia et al., 2014; Paulo et al., 2013). The majority of the studies are carried out in South and Southeast of Brazil, mainly in the states of Minas Gerais, Santa Catarina and São Paulo. This centralized researched focus, since is carried out by universities and research institutes is eventually

Table 1
Overview of the different CWSs experiments in Brazil: Influent characteristics, CWS design and dimensions.

CW type	Scale	Influent		Design	CW dimensions		Flow rate ($ml\ min^{-1}$)	Brazil region	Reference
		Source	Stage		Total area (m^2)[a]	Total volume (m^3)			
HF-CW	pilot	livestock	primary	1 cell	450	315	n.d.	S	Philippi et al., 1999
	pilot	municipal	secondary	3 parallel cells	10	n.d.	n.d.	NE	Sousa et al., 2004
	real	Domestic industrial	primary	1 cell	299	209.3	n.d.	S	Philippi et al., 2006a
		domestic		1 cell	50	35	n.d.		
		domestic		1 cell	72	50.4	n.d.		
		domestic		1 cell	40.5	28.4	n.d.		
	pilot	industrial	secondary	5 parallel cells	0.75	0.3	n.d.	SE	Fia et al., 2010
	pilot	livestock	secondary	5 parallel cells	26.4	18.48	555.56	SE	Matos et al., 2010
	pilot	municipal	primary	2 parallel cells	72.3	21.7	5902.78	SE	Von Sperling et al., 2010
	pilot	industrial	secondary	3 parallel cells	n.d.	0.9	41.67	SE	Matos et al., 2012
	pilot	industrial	primary aerated	2 parallel cells	1	0.6	13.89	SE	Rossmann et al., 2012 Rossmann et al., 2013
			primary non-aerated	2 parallel cells					
	pilot	domestic	primary	n.d	10	5	666.7	S	Sezerino et al., 2012
	pilot	municipal	primary	3 parallel cells	12	12	10347.2	CWE	Colares and Sandri, 2013
	pilot	municipal	primary	2 parallel cells	72.3	21.7	5902.78	SE	Costa et al., 2013 Dornelas et al., 2009
	pilot	river	raw	8 parallel cells	222.9	6.5	n.d.	NE	Meira et al., 2013
	pilot	municipal	primary	1 cell	24	7.2	3.9	SE	Prata et al., 2013
				1 cell	24	7.2	2		
				1 cell	24	7.2	1		
			preliminary	1 cell	24	7.2	0.75		
	pilot	municipal	primary	3 successive cells	1,52	0.88	100	S	Horn et al., 2014
	pilot	industrial	primary	1 cell	26,5	21.17	n.d.	S	Pelissari et al., 2014
	pilot	domestic	primary	n.d.	n.d.	n.d.	n.d.	CWE	Teodoro et al., 2014
	pilot	municipal	primary	2 parallel cells	75	30	5208.33	SE	Barreto et al., 2015
	pilot	municipal	secondary	2 parallel cells	72,3	21.7	5902.78	SE	Costa et al., 2015
	pilot	livestock	n.d.	1 cell	1	0.6	0.02	SE	Fia et al., 2015
				1 cell	1	0.6	0.04		
				1 cell	1	0.6	0.06		
				1 cell	1	0.6	0.06		
				1 cell	1	0.6	0.02		
				1 cell	1	0.6	0.04		
				1 cell	1	0.6	0.06		
				1 cell	1	0.6	0.08		
	pilot	municipal	primary	1 cell	72.3	21.7	5902.78	SE	Von Sperling, 2015
VF-CW	pilot	livestock	secondary	2 series of 2 parallel cells	7.59	4.92	n.d.	S	Sezerino et al., 2003
	mesocosm	artificial	primary artificial	4 parallel cells	n.d.	0.03	3000	SE	Mant et al., 2006
	pilot	domestic	secondary	1 cell	2.57	n.d.	0.11	S	Philippi et al., 2006b
				1 cell	2.57	n.d.	0.16		
				1 cell	2.57	n.d.	n.d.		
	pilot	domestic	preliminary	1 cell	4.44	4.44	451.39 631.94	S	Platzer et al., 2007
	mesocosm	domestic	tertiary	2 successive cells	0.56	n.d.	1166.7	SE	Paterniani et al., 2011
				2 successive cells	0.56	n.d.			
	pilot	domestic	primary	n.d.	2.27	n.d.	138.9	S	Sezerino et al., 2012
	pilot	municipal	n.d.	n.d.	2.57	n.d.	416.7		
	pilot	domestic	preliminary	2 parallel cells	28.83	n.d.	n.d.	SE	Lana et al., 2013
	mesocosm	livestock	n.d.	4 parallel cells	1.13	0.085	n.d.	SE	Sarmento et al., 2013

(*continued on next page*)

Table 1 (*continued*)

CW type		Scale	Influent		Design	CW dimensions		Flow rate ($ml\ min^{-1}$)	Brazil region	Reference
			Source	Stage		Total area (m^2)[a]	Total volume (m^3)			
		pilot	industrial	primary	1 cell	14.3	11.44	n.d.	S	Pelissari et al., 2014
		full	municipal	primary	2 parallel cells	29.1	n.d.	n.d.	SE	Calderón-Vallejo
		pilot			6 parallel cells	0.0165	n.d.	n.d.		et al., 2015
		pilot	n.d.	primary	1 cell	1.6	n.d.	n.d.		Kafer et al., 2015
		pilot	domestic	raw	2 parallel cells	2	1.4	n.d.	S	Silveira et al., 2015
		pilot	municipal	preliminary	3 parallel cells	28.83	11.532	n.d.	SE	Von Sperling, 2015
		real	domestic	primary	1 cell	189	170.1	n.d.	S	Trein et al., 2015
					1 cell	3141	2826.9	n.d.		
H-CW	SF-CW	pilot	river	raw	1 cell	n.d.	0.25	n.d.	SE	Borges et al., 2008
	SF + HF				2 successive cells	n.d.	0.5	n.d.		
	SF + HF				2 successive cells	n.d.	0.5	n.d.		
	HF	pilot	domestic	primary	2 successive	4.64	1.86	n.d.	CWE	Paulo et al., 2009
	VF				cells	9.88	2.27	n.d.		Paulo et al., 2013
	VF	pilot	livestock	secondary	1 cell	n.d.	0.1	n.d.	SE	Fia et al., 2014
	VF + HF				2 successive cells	n.d.	0.7	n.d.		
SF-CW		pilot	n.d.	secondary	3 parallel cells	24	n.d.	1041.67	SE	Bastos et al., 2010
						24		694.4		
						11.3		1736.1		
		mesocosm	reservoir	preliminary	2 parallel cells	n.d.	1	n.d.	SE	Gomes et al., 2014

[a] Area of each individual cell.

linked to the economic and development indices along the country. From Northeast region only the works of Sousa et al. (2004) and Meira et al. (2013) were reported, while in Central-west region the available data is provided by the studies of Colares and Sandri, 2013, Teodoro et al., 2014 and Paulo et al., 2009, 2013. The exception to this was the North region of Brazil, were no comprehensive study was available.

From the reviewed research it was possible to prepare an overview on the different CWs experiments in Brazil, indicating influent characteristics, CWs design and dimensions (Table 1). The reviewed works show that CWs in Brazil are mostly applied on municipal wastewaters what is probably explained by the reduction in the operation and maintenance costs of the treatment facilities (Siracusa and La Rosa, 2006). However, CWs are more difficult to implement in high-populated cities due to the high area/PE requirement of this type of treatment (Verlicchi et al., 2013). Hence, small communities and low flow in-situ effluent sources (i.e. domestic, industrial, livestock and agriculture) are more appealing for applying CWs as wastewater treatment. Another advantage of their use in domestic sources is the aesthetic element, where flowering aquatic plants can be favoured. Paulo et al. (2009, 2013) in a H-CW consisting of a HF and a VF-CW to treat a domestic effluent of a nine persons-household located in Mato Grosso do Sul, used a combination of flowering plant species such Arundina bambusifolia and Alpinia purpurata, as well as a mixture of Heliconia psittacorum L.F., Cyperus isocladus and Canna sp., achieving good removal efficiency values for both nutrients and organic matter.

CWs can be used as a secondary or tertiary treatment process, receiving the effluents from primary or secondary treatment, respectively (Table 1). The influent source will have an impact on nutrients and organic contaminants loads inputted in the CW system and consequently on cost associated with required area and system's lifetime. CW French systems, comprising a VF-CW, have been applied in Brazil (Silveira et al., 2015), for the treatment of domestic wastewater without previous primary treatment. Nevertheless, a pre-treatment of the influent is desirable to avoid coarse materials or high organic load that can create clogging of the system.

3.3. Contaminants and organic loads removals

3.3.1. Effect of the support matrix

From the reviewed studies, gravel is the most applied type of support matrix in CW followed by sand. Other support matrices commonly used are the mixture of gravel with sand, pea gravel and steel slag (Table 2).

CWs applying gravel can achieve good results for the removal of reviewed contaminants but particularly appear mostly effective for COD and BOD_5. When comparing the different CW studies that used gravel as support matrix, the work Matos et al., 2012 that study the performance of a HF-CW pilot to treat a dairy industrial wastewater achieved the combined highest COD and BOD_5 removal efficiencies, with 95.5 and 93.2% respectively. However, for COD

Table 2
Different support matrix types of support matrix used in CWs of Brazil.

	References
Gravel	Mant et al., 2006; Fia et al., 2010; Matos et al., 2012; Rossmann et al., 2012, 2013; Colares and Sandri, 2013; Lana et al., 2013; Meira et al., 2013; Prata et al., 2013; Sarmento et al., 2013; Gomes et al., 2014; Calderón-Vallejo et al., 2015; Fia et al., 2015
Sand	Sousa et al., 2004; Sezerino et al., 2003, 2012; Meira et al., 2013; Pelissari et al., 2014
Gravel sand	Philippi et al., 2006b; Platzer et al., 2007; Trein et al., 2015
Pea gravel	Borges et al., 2008
Steel slag	Costa et al., 2013, 2015; Dornelas et al., 2009; Von Sperling et al., 2010, 2015; Barreto et al., 2015

alone was the mixture of gravel and sand that had the highest value (99%) being reached by the work Kafer et al., 2015 that used a VF-CW pilot planted with *Zizaniopsis bonarienses.* CWs that use this materials mixture show generally good results for COD, BOD_5 and nutrient removal (Kafer et al., 2015; Paulo et al., 2009, 2013; Platzer et al., 2007; Trein et al., 2015). The study Trein et al. (2015) that explore the use of planted VF-CW as decentralized treatment wastewater system, showed particularly good results for all contaminants, especially in terms of N and P, reaching maximum values of 94 and 93% respectively. The reviewed studies that used sand as support matrix by itself achieved moderate contaminants removal results. The better results were found in the work of Pelissari et al., 2014 where was study the nitrogen transformation in a HF-CW and a VF-CW working in parallel to treat dairy cattle wastewater. HF-CW reached in overall the higher results with 74% of COD removed and the different N fractions achieving the following values: TKN – 59.4%, NH_4 – 58.2% and NO_3 – 40%.

The use of pea gravel in Brazil is only studied in the works of Rossmann et al. (2012, 2013) showing good removal percentages. This experiment compares the influence of aeration in the industrial wastewater influent as well as the presence of vegetation in the nutrients, COD and BOD_5 elimination, while using pea gravel as support material. The results show similar efficiencies for the different variables tested (COD: 87.9–91.5%; BOD_5: 84.4–87.7%; N: 45.3–69.1% and P: 54.3–72.1%), having, in overall, the planted CW with aerated influent slighter better performance.

Steel slag was explored as CW support material in the studies carried out in the Federal University of Minas Gerais (Barreto et al., 2015; Costa et al., 2013; Dornelas et al., 2009; Von Sperling et al., 2010; Von Sperling, 2015). Comparing to the previous referred materials, studies using steel slag as support matrix presented lower performances for nutrients, COD and BOD_5 removal. From those studies, Costa et al., 2015 was the one that presented higher removal efficiencies. The secondary municipal wastewater effluent had reduction of 76 and 71% for COD in planted and unplanted systems respectively. TP also achieved good results with 69% in the CW planted with *Typha latifolia* and 68% for unplanted systems. However, low removals were reached for TN, with 25 and 18% for planted and unplanted systems respectively. In Spain, Blanco et al. (2016) also study the potential of steel slag to be use in CWs and found even more promising results on the removal of P, achieving efficiencies of 84–99%.

Phosphorus removal efficiencies in CWs systems are deeply connected with the presence of substrate, having HF-CWs an advantage in the long-term removal (Luederitz et al., 2001). Vymazal (2007, 2011) reports that unless specific substrates with higher sorption capacity are used, the removal of P is expected to be low. Furthermore, Vymazal (2007) states that the elimination of P from the effluent to be treated is achieved by the process sorption, precipitation, plant uptake and followed harvest, as well as peat/soil accretion. P precipitation occurs in association of the presence of cations such Ca, Al and Fe. While P favours binding with Ca in the presence of high pH conditions, Al and Fe under aerobic conditions, bonds with this nutrient on more acidic environments (Verhoeven et al., 1999). Most of the material used in these systems has high content of Ca and CaO as well as high pH values, enhancing precipitation to be the main removal process for P in the effluent (Vohla et al., 2011).

In Brazil, studies with support matrix performance focus are unusual to be found and from the reviewed studies an example is Paterniani et al. (2011) that compared different composite matrices to be used in a constructed wetland system while treating a domestic effluent. Two column system schemes were tested where one used a slow filtrating system with non-woven synthetic fabric followed by sand and where in the other slow filtrating system was applied a layer of non-woven synthetic fabric followed by sand, activated granular carbon and again a second sand layer. Both systems had a pre-filter composed by boulders. Overall, the higher removal efficiencies for the parameters tested in this study were achieved in the slow filter system that used activated carbon (apparent color – 39.3%; turbidity – 44.0%; total coliform - 70.9% and *Escherichia coli* – 76.7%). However, relatively to the parameters studied in the present review, only the slow system with the non-woven synthetic fabric followed by a sand layer shows efficiency removal values (COD – 33.3%).

3.3.2. Effect of the macrophytes

Table 3 presents the wide variety of plant species applied to these systems in Brazil. This review shows that plants from the family Poaceae are the most commonly used, being the genus *Cynodon spp* the primarily choice in this group. The family Typhaceae is also well represented with *Typha domingensis* and *Typha latifolia* being used both in HF and VF-CWs. The most common type of macrophytes used in CW worldwide is *Phragmites australis* and *Typha spp* (Kadlec and Wallace, 2009; Vymazal, 2013). Characteristic's such as deep rhizome and root system, high potential productivity and worldwide distribution makes plants such *Phragmites australis* a common choice to be used in CWs (Luederitz et al., 2001). In Brazil, this plant is considered naturalized and therefore the preference goes to the native plant *Typha spp*, well adapted to the more warm climates.

In the revised literature few are the studies that focus on the comparison of different types of plants species regarding their effect in removing pollutants. An example is the work Mant et al., 2006, where in a VF-CW mesocosm treating an artificial effluent and using gravel as support matrix, compared the effect of a non-vegetated system with mono-vegetated systems. A clear positive effect for the removal of the Chromium was show with the presence of vegetation, whereas the non-vegetation system only achieved 47.2%. From the different tested plants, *Penisetum purpureum* had the highest removal value with 78.1% follow by *Brachiaria decumbens* (68.5%) and *Phragmite australis* (56.7%). Sarmento et al. (2013) also compared the efficiency of different cultivated species (*Cyperus spp., Hedychium coronarium and Heliconia rostrata*) on removing pollutants where a VF-CW was tested using a swine wastewater. Differences between plants species were not found, however for planted systems, 1.3 times higher TKN removal values were found when compared with the non-vegetated system. Matos et al., 2012, in a HF-CW pilot treating a secondary industrial effluent, showed no effects in the present of vegetation on removing COD and BOD_5. Again similar results were achieved, where a positive effect was only show for TKN removal, while the non-vegetated system attained the low removal value of 29.3% compared to the 70.4% for the system planted with *Cynodon spp* and the 43.3% for the one with *Pennisetum purpureum schum*. The same pattern appears in Lana et al. (2013) that used a VF-CW treating domestic wastewater, pointing out the positive effect of the presence of the *plant Cynodon spp* on removing solids, COD and BOD_5 as well as in increasing the nitrification process and microorganisms growth. However, no substantial effect was visible on phosphorus and *Escherichia coli* between panted and unplanted systems. The better performance results in removing nitrogen from vegetated systems compared to non-vegetated can be related to nitrogen uptake by the plants, as well as by the aerobic process like the microbial ammonium oxidation in the rhizosphere promoted by the oxygen input through the plant (Carranza-Diaz et al., 2014).

Nevertheless, some studies do not encounter this positive effect of vegetation. Costa et al., 2013, 2015 using an HF-CW to treat a primary municipal effluent with steel slag as support matrix did not found any effect in the removal of nutrients, COD and BOD_5

Table 3
Plants family, specie and origin used in the CW from Brazil.

Plant family	Plant	Origin (Brazil)	CWS design	Study
Amaranthaceae	*Alternanthera philoxeroides Griseb*	native	HF	Matos et al., 2010
Zingiberaceae	*Alpinia purpurata*	non-native	VF	Paulo et al., 2013
Orchidaceae	*Arundina bambusifolia*	non-native	VF	Paulo et al., 2013
Poaceae	*Avena strigosa Schreb*	native	HF	Matos et al., 2010
	Brachiaria decumbens	naturalized	VF	Mant et al., 2006
	Brachiaria humidicola	non-native	SSF	Bastos et al., 2010
Cannaceae	*Canna sp.*	native	HF	Paulo et al., 2013
Poaceae	*Cynodon spp*	native	VF	Fia et al., 2014
			HF	Matos et al., 2012
			VF	Calderón-Vallejo et al., 2015
			VF	Lana et al., 2013
			VF	Von Sperling, 2015
			HF	Fia et al., 2015
	Cynodon dactylon Pers.	native	HF	Matos et al., 2010
Cyperaceae	*Cyperus spp.*	native	VF	Sarmento et al., 2013
	Cyperus isocladus	non-native	HF	Paulo et al., 2013
	Cyperus papyrus	native	HF	Sezerino et al., 2012
			VF	Trein et al., 2015
	Cyperus papyrus nanus	n.d.	VF	Trein et al., 2015
Pontederiaceae	*Eichhornia crassipes*	native	SF	Borges et al., 2008
Zingiberaceae	*Hedychium coronarium*	naturalized	VF	Sarmento et al., 2013
Heliconiaceae	*Heliconia psittacorum L.F.*	native	HF	Paulo et al., 2013
				Teodoro et al., 2014
	Heliconia rostrata	native	VF	Sarmento et al., 2013
Xanthorrhoeaceae	*Hemerocallis flava*	non-native	HF	Prata et al., 2013
Poaceae	*Hymenachne grumosa*	native	HF	Horn et al., 2014
Juncus	*Juncus spp.*	native	HF	Sousa et al., 2004
Poaceae	*Lolium multiflorum Lam.*	cultivated	HF	Rossmann et al., 2012·Rossmann et al., 2013
				Fia et al., 2010
	Oryza sativa	cultivated	HF	Meira et al., 2013
	Pennisetum purpureum schum	native	HF	Matos et al., 2012
			VF	Mant et al., 2006
	Phragmites australis	naturalized	VF	Mant et al., 2006
				Silveira et al., 2015
Typhaceae	*Typha spp*	native	VF	Platzer et al., 2007
			VF + HF	Fia et al., 2014
			HF	Bastos et al., 2010
			SF	
	Typha domingensis	native	VF	Philippi et al., 2006a
			VF	Sezerino et al., 2012
			HF	Pelissari et al., 2014
			VF	
	Typha latifolia	native	SSF	Gomes et al., 2014
			HF	Matos et al., 2010
			HF	Costa et al., 2013
			HF	Costa et al., 2015
			HF	Dornelas et al., 2009
			HF	Von Sperling et al., 2010
			HF	Von Sperling, 2015
			HF	Barreto et al., 2015
Poaceae	*Zizaniopsis bonarienses*	native	HF	Fia et al., 2015
			VF	Kafer et al., 2015
			HF	Philippi et al., 2006b
			HF	Philippi et al., 1999

with the presence of the plant *Typha latifolia*. However, Dornelas et al., 2009 with a similar pilot and operation conditions as the previous studies, achieved a positive effect on the removal of both nutrients, COD and BOD_5 with the presence of vegetation. Simple variable alteration in the vast CW design and operation characteristics (i.e. HRT, flow rates and organic load) seems to be capable of deliver a different result, promoting unclear conclusion between studies.

3.3.3. *Effect of system design*

Figs. 2–5 show the removal efficiencies regarding the 4 different types of CW studied for TN, TP, COD, BOD_5 and other contaminants. In overall, SSF-CWs achieved higher removal percentages, especially in terms of COD and BOD_5. HF-CW reaches an average value of 76.5% and 81.5%, while VF-CW attains 61.0% and 67.6% for COD and BOD_5 respectively. SF-CW showed poorer values compared to the others types of CWs due to the average removal efficiencies lower than 20% achieved for nitrogen, COD and BOD_5. H-CWs in the present study achieved the higher removal values for phosphorus, with an average of 83.7%, however showed low removal efficiency for the others studied parameters. In opposition to the present results, the review study Zhang et al. (2015) reported higher removal percentages for H-CWs compared to others CW types, where was attained values of 81.6% and 84.3%, for BOD_5 and COD, respectively. Vymazal (2013) in a review of 60 hybrid constructed wetlands from 24 countries, encounter higher removal efficiencies for TN in H-CWs compared to single VF and HF-CWs, but not for BOD_5, COD, TSS and TP. Vymazal (2007) states that in single-stage constructed wetlands is expected to reach lower removal efficiencies for nitrogen, compared to hybrid systems that combined

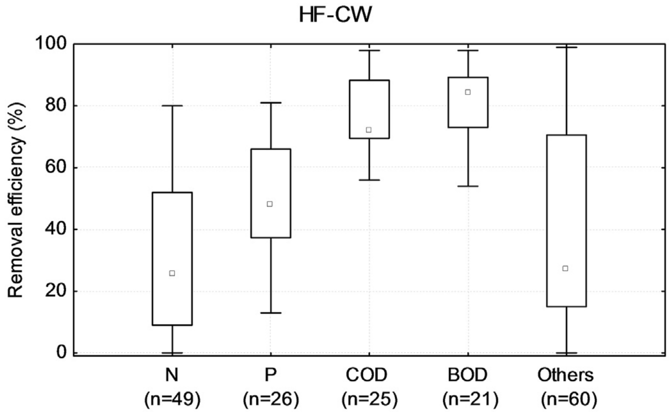

Fig. 2. Horizontal subsurface flow constructed wetland removal efficiency (%) for N, P, COD, BOD_5 and other contaminants (□ median; ○ outliers).

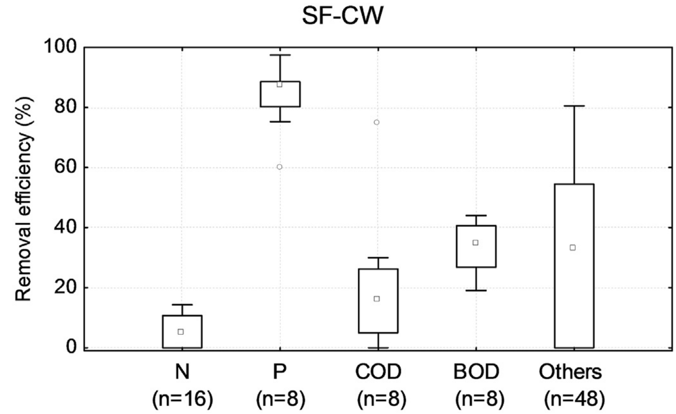

Fig. 5. Surface flow constructed wetland removal efficiency (%) for N, P, COD, BOD_5 and other contaminants (□ median; ○ outliers).

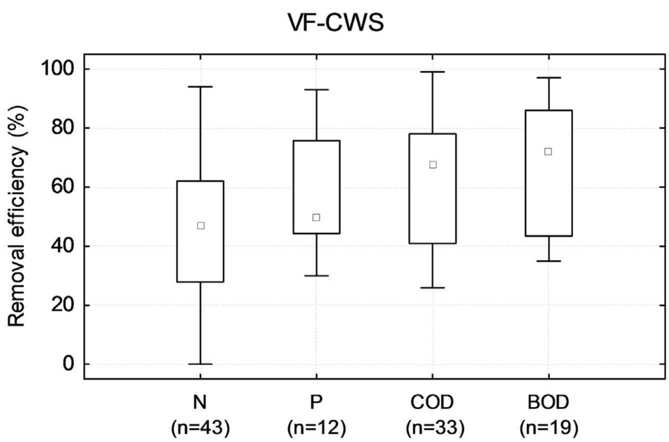

Fig. 3. Vertical subsurface flow constructed wetland removal efficiency (%) for N, P, COD, BOD_5 and other contaminants (□ median; ○ outliers).

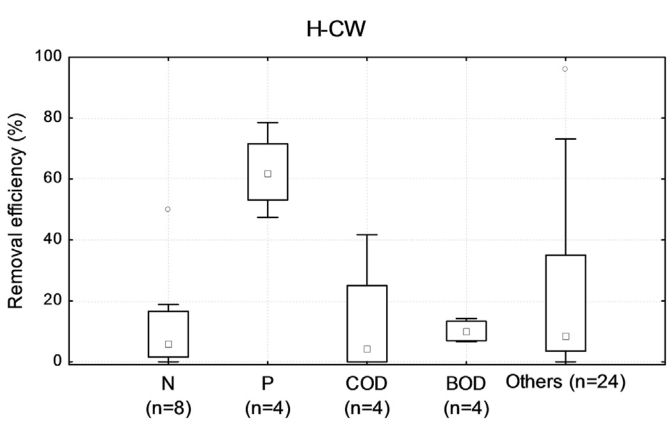

Fig. 4. Hybrid constructed wetland removal efficiency (%) for N, P, COD, BOD_5 and other contaminants (□ median; ○ outliers).

both types of SSF-CWs. Each type of SSF-CW can have different transformation mechanisms, with VF-CW having aerobic conditions that enhance the ammonia-N removal, while HF-CW has an anoxic environment prone to provide successfully denitrification. The nitrogen removal efficiency results showed in the present study comprise several forms of nitrogen as was previous referred in the methodology section. Additionally, several of the present studies report negative nitrogen removal percentages. A clear example is the work developed by Philippi et al. (2006a) where in a VF-CW, planted with *Typha domingensis* in a mixture of sand and gravel as support matrix, was tested the efficiency of the system to remove NH_4^+ from the secondary domestic effluent from WWTP. In the experiment were tested influents with different suspended solids (SS) loads and were achieved good results for nitrification process (with a NH_4^+: minimum removal efficiency of 69.3% for 20 g/m^2.d of SS). Nonetheless, the effluent had an increase of NO_3^- and NO_2^-. Altogether, the low average removal efficiencies for nitrogen seen in the present review can be a result of the removal variations between the different forms of the contaminant.

In terms of phosphorus removal, although VF-CWs showed higher average removal efficiency than HF-CWs, the later had a wider range of variability, being able to reach higher efficiencies. Typically, is expected higher phosphorus removals from SSF-CWs compared to SF-CW (Vymazal, 2010). The study Greenway (2005), carried out in Queensland, Australia, that evaluated the performance efficiency of 7 SF-CWs, encounter very low removal efficiencies for phosphorus, while had good nitrogen removal values. In the present review it is showed the opposite results. However, this contrast can be a result of the low number of studies that portray SF-CWs in comparison with the higher number of studies with SSF-CWs. Furthermore, the differences in the type of influent, organic load as well as other parameters, between the studies that applied SSF-CWs and the works that used SF-CWs can be another possible explanation for these results.

4. Conclusion

The following conclusions can be drawn:

- The most used support matrix in Brazilian CWs studies are gravel and sand, flowed by the mixture of these two materials. Studies applying gravel and the mixture of gravel and sand as support matrix showed good removal efficiencies. However, more highly porous material, easily available and relatively low-priced, should be further explored since there are few studies in Brazil and they could enhance higher removals of phosphorous, extending the CW life-time.
- No clear patterns were found regarding the effect of plant species on contaminants removal efficiency. The wide variety of plants studied in Brazil and the low repetitiveness of studies with the same plant species weakens the high removal results

robustness. Nonetheless, in most of the studies when comparing directly planted and unplanted CW, higher removal efficiencies are attained for the first. These results are clearer in terms of nitrogen removal compared to other pollutants, probably due to the degradation process occurring in the rhizosphere by the symbiosis macrophytes roots/microorganisms.

- In each type of CW certain chemical, physical and biological transformation mechanisms are enhanced, favouring the elimination of some contaminants rather than others. Hybrid CWs would be expected to achieve higher contaminants removal due the possibility of combining aerobic and anaerobic processes. However, in the reviewed studies, these patterns occur only for phosphorus, the highest removal of nitrogen was achieved in VF-CW. COD and BOD_5 had the highest removal for HF-CW. Even so, these results have to be carefully evaluated since the number of studies cases was not the same for each system design. HF-CW and VF-CW are the most used system designs in Brazil, while few are the studies that investigate the potential of hybrid systems or surface flow systems.

CWs are an interesting solution for decentralized wastewater treatment in Brazil since it has warm temperatures, extensive radiation hours and available land. Additionally, the low percentage of population with access to the sewage network in the North and Northeast regions makes these systems especially attractive for these regions. Therefore, as CWs show good contaminants removal efficiencies in the reviewed studies, it is suggested that further research on CWs should be developed, particularly in the above referred regions. Furthermore, the present results show that CWs are also feasible in countries with similar climate, where the extensive radiation hours per day and warm climate can enhance the pollutants removal, taking advantage of native plants locally available.

Acknowledgement

This work was supported by the FCT - Fundação para a Ciência e a Tecnologia (doctoral grant SFRH/BD/52511/2014), inserted in the doctoral program FCT-FLUVIO – River Restoration and Management (Reference: PD/00424/2012).

References

Arias, M.E., Brown, M.T., 2009. Feasibility of using constructed treatment wetlands for municipal wastewater treatment in the Bogotá Savannah, Colombia. Ecol. Eng. 35 (7), 1070–1078. http://dx.doi.org/10.1016/j.ecoleng.2009.03.017.

Ávila, C., Pedescoll, A., Matamoros, V., María, J., García, J., 2010. Capacity of a horizontal subsurface flow constructed wetland system for the removal of emerging pollutants: an injection experiment. Chemosphere 81, 1137–1142. http://dx.doi.org/10.1016/j.chemosphere.2010.08.006.

Barreto, A.B., Vasconcellos, G.R., von Sperling, M., Kuschk, P., Kappelmeyer, U., Vasel, J.L., 2015. Field application of a planted fixed bed reactor (PFR) for support media and rhizosphere investigation using undisturbed samples from full-scale constructed wetlands. Water Sci. Techn 72 (4), 553–560. http://dx.doi.org/10.2166/wst.2015.238.

Bastos, R.K.X., Calijuri, M.L., Bevilacqua, P.D., Rios, E.N., Dias, E.H.O., Capelete, B.C., Magalhães, T.B., 2010. Post-treatment of UASB reactor effluent in waste stabilization ponds and in horizontal flow constructed wetlands: a comparative study in pilot scale in Southeast Brazil. Water Sci. Technol. 61 (4), 995–1002. http://dx.doi.org/10.2166/wst.2010.960.

Blanco, I., Molle, P., Sáenz de Miera, L.E., Ansola, G., 2016. Basic oxygen furnace steel slag aggregates for phosphorus treatment. Evaluation of its potential use as a substrate in constructed wetlands. Water Res. 89, 355–365. http://dx.doi.org/10.1016/j.watres.2015.11.064.

Borges, A.K.P., Tauk-Tornisielo, S.M., Domingos, R.N., Angelis, D.D.F., 2008. Performance of the constructed wetland system for the treatment of water from the Corumbataí River. Braz Arch. Biol. Technol. 51 (6), 1279–1286. http://dx.doi.org/10.1590/S1516-89132008000600024.

Brisson, J., Chazarence, F., 2009. Maximizing pollutant removal in CWs: should we pay more attention to macrophyte species selection. Sci. Total Environ. 407, 3923–3930. http://dx.doi.org/10.1016/j.scitotenv.2008.05.047.

Brix, H., 1994. Functions of macrophytes in constructed wetlands. Water Sci. Techn 29 (4), 71–78. http://dx.doi.org/10.1016/S0273-1223(97)00047-4.

Brix, H., Koottatep, T., Fryd, O., Laugesen, C.H., 2011. The flower and the butter fly constructed wetland system at Koh Phi Phie - system design and lessons learned during implementation and operation. Ecol. Eng. 37 (5), 729–735. http://dx.doi.org/10.1016/j.ecoleng.2010.06.035.

Bustillo-Lecompte, C.F., Mehrvar, M., Quiñones-Bolaños, E., Castro-Faccetti, C.F., 2016. Modeling organic matter and nitrogen removal from domestic wastewater in a pilot-scale vertical subsurface flow constructed wetland. J. Environ. Sci. Health - Part A 51 (5), 414–424. http://dx.doi.org/10.1080/10934529.2015.1120528.

Calderón-Vallejo, L.F., Andrade, C.F., Manjate, E.S., Madera-Parra, C.A., Von Sperling, M., 2015. Performance of a system with full- and pilot-scale sludge drying reed bed units treating septic tank sludge in Brazil. Water Sci. techn. 71 (12), 1751–1759. http://dx.doi.org/10.1080/09593330.2012.724210.

Carranza-Diaz, O., Schultze-Nobre, L., Moeder, M., Nivala, J., Kuschk, P., Koeser, H., 2014. Removal of selected organic micropollutants in planted and unplanted pilot-scale horizontal flow constructed wetlands under conditions of high organic load. Ecol. Eng. 71, 234–245. http://dx.doi.org/10.1016/j.ecoleng.2014.07.048.

Colares, C.J.G., Sandri, D., 2013. Eficiência do tratamento de esgoto com tanques sépticos seguidos de leitos cultivados com diferentes meios de suporte. Revista Ambiente Água 8 (1), 172–185.

Costa, J.F., Paoli, A.C., Seidl, M., von Sperling, M., 2013. Performance and behaviour of planted and unplanted units of a horizontal subsurface flow constructed wetland system treating municipal effluent from a UASB reactor. Water Sci. Techn 68 (7), 1495–1502. http://dx.doi.org/10.2166/wst.2013.391.

Costa, J.F., Martins, W.L.P., Seidl, M., von Sperling, M., 2015. Role of vegetation (Typha latifolia) on nutrient removal in a horizontal subsurface-flow constructed wetland treating UASB reactor–trickling filter effluent. Water Sci. Techn 71 (5), 1004–1010. http://dx.doi.org/10.2166/wst.2015.055.

Dordio, A.V., Carvalho, A.J.P., 2013. Organic xenobiotics removal in constructed wetlands, with emphasis on the importance of the support matrix. J. Hazard. Mater 252–253, 272–292. http://dx.doi.org/10.1016/j.jhazmat.2013.03.008.

Dornelas, F.L., Machado, M.B., Von Sperling, M., 2009. Performance evaluation of planted and unplanted subsurface-flow constructed wetlands for the post-treatment of UASB reactor effluents. Water Sci. Techn 60 (12), 3025–3033. http://dx.doi.org/10.2166/wst.2009.743.

Fia, R., Matos, A.T., Lambert, T.F., Fia, F.R.L., Matos, M.P., 2010. Tratamento das águas do processamento dos frutos do cafeeiro em filtro anaeróbio seguido por sistema alagado construído: II - Remoção de nutrientes e compostos fenólicos. Eng. Agrícola 30, 1203–1213.

Fia, R., Vilas Boas, R.B., Campos, A.T., Fia, F.R.L., Souza, E.G., 2014. Removal of nitrogen, phosphorus, copper and zinc from swine breeding waste water by bermudagrass and cattail in constructed systems. Eng. Agric. Jaboticabal 34 (1), 112–123. http://dx.doi.org/10.1017/CBO9781107415324.004.

Fia, F.R.L., Matos, A.T., Fia, R., Borges, A.C., Abreu, E.C., 2015. Influência da carga de nutrientes e da espécie cultivada na remoção de K, Na, Cu e Zn da água residuária da suinocultura tratada em sistemas alagados construídos. Revista Ambiente Água 10, 542–553.

Fountoulakis, M.S., Terzakis, S., Kalogerakis, N., Manios, T., 2009. Removal of polycyclic aromatic hydrocarbons and linear alkylbenzene sulfonates from domestic wastewater in pilot constructed wetlands and a gravel filter. Ecol. Eng. 35, 1702–1709. http://dx.doi.org/10.1016/j.ecoleng.2009.06.011.

García-García, P.L., Ruelas-Monjardín, L., Marín-Muñíz, J.L., 2016. Constructed wetlands: a solution to water quality issues in Mexico? Water Policy 18 (3), 654–669. http://dx.doi.org/10.2166/wp.2015.172.

Gomes, M.V.T., Souza, R.R., Teles, V.S., Mendes, É.A., 2014. Phytoremediation of water contaminated with mercury using Typha domingensis in constructed wetland. Chemosphere 103, 228–233. http://dx.doi.org/10.1016/j.chemosphere.2013.11.071.

Greenway, M., 2005. The role of constructed wetlands in secondary effluent treatment and water reuse in subtropical and arid Australia. Ecol. Eng. 25 (5), 501–509. http://dx.doi.org/10.1016/j.ecoleng.2005.07.008.

Haberl, R., Grego, S., Langergraber, G., Kadlec, R.H., Cicalini, A.R., Dias, S.M., Hebner, A., 2003. Constructed wetlands for the treatment of organic pollutants. J. Soils Sediments 3 (2), 109–124. http://dx.doi.org/10.1007/BF02991077.

Horn, T.B., Zerwes, F.V., Kist, L.T., Machado, Ê.L., 2014. Constructed wetland and photocatalytic ozonation for universitysewage treatment. Ecol. Eng. 63, 134–141.

Jia, H., Sun, Z., Li, G., 2014. A four-stage constructed wetland system for treating polluted water from an urban river. Ecol. Eng. 71, 48–55. http://dx.doi.org/10.1016/j.ecoleng.2014.07.013.

Kadlec, R.H., Wallace, S.D., 2009. Treatment Wetlands. CRC Press, Boca Raton, FL. ISBN: 978-1-56670-526-4.

Kafer, S.C., Magri, M.E., Zaguini, J.G., Philippi, L.S., 2015. Application of high organic loading rate in sludge treatment wetlands as an option for developing countries with tropical as sub-tropical climate. In: 3rd International Faecal Sludge Managemente Conference-FSM3, Hanoi/Vietnã.

Kansiime, F., Oryem-Origa, H., Rukwago, S., 2005. Comparative assessment of the value of papyrus and cocoyams for the restoration of the Nakivubo wetland in Kampala, Uganda. Phys. Chem. Earth 30 (11–16), 698–705. http://dx.doi.org/10.1016/j.pce.2005.08.010.

Kivaisi, A.K., 2001. The potential for constructed wetlands for wastewater treatment and reuse in developing countries: a review. Ecol. Eng. 16 (4), 545–560. http://

dx.doi.org/10.1016/S0925-8574(00)00113-0.
Kyambadde, J., Kansiime, F., Gumaelius, L., Dalhammar, G., 2004. A comparative study of Cyperus papyrus and Miscanthidium violaceum-based constructed wetlands for wastewater treatment in a tropical country. Water Res. 38, 475–485. http://dx.doi.org/10.1016/j.watres.2003.10.008.
Lana, L.C.O., Moraes, D.C., von Sperling, M., Morato, M.L.N., Vasconcellos, G.R., Paraense, M.O., Moreira, T.P.A., 2013. Performance of a single stage vertical flow constructed wetland system treating raw domestic sewage in Brazil. Water Sci. Technol. 68 (7), 1599–1606. http://dx.doi.org/10.2166/wst.2013.408.
Luederitz, V., Eckert, E., Lange-Weber, M., Lange, A., Gersberg, R.M., 2001. Nutrient removal efficiency and resource economics of vertical flow and horizontal flow constructed wetlands. Ecol. Eng. 18, 157–171. http://dx.doi.org/10.1016/S0925-8574(01)00075-1.
Maine, M.A., Suñe, N., Hadad, H., Sánchez, G., 2007. Temporal and spatial variation of phosphate distribution in the sediment of a free surface water constructed wetland. Sci. Tot. Environ. 380 (1–3), 75–83. http://dx.doi.org/10.1016/j.scitotenv.2006.11.036.
Mant, C., Costa, S., Williams, J., Tambourgi, E., 2006. Phytoremediation of chromium by model constructed wetland. Bioresour. Technol. 97, 1767–1772. http://dx.doi.org/10.1016/j.biortech.2005.09.010.
Marrugo-Negrete, J., Enamorado-Montes, G., Durango-Hernández, J., Pinedo-Hernández, J., Díez, S., 2017. Removal of mercury from gold mine effluents using Limnocharis flava in constructed wetlands. Chemosphere 167, 188–192. http://dx.doi.org/10.1016/j.chemosphere.2016.09.130.
Matamoros, V., García, J., Bayona, J.M., 2005. Behavior of selected pharmaceuticals in subsurface flow constructed Wetlands: a pilot-scale study. Environ. Sci. Technol. 39 (14), 5449–5454. http://dx.doi.org/10.1021/es050022r.
Matos, A.T., Freitas, W.S., Brasil, M.S., Borges, A.C., 2010. Influência da espécie vegetal cultivada nas condições redox de sistemas alagados construídos. Eng. Agríc. Jaboticabal 30 (3), 518–526.
Matos, A.T., Abrahão, S.S., Lo Monaco, P.A.V., 2012. Eficiência de sistemas alagados construídos na remoção de poluentes de águas residuárias de indústria de lacticínios. Eng. Agríc., Jaboticabal 32 (6), 1144–1155. http://dx.doi.org/10.1590/S0100-69162012000600016.
Mburu, N., Tebitendwa, S.M., Rousseau, D.P.L., van Bruggen, J.J.A., Lens, P.N.L., 2013. Performance evaluation of horizontal subsurface flow-constructed wetlands for the treatment of domestic wastewater in the tropics. J. Environ. Eng. 139 (3), 358–367. http://dx.doi.org/10.1061/(ASCE)EE.1943-7870.0000636.
Meira, C.M.B.S., Oliveira, R., Ceballos, B.S.O., Coura, M.A., Nascimento, R.S., 2013. Warm season performance of horizontal subsurface flow constructed wetlands vegetated with rice treating water from an urban stream polluted with sewage. Afr. J. Biotechnol. 12 (25), 3992–3999. http://dx.doi.org/10.5897/AJB2012.2923.
Paulo, P.L., Azevedo, C., Begosso, L., Galbiati, A.F., Boncz, M.A., 2013. Natural systems treating greywater and blackwater on-site: integrating treatment, reuse and landscaping. Ecol. Eng. 50, 95–100. http://dx.doi.org/10.1016/j.ecoleng.2012.03.022.
Paulo, P.L., Begosso, L., Pansonato, N., Shrestha, R.R., Boncz, M.A., 2009. Design and configuration criteria for wetland systems treating greywater. Water Sci. Technol. 60 (8), 2001–2007. http://dx.doi.org/10.2166/wst.2009.542.
Paterniani, J.E.S., Silva, M.J.M., Ribeiro, T.A.P., Barbosa, M., 2011. Pré-filtração em pedregulho e filtração lenta com areia, manta não tecida e carvão activado para polimento de efluentes domésticos tratados em leitos cultivados. Eng. Agríc., Jaboticabal 31 (4), 803–812. http://dx.doi.org/10.1590/S0100-69162011000400018.
Pelissari, C., Sezerino, P.H., Decezaro, S.T., Wolff, D.B., Bento, A.P., Junio, O.C., Philippi, L.S., 2014. Nitrogen transformation in horizontal and vertical flow constructed wetlands applied for dairy cattle wastewater treatment in southern Brazil. Ecol. Eng. 73, 307–310. http://dx.doi.org/10.1016/j.ecoleng.2014.09.085.
Philippi, L.S., Costa, R.H.R., Sezerino, P.H., 1999. Domestic effluent treatment through integrated system of septic tank and root zone. Water Sci. Technol. 40, 125–131. http://dx.doi.org/10.1016/S0273-1223(99)00455-2.
Philippi, L.S., Sezerino, P.H., Bento, A.P., Magri, M.E., 2006a. Vertical flow constructed wetlands for nitrification of anaerobic pond effluent in southern Brazil under differents loading rates. In: 10th International Conference on Wetland Systems for Water Pollution Control, Lisboa: IWA, vol. I, pp. 631–639.
Philippi, L.S., Sezerino, P.H., Panceri, B., Olijnyk, D.P., Kossatz, B., 2006b. Root zone system to treat wastewater in rural areas in south of Brazil. In: 10th International Conference on Wetland Systems for Water Pollution Control, Lisboa: IWA, 2006, vol. II, pp. 901–908.
Platzer, C., Hoffmann, H., Cardia, W., Costa, R.H.R., 2007. Sizing of a vertical flow wetland for nitrification - adaption of European design to climatic conditions in Brazil. 24. In: Congresso Brazileiro de Engenharia Sanitária Ambiental (ABES), Belo Horizonte, Brazil.
Prata, R.C.C., Matos, A.T., Cecon, P.R., Lo Monaco, P.A.V., Pimenta, L.A., 2013. Tratamento de esgoto sanitário em sistemas alagados construídos cultivados com Lírio-Amarelo. Eng. Agríc., Jaboticabal 33 (6), 1144–1155. http://dx.doi.org/10.1590/S0100-69162013000600007.
Rossmann, M., de Matos, A.T., Abreu, E.C., e Silva, F.F., Borges, A.C., 2012. Performance of constructed wetlands in the treatment of aerated coffee processing wastewater: removal of nutrients and phenolic compounds. Ecol. Eng. 49, 264–269. http://dx.doi.org/10.1016/j.ecoleng.2012.08.017.
Rossmann, M., Matos, A.T., Abreu, E.C., Silva, F.F., Borges, A.C., 2013. Effect of influent aeration on removal of organic matter from coffee processing wastewater in constructed wetlands. J. Environ. Manage 128, 912–919. http://dx.doi.org/10.1016/j.jenvman.2013.06.045.
Salati Jr., E., Salati, E., Salati, E., 1999. Wetlands projects developed in Brazil. Water Sci. Technol. 40 (3), 19–25.
Saeed, T., Afrin, R., Muyeed, A., Sun, G., 2012. Treatment of tannery wastewater in a pilot-scale hybrid constructed wetland system in Bangladesh. Chemosphere 88, 1065–1073. http://dx.doi.org/10.1016/j.chemosphere.2012.04.055.
Saeed, T., Sun, G., 2012. A review on nitrogen and organics removal mechanisms in subsurface flow constructed wetlands: dependency on environmental parameters, operating conditions and supporting media. J. Environ. Manage 112, 429–448. http://dx.doi.org/10.1016/j.jenvman.2012.08.011.
Sarmento, A.P., Borges, A.C., Matos, A.T., 2013. Effect of cultivated species and retention time on the performance of constructed wetlands. Environ. Technol. 34 (8), 961–965. http://dx.doi.org/10.1080/09593330.2012.724210.
Schmitt, N., Wanko, A., Laurent, J., Bois, P., Molle, P., Mosé, R., 2015. Constructed wetlands treating stormwater from separate sewer networks in a residential Strasbourg urban catchment area: micropollutant removal and fate. J. Environ. Chem. Eng. 3 (4), 2816–2824. http://dx.doi.org/10.1016/j.jece.2015.10.008.
Sezerino, P.H., Reginatto, V., Santos, M.A., Kaiser, K., Kunst, S., Philippi, L.S., Soares, H.M., 2003. Nutrient removal from piggery effluent using vertical flow constructed wetlands in southern Brazil. Water Sci. Technol. 48 (2), 129–135.
Sezerino, P.H., Bento, A.P., Decezaro, S.T., Carissimi, E., Philippi, L.S., 2012. Constructed wetlands and sand filter applied as onsite post-treatment of anaerobic effluent. Water Pract. techn. 7, 1–9. http://dx.doi.org/10.2166/wpt.2012.047.
Sezerino, P.H., Alessandra Pellizaro Bento, A.P., Decezaro, S.T., Magri, M.E., Philippi, L.S., 2015. Experiências brasileiras com wetlands construídos aplicados ao tratamento de águas residuárias: parâmetros de projeto para sistemas horizontais. Eng. Sanit. Ambient. 20 (1), 151–158. http://dx.doi.org/10.1590/S1413-41522015020000096615.
Silveira, D.D., Filho, P.B., Philippi, L.S., Kim, B., Molle, P., 2015. Influence of partial saturation on total nitrogen removal in a single-stage French constructed wetland treating raw domestic wastewater. Ecol. Eng. 77, 257–264. http://dx.doi.org/10.1016/j.ecoleng.2015.01.040.
Sistema Nacional de Informações sobre Saneamento, 2014. Diagnóstico dos Serviços de Água e Esgotos – 2013. SNSA/MCIDADES, Brasília.
Siracusa, G., La Rosa, A.D., 2006. Design of a constructed wetland for wastewater treatment in a Sicilian town and environmental evaluation using the emergy analysis. Ecol. Model 197, 490–497. http://dx.doi.org/10.1016/j.ecolmodel.2006.03.019.
Song, H.-L., Nakano, K., Taniguchi, T., Nomura, M., Nishimura, O., 2009. Estrogen removal from treated municipal effluent in small-scale constructed wetland with different depth. Bioresour. Technol. 100, 2945–2951. http://dx.doi.org/10.1016/j.biortech.2009.01.045.
Sousa, J.T., Haandel, A., Lima, E.P.C., Henrique, I.N., 2004. Utilização de wetland construído no pós-tratamento de esgotos domésticos pré-tratados em reator UASB. Eng. Sanit. Ambient. 9 (4), 285–290. http://dx.doi.org/10.1590/S1413-41522004000400004.
Teodoro, A., Boncz, M., Júnior, A., Paulo, P., 2014. Disinfection of greywater pre-treated by constructed wetlands using photo-Fenton: influence of pH on the decay of Pseudomonas aeruginosa. J. Environ. Chem. Eng. 2, 958–962. http://dx.doi.org/10.1016/j.jece.2014.03.013.
Trein, C.N., Pelissari, C., Hoffmann, H., Platzer, C.J., Sezerino, P.H., 2015. Tratamento descentralizado de esgotos de empreendimentos comercial e residencial empregando a ecotecnologia dos wetlands construídos, 15(4). Ambiente Construído, Porto Alegre, pp. 351–367. http://dx.doi.org/10.1590/s1678-86212015000400055.
Verlicchi, P., Galletti, A., Petrovic, M., Barceló, D., Al Aukidy, M., Zambello, E., 2013. Removal of selected pharmaceuticals from domestic wastewater in an activated sludge system followed by a horizontal subsurface flow bed — analysis of their respective contributions. Sci. Total Environ. 454–455, 411–425. http://dx.doi.org/10.1016/j.scitotenv.2013.03.044.
Verma, R., Suthar, S., 2014. Synchronized urban wastewater treatment and biomass production using duckweed Lemna gibba L. Ecol. Eng. 64, 337–343. http://dx.doi.org/10.1016/j.ecoleng.2013.12.055.
Verhoeven, J.T.A., Arthur, F.M., Meuleman, A.F.M., 1999. Wetlands for wastewater treatment: opportunities and limitations. Ecol. Eng. 12 (1–2), 5–12. http://dx.doi.org/10.1016/S0925-8574(98)00050-0.
Vohla, C., Kõiv, M., Bavor, H.J., Chazarenc, F., Mander, Ü., 2011. Filter materials for phosphorus removal from wastewater in treatment wetlands - a review. Ecol. Eng. 37, 70–89. http://dx.doi.org/10.1016/j.ecoleng.2009.08.003.
Von Sperling, M., Chemicharo, C.A.L., 2005. Biological Wastewater Treatment in Warm Climate Regions. IWA Publishing, London.
Von Sperling, M., Dornelas, F.L., Assunção, F.A.L., de Paoli, A.C., Mabub, M.O.A., 2010. Comparison between polishing (maturation) ponds and subsurface flow constructed wetlands (planted and unplanted) for the post-treatment of the effluent from UASB reactors. Water Sci. Technol. 61 (5), 1201–1209. http://dx.doi.org/10.2166/wst.2010.961.
Von Sperling, M., 2015. Comparison of simple, small, full-scale sewage treatment systems in Brazil: UASB–maturation ponds–coarse filter; UASB–horizontal subsurface-flow wetland; vertical-flow wetland (first stage of French system). Water Sci. Technol. 71(3), 329. http://dx.doi.org/10.2166/wst.2014.496.
Vymazal, J., 2007. Removal of nutrients in various types of constructed wetlands. Sci. Total Environ. 380, 48–65. http://dx.doi.org/10.1016/j.scitotenv.2006.09.014.
Vymazal, J., 2010. Constructed wetlands for wastewater treatment. Water 2, 530–549. http://dx.doi.org/10.3390/w2030530.
Vymazal, J., 2011. Constructed wetlands for wastewater treatment: five decades of

experience. Environ. Sci. Technol. 45, 61–69. http://dx.doi.org/10.1021/es101403.
Vymazal, J., 2013. The use of hybrid constructed wetlands for wastewater treatment with special attention to nitrogen removal: a review of a recent development. Water Res. 47, 4795–4811. http://dx.doi.org/10.1016/j.watres.2013.05.029.
Vymazal, J., 2014. Constructed wetlands for treatment of industrial wastewaters: a review. Ecol. Eng 73, 724–751. http://dx.doi.org/10.1016/j.ecoleng.2014.09.034.
Vymazal, J., Březinová, T., 2015. The use of constructed wetlands for removal of pesticides from agricultural runoff and drainage: a review. Environ. Int. 75, 11–20. http://dx.doi.org/10.1016/j.envint.2014.10.026.
Vymazal, J., Kröpfelová, L., 2008. Wastewater Treatment in Constructed Wetlands with Horizontal Sub-surface Flow. Springer, The Netherlands. http://dx.doi.org/10.1007/978-1-4020-8580-2.
Weragoda, S.K., Jinadasa, K.B.S.N., Zhang, D.Q., Gersberg, R.M., Tan, S.K., Ng, W.J., 2012. Tropical application of floating treatment wetlands. Wetlands 32 (5), 955–961.
Zhang, D., Gersberg, R.M., Keat, T.S., 2009. Constructed wetlands in China. Ecol. Eng. 35, 1367–1378. http://dx.doi.org/10.1016/j.ecoleng.2009.07.007.
Zhang, D.-Q., Jinadasa, K.B.S.N., Gersberg, R.M., Liu, Y., Tan, S.K., Ng, W.J., 2015. Application of constructed wetlands for wastewater treatment in tropical and subtropical regions (2000–2013). J. Environ. Sci. 30, 30–46. http://dx.doi.org/10.1016/j.jes.2014.10.013.
Zurita, F., Carreón-Álvarez, A., 2015. Performance of three pilot-scale hybrid constructed wetlands for total coliforms and Escherichia coli removal from primary effluent - a 2-year study in a subtropical climate. J. Water Health 13 (2), 446–458. http://dx.doi.org/10.2166/wh.2014.135.

Further reading

Bundschuh, J., Litter, M., Ciminelli, V.S.T., Morgada, M.E., Cornejo, L., Hoyos, S.G., Hoinkis, J., Alarcón-Herrera, M.T., Armienta, M.A., Bhattacharya, P., 2010. Emerging mitigation needs and sustainable options for solving the arsenic problems of rural and isolated urban areas in Latin America - a critical analysis. Water Res. 44 (19), 5828–5845. http://dx.doi.org/10.1016/j.watres.2010.04.001.
Guo, Y.-M., Liu, Y.-G., Zeng, G.-M., Hu, X.-J., Xu, W.-H., Liu, Y.-Q., Huang, H.-J., 2014. An integrated treatment of domestic wastewater using sequencing batch biofilm reactor combined with vertical flow constructed wetland and its artificial neural network simulation study. Ecol. Eng. 64, 18–26. http://dx.doi.org/10.1016/j.ecoleng.2013.12.040.