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Hybrid constructed wetlands for wastewater treatment and reuse in the Canary Islands

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ABSTRACT

The performance of two substrates commonly available in the zone, gravel and lapilli, was tested for their use in hybrid constructed wetland pilot plants for the treatment and reuse of urban wastewater in Gran Canaria, Canary Islands, Spain. The first stage of the systems was a vertical subsurface-flow constructed wetland and the second stage was a horizontal subsurface-flow constructed wetland. Parallel experiments were carried out with one system containing only crushed stone basaltic gravel as substrate and the other with only lapilli, a very porous volcanic sediment. The comparative effect of substrate type, hydraulic loading rate and planting was studied.

Tracer studies indicated that the experimental TRHs were significantly lower than the theoretical ones, particularly for the vertical flow with gravel. Though the vertical flow with lapilli performed better than the one with gravel, the hybrids showed quite similar removals.

Planting or varying the hydraulic loading rate introduced little differences between the vertical flows or the hybrids. Average removals for the gravel-based hybrid constructed wetland were 86% for BOD, 80% for COD, 88% for ammonia-N, 96% for SS and turbidity, 24% for phosphate-P, and 99.5% for *faecal coliforms* and 99.7% for *faecal enterococci*. Thus, it can be concluded that hybrid constructed wetlands proved to be robust configurations for wastewater treatment in the Canary Islands.

1. Introduction

The Canary Islands (Spain) are located in the Atlantic Ocean, about 100 km west of the coast of Morocco. The weather is very stable with moderate temperatures and low rainfall. Consequently, hydraulic resources are reduced by the excessive aquifer exploitation, the rapid demographic increase and the economic development. Thus, wastewater treatment and reuse has become an essential issue in the region, not only for environmental reasons but also as an important water resource for irrigation. In addition to this, 83% of the existing centres of populations of the Archipelago have fewer than 2000 inhabitants (Martín et al., 2007). All these features suggest the great potential of application of the so-called natural wastewater treatment technologies, among which constructed wetlands (CWs) have became one of the most popular.

However, the high evaporation rates of CWs compared to those of ponds and lagoons reduce the potential of water reuse for irrigation. In this case, the use of hybrid CWs (horizontal + vertical flow) has been proposed as a powerful wastewater treatment with reduced water loss (Masi and Martinuzzi, 2007). Other authors have explored the potential of a combination of vertical + horizontal flow hybrid CWs for the removal of total nitrogen. In this case the influent would be nitrified in the first stage of vertical flow and denitrified in the second stage of horizontal flow (Molle et al., 2008).

Different substrates have been employed in the construction of CWs. The substrate (particle size, porosity, chemistry of the particle surface, etc.) will determine the hydraulic performance, ability of the plants to thrive or the possible clogging of the CW. In the Canary Islands, lapilli are cheap and abundant. These black, slightly welded and very vesicular pyroclastic materials are ejected by volcanoes. They are very porous, have a high permeability and a grain size between 2 and 64 mm. These raw materials have been traditionally exploited as aggregates for roads and concrete elements, in agriculture to cover earth surfaces and in industry for building blocks and bricks. A more recent use of lapilli from Gran Canaria has been as filter material in the control of gas emissions (Lomoschitz et al., 2003).

Considering the physical features of lapilli and its low cost in the Canaries, the main goal of this study was to determine and compare the performance of hybrid CWs containing non-stratified gravel or lapilli for the treatment of urban wastewater under the prevailing

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Canarian climatic conditions. For this, two CW pilot plants, each containing only one of the selected substrates were studied in parallel. One of them contained only crushed stone basaltic gravel and the other one contained only lapilli. The comparative effect of planting the system with *Phragmites australis* and *Scirpus* sp. and the variation of the hydraulic loading rate (HLR) was also evaluated.

2. Materials and methods

2.1. Description of the wetlands

The study was carried out at the University Campus of Tafira (28°04′ N, 15°27′ W), in Gran Canaria, Canary Islands, Spain. Two hybrid CW pilot plants were constructed with two different non-stratified substrates: gravel and lapilli. For both systems the first stage was a subsurface vertical flow constructed wetland (VF) and the second stage a subsurface horizontal flow constructed wetland (HF) (Fig. 1). For the gravel system, a 200 L cylindrical recipient was used and for the lapillli system the recipient had a volume of 250 L. The HFs were in each case a rectangular plastic box measuring 1.22 m × 0.55 m × 0.52 m ($L \times W \times H$) containing the same substrate as the corresponding VFs. The substrate depth was 37 cm but the water level was 5 cm below the surface, thus the water depth was 35 cm.

In the HFs, the influent entered at the bottom and the effluent exited at the surface. Coarse substrate (Ø: 5–10 cm) was disposed vertically at the entrance and exit of the HFs to favour water dispersion through the whole substrate and to avoid the clogging of the influent pipe by the filter substrate.

At the beginning of November 2007, the systems were filled with treated wastewater to favour bacterial colonisation. Two weeks later wastewater was started to be pumped into the systems. The influent, raw wastewater from the campus, was pumped into a 500 L deposit, from which a peristaltic pump was employed to apply the desired HLR onto the CWs. In contrast to the usual “cyclic flooding and draining” hydraulic regime applied to VFs, the influent was pumped continuously. Owing to the slightly higher surface of the VF with lapilli, the inflow rate applied to this system was also slightly increased to obtain similar mean HLRs.

The two different substrates employed in this study are commonly available in the Canary Islands due to their volcanic origin. This was an important point as the main goal of this work was to asses the feasibility of building low-cost treatment systems for rural areas of the Archipelago. The main features of both substrates and CWs are shown in Table 1.

Table 1
Features of the substrates employed in the CWs.

	Gravel	*Lapilli*
Type of substrate	Crushed basaltic rock	Rough volcanic sediment
Porosity	49%	54%
Average diameter	6.5 mm	2.7 mm
Granulometric analysis	Gravel: 99.8% Sand: 0.1%	Gravel: 68.9% Sand: 30.9% Mud: 0.2%
d_{10}–d_{60} (mm)	4.11–5.51	1.09–2.53
Surface area (m^2)	*V*: 0.21, *H*: 0.67 *V*+*H*: 0.88	*V*: 0.26, *H*: 0.67 *V*+*H*: 0.93
Depth of substrate (m)	*V*: 0.75, *H*: 0.32	*V*: 0.8, *H*: 0.32

2.2. Experimental design

Wastewater treatment was started during the last week of November 2007. In the first experimental period from December 2007 to the 15th of March 2008, the systems had no plants and the HLR applied was low, 37 (±0.2) mm d^{-1}, corresponding to a nominal HRT of about 6 d (Fig. 2). To determine how the systems responded to a doubled inflow rate, from the 15th of March to June 2008 the applied HLR was high, 79 (±0.7) mm d^{-1} corresponding to an experimental HRT of about 3 d. During the last week of April 2008, the systems were planted. To avoid interferences from the acclimatization and initial growing stages of the plants on the results, the analyses were not re-started until the end of May 2008. During June and July 2008, the HLR was again reduced down to a low HLR, 41 (±0.5) mm d^{-1} to achieve again a theoretical HRT of about 6 d. This last period of low HLR was included to counteract the possible “memory effects” of the previous experimental periods on organic matter and/or SS accumulation, different plant sizes, etc.

2.3. Sampling and laboratory analysis

Most parameter measurements started after 1 month of acclimatization and microbial colonisation, in December 2007. Samples were taken once or twice a week at five points: at the input of the system and at the output of each CW (Fig. 1). Chemical and biological water quality parameters were measured as described by standard methods (APHA, 1998). For the analysis of cations

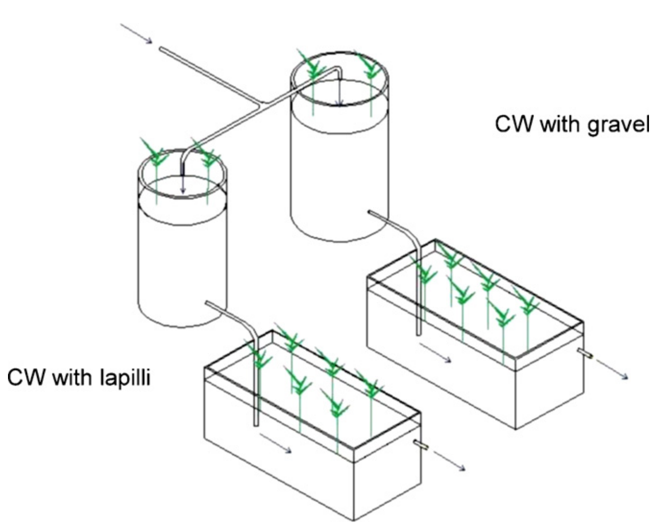

Fig. 1. Schematic representation of the CWs employed in this study.

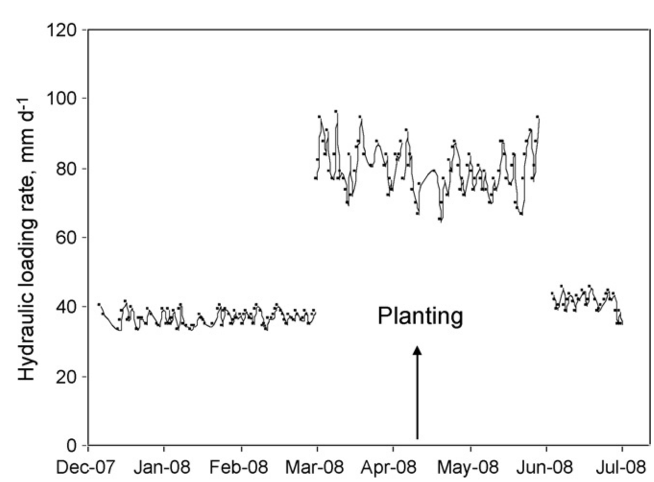

Fig. 2. Temporal variation of the hydraulic loading rate and planting of the CWs.

(NH_4^+, Ca^{2+}, K^+, Mg^{2+} and Na^+) and anions (Cl^-, NO_2^-, NO_3^-, SO_4^{2-} and PO_4^{3-}), an ionic chromatograph Dionex ED50 with an IonPac AS9-HC 4 mm × 250 mm analytical column and equipped with a LD25 oven and an ED50 pump was employed. The mobile phase was 9 mM Na_2CO_3 for anions and 20 mM meta-sulphonic acid for cations. The electrical conductivity (EC) was measured at the outlet point of each reactor employing a conductivity-meter AquaLytic CD-22.

For the analysis of the microbiological parameters, faecal coliforms and enterococci, samples were taken in glass bottles previously sterilized in autoclave (15 min at 120 °C), transported to the laboratory and processed in <3 h.

2.4. Tracer studies

In most chemical reactors, the actual HRT has substantial deviations from the theoretical value caused by canalizations, flow recirculation or creation of the so-called "dead-zones" (Fogler, 2001; Levenspiel, 2004). This experimental or average HRT can be calculated by different ways, being the tracer pulse injection and step the most popular ones. For the theory and mathematical calculations about trace pulse injection for studies in CWs the reader is referred to the above authors in addition to García et al. (2004) and Kim et al. (2007).

To determine the actual HRT of the biological reactors, 5 L of 20 g L^{-1} NaCl were injected into the VFs. After this, EC and flow of the effluents were measured every hour until the EC reached the background level (1.51 mS cm^{-1}). Due to stratification problems with the tracer pulse experiments with the HFs, tracer step experiments were performed with these reactors.

2.5. Dissolved oxygen transfer rate

The theoretical oxygen transfer rate (OTR, g m^{-2} d^{-1}) was calculated according to Cooper (2005), Platzer (1999) and Kantawanichkul et al. (2009):

$$OTR = 0.7[COD_{in} - COD_{out}] + 4.3\,[NH_4\text{-}N_{in} - NH_4\text{-}N_{out}] \quad (1)$$

in which $[COD_{in} - COD_{out}]$ is the COD mass removed (g m^{-2} d^{-1}) and $[NH_4\text{-}N_{in} - NH_4\text{-}N_{out}]$ is the mass of nitrogen (g m^{-2} d^{-1}) nitrified in the beds. The factor 0.7 is included to compensate for the fact that BOD instead of COD is more commonly used in this expression. However OTR values from BOD were also determined for comparison. The factor 4.3 results from the stoichiometry of ammonia oxidation with O_2.

2.6. First order area-based rate constant

The main goals of this study were to determine the performance of vertical and hybrid CWs for the treatment of domestic wastewater under local climatic conditions and using the obtained information for the design of full-scale CWs in the region. In this sense, the most widely accepted model for the design of subsurface-flow CWs is probably the k–C^* first order model (Rousseau et al., 2004; Stein et al., 2006; Jamieson et al., 2007; Zurita et al., 2009). This model requires the determination of k constants which will allow to calculate the required surface area for the full-scale CWs under the same operating conditions (Kadlec, 2000). For this, the following expression (Zurita et al., 2009) was used:

$$k = \frac{365 \times \ln(C_i - C^*)/(C_e - C^*)}{A} \quad (2)$$

where A is the area of the wetland (m^2), Q is the flow rate (m^3 d^{-1}), k is the removal rate constant (m yr^{-1}), C_i is the pollutant concentration in the influent (mg L^{-1}), C^* is the apparent background concentration of the pollutant (mg L^{-1}) and C_e is the target pollutant concentration in the effluent (mg L^{-1}).

2.7. Statistics

The statistical analysis was performed by using the programs R and SPSS (14.0). Significant differences at a confidence level of 95% (p-value < 0.05) between the performances of VFs and also between those of the hybrid CWs, were determined by subtracting those performances (gravel VF–lapilli VF and gravel hybrid–lapilli hybrid) for the periods with/without plants, high/low HLR, and estimating the main effects and the interaction by means of the Yate's algorithm. Such a subtraction would minimize the effect of other variables on the possible differences between the systems compared.

3. Results and discussion

3.1. Tracer experiments

Salt tracer experiments were carried out separately with VFs and HFs. The goal was to determine and compare the actual mean HRT of the wetlands between them, to their theoretical HRT and to determine the hydraulic efficiency (HE) of the VFs used in this study.

The applied inflow rate was the one that gave a theoretical HRT of 3 ± 1 d for each hybrid CW. In the case of the gravel-based CWs, the inflow rate was 66 (±0.77, n: 27) L d^{-1}, and 76 (±0.6, n: 27) L d^{-1} for the lapilli-based CW.

The experiments with the VFs consisted of a pulse of 5 L of 20 g/L NaCl solutions. Electrical conductivity of the effluent was monitored until background values (1510 mS cm^{-1}) were obtained. Fig. 3 shows the obtained results as the normalized EC *versus* time for the vertical CW with gravel and lapilli. The experimental HRTs obtained are indicated with arrows.

In the tracer test experiment with the VFs, tracer recovery was 83% which is lower but comparable to recoveries obtained by other authors such as Lin et al. (2003) who obtained Br^- recoveries in a full-scale experiment of 85–100% or Kim et al. (2007) with Li^+ recoveries between 85% and 97%.

Table 2 shows the theoretical and experimental HRTs for the CWs. The HRT of the VF with gravel was calculated to be 28 h but the tracer study showed an actual or experimental HRT of only 4.1 h. In the case of the VF with lapilli, the theoretical HRT was 34 h and the tracer study showed an actual HRT of only 6.2 h. Singh et al. (2009) observed similar differences among the theoretical and experimental HRTs for a VF, as they obtained an experimental HRT of 5.6 h while the theoretical value was 24.2 h. In addition to this, in many subsurface HFs the mean HRT is about 40–80% lower than the nominal HRT because of loss of dead volume, loss of pore volume

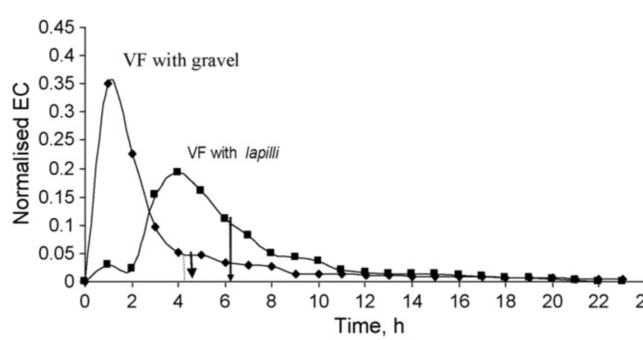

Fig. 3. Normalised electrical conductivity in the effluents of the VFs.

Table 2
Theoretical and experimental HRT (in hours) for the VF, HF and hybrid CWs with gravel and *lapilli* as determined from the tracer experiments for the period of high HLR.

	Gravel	Lapilli
Theoretical HRT (h)	VF: 28 HF: 38 Hybrid: 66	VF: 34 HF: 36 Hybrid: 70
Experimental HRT (h)	VF: 4 HF: 12 Hybrid: 16	VF: 6 HF: 21 Hybrid: 27

or preferential flow (US EPA, 2000), thus is not surprising that in VFs the difference can be similar or greater.

Persson et al. (1999) defined the hydraulic efficiency (HE) of wetlands and ponds as a measure of the effective utilization of the storage volume. HE can be calculated from hydraulic residence time distribution data by using the following expression:

$$HE = \frac{t_p}{t_{exp}} \quad (3)$$

where, t_p is the time to peak and t_{exp} is the experimental HRT obtained from tracer study.

Low values of HE are caused by short-circuits and poor utilization of available detention storage. Several factors such as shape and depth of the wetland, location and type of inflow and outflow structures will determine the values of a HE for a particular CW. HE can be calculated by using the ratio between time to peak and experimental TRH as obtained from tracer studies. Thus, according to the values of HE >0.75, 0.75–0.5 or <0.5, a CW can be considered to have good, satisfactory or poor HE, respectively (Persson et al., 1999).

The HE of the VFCW with gravel was 0.24, which is considered to be a poor HE. In the case of the VF with lapilli, the obtained HE of 0.65 indicates a satisfactory HE. These differences can be caused by the different grain sizes of the particles of the substrates employed. The higher HE of the VF with lapilli can be attributed to a higher retention of the water, i.e. higher actual HRT caused by a lower particle size and higher porosity.

3.2. Electrical conductivity, sodium and sodium absorption ratio (SAR)

One of the main constrains of CWs for wastewater treatment and reuse in dry countries is water loose by evaporation and plant transpiration and the consequent salinity increment (Masi and Martinuzzi, 2007). Another important factor to take into account when wastewater reuse is considered is its content in Na^+, particularly with respect to Ca^{2+} and Mg^{2+} ions, which is known as sodium absorption ratio (SAR). High concentrations of Na^+ ions in irrigation water can cause many problems such as the reduction of soil permeability, the formation of crusting seed beds, temporary saturation of the surface soil, high pH and the increased potential for diseases, weeds, soil erosion, lack of oxygen and inadequate nutrient availability (Mandal et al., 2008; Pereira Leal et al., 2009).

To determine the possible increment in water salinity, the EC, Na^+ and SAR of wastewater before and after the treatment were analysed. Table 3 shows the obtained results for the CW with gravel.

As can be observed, EC was greatly increased by the use of water in the buildings (laboratories, cafeterias, toilets, etc.) of the campus, as EC of the influent of the CWs was 68% higher than that of tap water. However, no significant increment on EC, Na^+ concentration and SAR was caused by wastewater treatment in the gravel-CW. Similar results were observed for the CW with lapilli. This nil EC increment in the CWs can be explained according to the low experimental HRTs, the fact that the systems were planted in April at the middle of the experimental time (thus evapo-transpiration was reduced), and that the average water temperature in the horizontal CWs varied only from 18 (±1.6) °C in December–January 2007–2008 to 24.5 (±1.2) °C in July 2008.

Table 3
Average ± typical error and (number of samples) values of EC, sodium concentration and SAR for tap water, influent and effluent of gravel CW.

	EC (mS cm^{-1})	Na^+ (mg L^{-1})	SAR[a]
Tap water	1.45 ± 0.01 (34)	–	–
CW influent	2.44 ± 0.06 (33)	407 ± 46 (23)	9.56 ± 0.86 (23)
CW effluent	2.31 ± 0.05 (34)	395 ± 33 (24)	8.16 ± 0.47 (24)

[a] $SAR = \frac{[Na]^+/28}{\sqrt{0.5\times(([Ca^{2+}]/20)+([Mg^{2+}]/12))}}$ where concentrations are mg L^{-1}.

3.3. BOD_5

The average concentration of BOD in the influent was 230 mg L^{-1}, and resulting BOD_5 loads for the VF, HF and hybrid CWs were 59, 3.6 and 14 g m^{-2} d^{-1}, respectively (Table 4). The BOD_5 loads of the VF of this study doubled those reported by Puigagut et al. (2007) for full-scale CWs in Spain, which ranged from 22.8 to 29.8 g m^{-2} d^{-1}. Those of the VF and hybrid CWs of this study fall in the range provided for the country (0.8–23 and 3.6–16.7 g m^{-2} d^{-1} for HF and combined systems, respectively).

Fig. 4 shows the BOD values of the influent and effluents of the VF, and HF, and the corresponding removal for the lapilli-based system. As can be observed, notably higher concentrations than the average value were recorded in the influent. However, the removal of BOD for the hybrids was very constant and high, being that of the system with lapilli significantly greater (89–90%) than the one with gravel (88–87%). These BOD removal efficiencies are in the range of those found by other authors such as O'Hogain (2003) who obtained 88% removal of the BOD load for a full-scale hybrid system or Puigagut et al. (2007) who found 80–95% BOD removal for other systems in Spain. Planting or changing the HLR did not make any difference between the performances of BOD removals of both hybrids.

BOD removal for the VF with lapilli (89–90%) was higher than that of the VF with gravel (78–89%) but not statistically different. When the HLR was doubled, the lapilli-VF did not show any removal reduction (88% at high HLR *versus* 90% at low HLR) while the efficiency of the gravel-VF was significantly reduced from 89% at high HLR down to 78% at low HLR. These different behaviours could be explained by the lower diameter and higher porosity of lapilli particles in comparison to those of the gravel, providing better filtration and sedimentation of organic particles and colloids and hosting a larger bacterial population for BOD degradation. Nevertheless, at

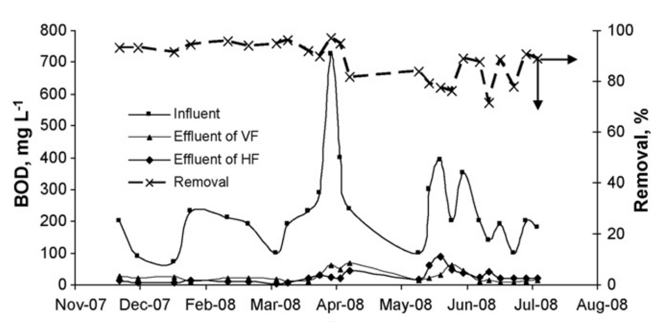

Fig. 4. Concentration of BOD (mg L^{-1}) in the influent (—■—), effluents of VF (- -▲- -) and HF (—◆—) and removal of the hybrid (%,—x—), for the CW with lapilli.

Table 4
Performance summary for the VF, HF and their combination (hybrid) at high and low HLR.

	Influent ($mg\,L^{-1}$)	Loading rate[a] ($m^{-2}\,d^{-1}$)	Removal rate[a] ($g\,m^{-2}\,d^{-1}$)	Removal (%)	
				Gravel	*lapilli*
BOD_5					
Low HLR	162 ± 15 (13)				
VF		25 ± 2.5	22 ± 2	89	90
HF		0.9 ± 0.1	−0.3 ± 0.3	–	0
Hybrid		6 ± 0.6	5 ± 0.6	85	90
High HLR	310 ± 50 (11)				
VF		97 ± 16	76 ± 16	78	88
HF		6.7 ± 0.7	2.4 ± 0.9	36	2.8
Hybrid		23 ± 4	20 ± 4	87	89
COD					
Low HLR	274 ± 23 (16)				
VF		42 ± 3	23 ± 3	55	58
HF		6 ± 0.8	2.6 ± 0.5	43	30
Hybrid		10 ± 0.8	7.6 ± 0.8	74	71
High HLR	462 ± 73 (15)				
VF		144 ± 23	105 ± 23	73	71
HF		12.5 ± 1	5 ± 1	40	39
Hybrid VF		35 ± 6	29 ± 5.5	83	82
NH_4^+-N					
Low HLR	122 ± 13 (13)				
VF		25 ± 2	21.5 ± 2	86	82
HF		1.1 ± 0.2	0.4 ± 0.1	33	37
Hybrid		6 ± 0.6	5 ± 0.5	91	89
High HLR	124 ± 9 (15)				
VF		50 ± 4	40 ± 3	80	81
HF		3 ± 0.3	0.8 ± 0.4	25	1
Hybrid		12 ± 0.9	10 ± 0.8	85	81
SS					
Low HLR	72 ± 14 (13)				
VF		11 ± 3	9 ± 2	83	85
HF		0.4 ± 0.1	0.3 ± 0.1	73	67
Hybrid		2.6 ± 0.6	2.5 ± 0.6	95	95
High HLR	80 ± 14 (15)				
VF		25 ± 4	20 ± 3.5	81	83
HF		1.1 ± 0.2	0.8 ± 0.2	75	60
Hybrid VF		5.9 ± 1	5.6 ± 1	95	96
Turbidity[a]					
Low HLR	74 ± 17 (14)				
VF		11.5 ± 2.6	9.9 ± 2.7	86	88
HF		0.5 ± 0.1	0.4 ± 0.1	73	57
Hybrid		2.9 ± 0.6	2.8 ± 0.6	96	95
High HLR	149 ± 23 (18)				
VF		47 ± 2.5	42 ± 8	89	89
HF		1.7 ± 0.3	1.2 ± 0.3	75	54
Hybrid VF		11 ± 2	10 ± 2	97	97
FE[a]					
Low HLR	$6.6 \pm 2.7 \times 10^4$ (11)				
VF		$1 \pm 0.4 \times 10^8$	$9.2 \pm 0.4 \times 10^7$	90	83
HF		$3.1 \pm 1 \times 10^6$	$3 \pm 1.2 \times 10^6$	95	97
Hybrid		$2.43 \pm 1 \times 10^7$	$2.41 \pm 1 \times 10^7$	99.5	99.5
High HLR	$9.7 \pm 3 \times 10^4$ (14)				
VF		$3.05 \pm 1 \times 10^8$	$3.03 \pm 1 \times 10^8$	99.5	96
HF		$9 \pm 3 \times 10^6$	$8.7 \pm 0.3 \times 10^6$	95	89
Hybrid VF		$7.32 \pm 2.3 \times 10^9$	$7.28 \pm 2.3 \times 10^6$	99.5	99.6
FC[a]					
Low HLR	$4.9 \pm 1.7 \times 10^6$ (14)				
VF		$9.1 \pm 4.3 \times 10^9$	$9 \pm 4.3 \times 10^9$	99.6	87
HF		$2.2 \pm 0.9 \times 10^8$	$2.1 \pm 0.9 \times 10^8$	95	97
Hybrid		$2.18 \pm 1 \times 10^9$	$2.17 \pm 1 \times 10^9$	99.6	99.7
High HLR	$5.6 \pm 2.6 \times 10^6$ (10)				
VF		$1.5 \pm 0.5 \times 10^{10}$	$1.5 \pm 0.5 \times 10^{10}$	99.8	99.0
HF		$1.98 \pm 0.7 \times 10^8$	$1.9 \pm 0.7 \times 10^8$	94.7	87
Hybrid VF		$3.6 \pm 1.2 \times 10^9$	$3.6 \pm 1.2 \times 10^6$	99.8	99.9

Average values ± typical error and the number of data (n) are provided.
Concentrations are in $mg\,L^{-1}$, with the exception of turbidity and faecal indicators which are NTU and CFU/100 mL, respectively. Loading rates are in $g\,m^{-2}\,d^{-1}$ with the exception of turbidity ($NTU\,m^{-2}\,d^{-1}$) and faecal indicators ($CFU\,m^{-2}\,d^{-1}$).
[a] Average loading and removal rates are provided only for the system with gravel for clarity. For comparison the values for the system with gravel are also provided.

Table 5
Average OTR (±typical error) values for the periods with high and low HLRs, for the VF and hybrid CWs. The concentrations of COD and NH_4^+-N in the influent for each period are also provided.

	COD in the influent (mg L^{-1})	NH_4^+-N in the influent (mg L^{-1})	OTR			
			VFs		Hybrids	
			Gravel	Lapilli	Gravel	Lapilli
High HLR	462	124	208 ± 20	195 ± 21	64 ± 4	62 ± 6
Low HLR	274	122	101 ± 9	88 ± 11	27 ± 2	28 ± 3

high HLR the VF with lapilli was more prone to undergo clogging than the one with gravel. This must be taken into account when considering what substrate is to be used in each stage of the hybrid CW.

In general, the obtained results clearly indicate a greater performance of the VFs in comparison to that of the HFs (Table 4). This is particularly evident in the case of BOD, as removals achieved by HFs were notably lower than those of the VFs although the actual HRTs of the VFs (gravel: 4.1 h lapilli: 6.2 h) were lower than those of the HFs (gravel: 12 h, lapilli: 21 h). The greater efficiency at BOD removal of the VFs could be due to several factors, in particular their higher oxygenation. In this sense, the obtained OTR values for the systems were higher than the obtained by other authors (Kantawanichkul et al. 2009). Another reason for the higher BOD removal efficiency of the VF is the fact that they were the first stage of the system, thus received the full organic load, and that the performance of CWs increases at higher loads (Molle et al., 2005; Herrera Melián et al., 2009). In fact, at high HLR the VF with gravel received an average BOD loading rate of 97 g m^{-2} d^{-1} and removed 76 g m^{-2} d^{-1} (78% removal) while in the case of the HF the BOD loading rate was 6.7 g m^{-2} d^{-1} and removed only 2.44 g m^{-2} d^{-1} (36% removal). It must be underlined that these results are only valid for the configuration used in this study and cannot be generalised, as the loadings to the VFs and HFs were not the same. However, Zurita et al. (2009) found higher average BOD removal efficiencies in parallel experiments with pilot plant VFs (80–83%) with respect to HFs (76–80%).

Based on a population equivalent of 60 g BOD $person^{-1}$ d^{-1} the average loading to the gravel-based VF, HF and hybrid systems were 1.02, 16.7 and 4.3 m^2 $person^{-1}$, respectively. These loadings are similar to those from O'Hogain (2003) who obtained 0.58 and 1.72 m^2 $person^{-1}$ for the VFs and 12 m^2 $person^{-1}$ for the HF.

3.4. COD

Average COD concentration in the influent (365 mg L^{-1}) was quite similar to that of 13 HFs located in Spain (347 mg L^{-1}, Puigagut et al., 2007). In the present study, the overall removal of COD was not significantly different for the hybrids with gravel and those with lapilli, being 80% and 78%, respectively. These values are in accordance with those obtained by Zurita et al. (2009), but are lower than those reported by O'Hogain (2003) who obtained 89% COD removal for a full-scale hybrid CW. Regarding COD performance, planting or changing the HLR did not make any significant difference between both hybrids. However, the effect of HLR on the performance of the hybrids was interesting, as in the period of high HLR both hybrids performed better (gravel: 83%, lapilli: 82%, Table 4) in comparison to the periods of low HLR (gravel: 74%, lapilli: 71%), although the concentration of COD in the period of high HLR was notably greater (462 mg L^{-1}) than that of the low HLR (274 mg L^{-1}). These results illustrate the ability of CWs at coping with high COD loads without loosing efficiency.

Average COD loading rate for the VFs was 93 g m^{-2} d^{-1} (Table 4) which is almost double of the value reported for 4 VFs located in Spain (48.8 g m^{-2} d^{-1}, Puigagut et al., 2007).

3.5. NH_4^+-N

The NH_4^+-N concentration of the influent was clearly above those from standard urban wastewaters, with an average of 123 ± 7 mg L^{-1} (Table 4, Fig. 5). This high concentration of NH_4^+-N can be caused by the presence of a small farm inside the Campus. The average NH_4^+-N loading rates were 25–50, 1.1–3 and 6–12 g m^{-2} d^{-1} for the VF, HF and hybrid CWs with gravel for the periods of high and low HLRs, respectively (Table 4). The values for the hybrid system are notably greater than those reported for Spain (0.3–3.3 g m^{-2} d^{-1}, Puigagut et al., 2007).

One of the most interesting results of this study is the high NH_4^+-N removal being 83–81%, 28–17% and 88–84%, on average for the VF, HF and hybrids with gravel and lapilli, respectively. In general, there were no significant differences in performance between the VFs or the hybrids with gravel and lapilli, respectively. However, the high removals obtained at low HLR by the hybrids (gravel: 91%, lapilli: 89%) were reduced but still very high in the period of high HLR (gravel: 85%, lapilli: 81%). The average concentration of ammonia-N in the influent remained the same for both periods (high HLR: 124 ± 9 mg L^{-1}, low HLR: 122 ± 10 mg L^{-1}).

These high NH_4^+-N removals were mainly due to nitrification in the VFs as corresponded to remarkable increments of the concentrations of NO_2^--N and NO_3^--N. For instance, in the VF with gravel the average concentration of NO_2^--N was increased from 0.07 ± 0.01 mg L^{-1} in the influent up to 0.79 ± 0.01 mg L^{-1} in the effluent. In the case of NO_3^--N, such increment was even greater as the average concentration in the influent was 0.41 ± 0.1 mg L^{-1} and achieved 65 ± 13 mg L^{-1} in the effluent. This result is particularly interesting when the treated water is intended to be reused for irrigation (Masi and Martinuzzi, 2007). For instance, Hussain and Al-Saati (1999) found that the use of wastewater can save up to 50% application of inorganic nitrogen fertilizer by using wastewater with N content of 40 mg L^{-1}.

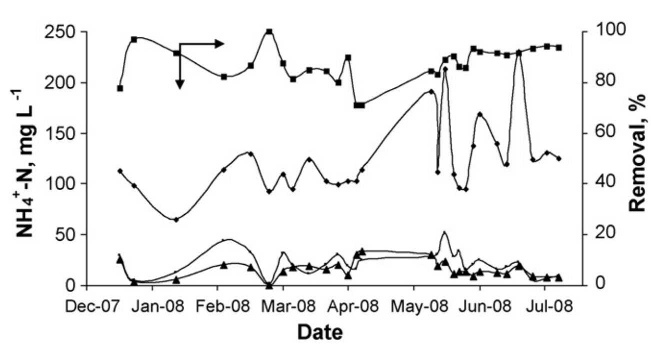

Fig. 5. Concentration of NH_4^+-N (mg L^{-1}) in the influent (—●—), effluents of VF (- - - -) and HF (—♦—) and removal of the hybrid (%, - - ■ - -), for the CW with gravel.

Table 6
Removal rate constants k (m yr^{-1}) as determined by the k–C^* model described by Kadlec and Knight (1996) for the wetlands with gravel: the VF as first stage and the HF as a refining system. Values reported in the literature are also shown for comparison.

	BOD	COD	SS	NH_4^+-N	PO_4^{3-}-P
VFCW					
C^{*a}	16	23	13	0	0
k	169	94	329	137	12
HFCW					
C^{*a}	6	10	0[b]	0	0
k	8	18	45	10	4
Hybrid hybrid					
k	57	42	80	47	6
Literature data for k					
HFCW (Kadlec and Knight, 1996)	31–365	–	1000	1.7–37.3	3.4–23.7[c]
Hybrid CW (Öövel et al., 2007)	20.1	–	–	18.2	17.1[c]
HFCW (Zurita et al., 2009)	30.2	27.3	25.5	8.8	7.6[c]

[a] $C^*_{BOD} = C^*_{COD} = 3.5 + 0.053C_i$, $C^*_{TSS} = 7.8 + 0.063C_i$.
[b] Calculated using $C^* = 0$ because $C_e < C^*$.
[c] Data for total phosphorus.

3.6. Oxygen transference rate, OTR

COD (or BOD) and NH_4^+-N results can be combined to obtain hypothetical oxygen transfer rate values for the system. These OTR values can be used for design purposes. In fact, design OTRs of around 30 g m^{-2} d^{-1} have been recommended (Vymazal et al., 1998; Cooper, 1999; Platzer, 1999). In the present study the obtained OTRs for the complete experimental period for the VF, HF and hybrid CWs were 155 ± 15, 5 ± 1 and 45.6 ± 4 g m^{-2} d^{-1}, respectively. The OTRs for the VFs of the present study are much higher than those obtained by Kantawanichkul et al. (2009) for the treatment of high-strength wastewater under tropical conditions with VFs, for which they obtained OTRs between 60 and 80 g m^{-2} d^{-1}. OTR values above 100 g m^{-2} d^{-1} have been reported by Brix et al. (2002).

In addition to this, the HLR exerted an important effect on OTR (Table 5), becoming increased in more than 100% at high HLR in comparison to the periods of low HLR, even when the concentration of COD in the influent was notably greater. A similar result was obtained by Kantawanichkul et al. (2009) who obtained increased OTR values at increasing loading rates and concluded that it was not the OTR that had limited degradation but the insufficient contact time of the wastewater in the filter.

3.7. SS and turbidity

If wastewater is intended to be reused for irrigation, achieving high SS and turbidity removals is important to avoid the clogging of soil pores and irrigation devices, particularly when drip-irrigation is applied (Liu and Huan, 2009). Additionally, sedimentation is considered to be an important disinfection mechanism in CWs. In the case of viruses it has been indicated that design criteria that enhance SS removal can also achieve high virus removal (Kadlec and Knight, 1996).

In this study, the turbidity and concentration of SS in the influent were 116 NTU and 76 mg L^{-1}, respectively (Table 4). Removals of SS and turbidity for both hybrids were very high and similar, achieving values >95% for both parameters and systems. The VFs yielded higher removals of SS and turbidity than those of the HFs, but in this case the contribution of the former ones to the efficiencies of the hybrid CWs was higher than for BOD, COD and NH_4^+-N. The VF with lapilli provided significantly higher efficiencies at turbidity removals than the VF with gravel (79–84%, respectively). However, the latter showed increased tendency to clogging when high HLRs were applied.

Planting or altering the HLR did not make any difference between both VFs and hybrids. However, when the HLR was doubled, the removal of turbidity and SS for the hybrid with gravel (Table 4) were slightly increased, being particularly interesting for turbidity as the concentration in the influent was also doubled. Similar results were obtained for the hybrid with lapilli.

3.8. PO_4^{3-}-P

Oppositely to the obtained for the other parameters analysed in this study, phosphate-P removal was low, being 24% and 21% for the gravel and lapilli hybrids, respectively. However, these values are close to the 26% observed by O'Hogain (2003). Although higher removals were observed at the higher HLR, the differences were not significant. In any case, these low phosphate-P removals reveal that the P-binding ability of the substrates employed in this study was also low. Even though other authors have obtained much higher P removals with hybrid CWs (Öövel et al., 2007; Masi and Martinuzzi, 2007), agriculture can benefit from the N and P content of reclaimed water, as the amount of artificial fertilizers added can be greatly reduced (Hussain and Al-Saati, 1999; Gori et al., 2004; Papadopoulos and Savvides, 2002; Gikas and Tchobanoglous, 2009).

3.9. Disinfection

Faecal coliforms (FC) and faecal enterocci (FE) were used to determine the disinfection efficiency of the systems. The hybrids achieved disinfection efficiencies of about 99% for both bacterial indicators (Table 4). These values are in the range found in the literature for hybrid CWs. For instance, Singh et al. (2009) found 97.5% FC removal for a hybrid (H + V) CW in Nepal including an anaerobic reactor. However, Masi and Martinuzzi (2007) found efficiencies up to 99.97% with a hybrid (V + H) CW treating wastewater from a hotel in Italy (140 p.e.).

Regarding the removal of FC and FE, planting or altering the HLR did not make any significant difference between the hybrids. Doubling the loading rate of both microbial indicators did not result in any removal reduction for the hybrids with both substrates, remaining very constant along the time of the experiments, despite the fact that for the VFs and HFs, removal could vary notably (Fig. 6). This reinforces the idea of hybrid CWs as very robust systems for wastewater treatment in small communities for which loading rates can vary dramatically.

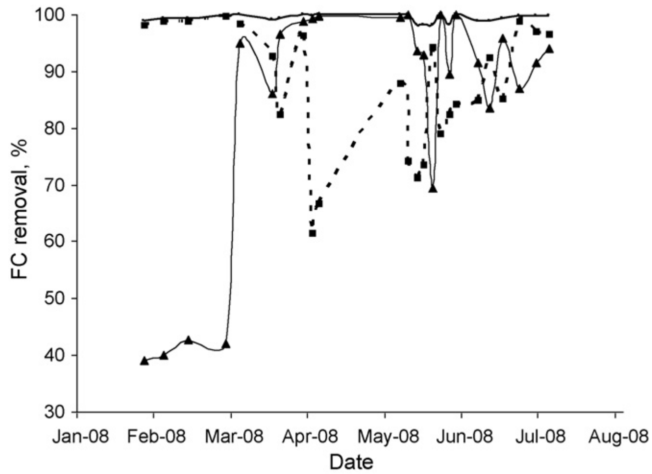

Fig. 6. FC removal in the VF (▲, solid line), HF (■, dotted line) and hybrid (no symbol, solid thick line) CWs with lapilli along time.

As can be observed in Table 4 and in opposition to the observed for all the other parameters, HFs performed at least equally than the VFs in terms of disinfection performance. For instance, FE removal in the VFs with gravel and lapilli were 90% and 91.8%, while those of the HFs were 95.6% and 95%, respectively. For FC, the figure is quite similar with comparable removals between VFs and also between those of the HFs. However, these results contrast with those from Vacca et al. (2005) and Zurita et al. (2009), who found higher reduction of Total Coliforms in VFs than in HFs. This has been justified by the fact that the more aerobic conditions of VFs would favour disinfection, probably due to higher predator abundance (Vymazal, 2005; Zurita et al., 2009). However, for hybrid systems Singh et al. (2009) found similar FC reduction in the HF and VF (69% and 74%, respectively), while Masi and Martinuzzi (2007) found much higher FC removal in the HF than in the VF. In the present study there were no differences in dissolved O_2 concentrations in the effluents of the VF (gravel: 4.95 mg L^{-1}) and the HF (gravel: 5.17 mg L^{-1}). Thus, the higher efficiency of the HF could be assigned to the greater experimental HRT measured for the HFs (gravel: 12 h, lapilli: 21 h) in comparison to those of the VFs (gravel: 4 h, lapilli: 6 h). In this sense, the fact that the systems, particularly the VFs, achieved removals of FE and FC between 84% and 92% with such low HRTs could be caused by the elimination of bacteria associated to SS and turbidity (particles and colloids), as the overall removal of these parameters was quite similar.

3.10. First order area-based rate constant

For the calculations of the first order area-based rate constants, the flow (Q) used was the average value for the whole study: 50 L d^{-1}, and the areas (A) were 0.235 and 0.59 m^2, those of the VF and HF with gravel, respectively. The input (C_i) and output concentration (C_e) of the pollutants were those measured in the treatment system (Table 4). The apparent background concentrations (C^*) were calculated according to Kadlec and Knight (1996). As the average water temperature in the CWs was 21.6 °C, the rate constants calculated in this work correspond to that temperature. Table 6 shows the results obtained for the VF, HF and hybrid system with gravel, and those obtained by other authors.

As expected, the k-values obtained for the VF are much higher than those of the HF. The k-values obtained by Zurita et al. (2009) for their HF lay between those obtained in this study by the VF and the HF. Greater k values indicate a more efficient removal and thus lower surface area to build the wetland. For the hybrid system, our k-values are comparable although greater than those obtained by Öövel et al. (2007) with the exception of P.

Additionally, the high k-values obtained for NH_4^+-N can be underlined. Although the one for the HF falls in the interval given by Kadlec and Knight (1996), those for the VF (137 m yr^{-1}) and the hybrid system (47 m yr^{-1}) are much greater than those reported by other authors. For instance, Öövel et al. (2007) found k-values between 14 and 25 m yr^{-1} for their VF, 11–21 for the HF and about 18 m yr^{-1} for the hybrid system. These differences could be explained by different facts: the higher temperatures in our system, with an average of 21.6 °C ranging between 17.2 and 28.6 °C, much higher NH_4^+-N concentrations in the influent and the high OTR obtained for the VFs of this study.

Nevertheless, although many studies indicate that the model gives satisfactory results for BOD removal in HFs (Kadlec and Knight, 1996), it is not confirmed that it can be used with confidence for VFs and for the removal of N (Kantawanichkul et al., 2009). Thus, the data obtained in this study should be used with caution.

4. Conclusions

The hydraulic behaviour and treatment performance of two hybrid CWs containing locally available and cheap substrates was studied for the treatment of urban wastewater in the Canary Islands. The following conclusions can be drawn:

1. Removals obtained by the hybrids were very high for BOD (>86%), COD (>78%), NH_4^+-N (>84%), SS (>95%), turbidity (96%) and faecal indicators (>98.7%). One of the most interesting results of this study is the elimination of ammonia-N, achieving in some cases 90%. The high nitrifying ability of the VFs is the main cause of ammonia-N elimination. However, removal of phosphate-P was rather low (>21%).
2. Although the experimental HRTs of the VFs were much lower than those of the HFs, the latter were in general more efficient, particularly for BOD, ammonia-N and phosphate-P. The contribution of the HFs to water purification was important in the elimination of COD, SS and turbidity and slightly higher than those of the VFs in disinfection. However, these results are valid only for the configuration used in this study and cannot be generalised, as the loadings to the VFs and HFs were not the same.
3. In comparison to the one with gravel, the VF with lapilli achieved significantly greater removal for the majority of the parameters measured. However, this substrate was more prone to undergo clogging. Thus, it should be used for well decanted wastewater and not great HLR. However, for the hybrid systems, most differences were not significant.
4. Planting and varying the HLR introduced few significant differences between VFs or hybrids. However, at high HLR the hybrids performed equally or better than at low HLR.
5. Disinfection efficiency for the VFs and HFs varied along the experimental time, but for the hybrids it was very high and constant. This and other conclusions stated above suggest that the hybrid CWs studied are a very robust configuration for wastewater treatment and reuse under the prevailing climatic conditions in the Canary Islands.

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