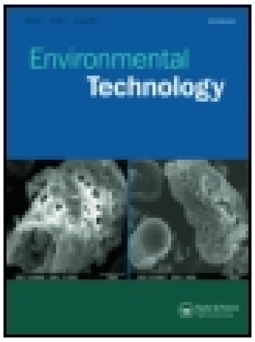

Taylor & Francis
Taylor & Francis Group

Environmental Technology

ISSN: 0959-3330 (Print) 1479-487X (Online) Journal homepage: http://www.tandfonline.com/loi/tent20

Hydrolytic anaerobic reactor and aerated constructed wetland systems for municipal wastewater treatment – HIGHWET project

A. Pascual, D. de la Varga, C. A. Arias, D. Van Oirschot, R. Kilian, J. A. Álvarez & M. Soto

To cite this article: A. Pascual, D. de la Varga, C. A. Arias, D. Van Oirschot, R. Kilian, J. A. Álvarez & M. Soto (2016): Hydrolytic anaerobic reactor and aerated constructed wetland systems for municipal wastewater treatment – HIGHWET project, Environmental Technology, DOI: 10.1080/09593330.2016.1188995

To link to this article: http://dx.doi.org/10.1080/09593330.2016.1188995

ENVIRONMENTAL TECHNOLOGY, 2016
http://dx.doi.org/10.1080/09593330.2016.1188995

Taylor & Francis
Taylor & Francis Group

Hydrolytic anaerobic reactor and aerated constructed wetland systems for municipal wastewater treatment – HIGHWET project

A. Pascual[a,b], D. de la Varga[c], C. A. Arias[d], D. Van Oirschot[e], R. Kilian[f], J. A. Álvarez[b] and M. Soto[a]

[a]Department of Physical Chemistry and Chemical Engineering I, University of A Coruña, A Coruña, Galiza, Spain; [b]AIMEN, Porriño – Pontevedra, Spain; [c]Sedaqua (Spin-off from University of A Coruña), O Porriño, Pontevedra, Spain; [d]Department of Bioscience, Aarhus University, Aarhus, Denmark; [e]Rietland bvba, Minderhout, Belgium; [f]Kilian Water, Bryrup, Denmark

ABSTRACT
The HIGHWET project combines the hydrolytic up-flow sludge bed (HUSB) anaerobic digester and constructed wetlands (CWs) with forced aeration for decreasing the footprint and improving effluent quality. The HIGHWET plant in A Coruña (NW of Spain) treating municipal wastewater consists of a HUSB and four parallel subsurface horizontal flow (HF) CWs. HF1, HF2 and HF3 units are fitted with forced aeration, while the control HF4 is not aerated. All the HF units are provided with effluent recirculation, but different heights of gravel bed (0.8 m in HF1 and HF2, and 0.5 m in HF3 and HF4) are implemented. Besides, a tobermorite-enriched material was added in the HF2 unit in order to improve phosphorus removal. The HUSB 76–89% of total suspended solids (TSS) and about 40% of chemical oxygen demand (COD) and biological oxygen demand (BOD). Aerated HF units reached above 96% of TSS, COD and BOD at a surface loading rate of 29–47 g $BOD_5/m^2 \cdot d$. An aeration regime ranging from 5 h on/3 h off to 3 h on/5 h off was found to be adequate to optimize nitrogen removal, which ranged from 53% to 81%. Average removal rates of 3.4 ± 0.4 g total nitrogen (TN)/$m^2 \cdot d$ and 12.8 ± 3.7 g TN/$m^3 \cdot d$ were found in the aerated units, being 5.5 and 4.1 times higher than those of the non-aerated system. The tobermorite-enriched HF2 unit showed a distinct higher phosphate (60–67%) and total phosphorus (54%) removal.

ARTICLE HISTORY
Received 15 February 2016
Accepted 9 May 2016

KEYWORDS
HUSB anaerobic digester; aerated constructed wetlands; nitrogen removal; phosphorus removal; municipal wastewater

1. Introduction

Wastewater treatment of small populations, food and beverage companies, and livestock farms is one of the most important problems due to decentralized location, limited economic resources and lack of specialized personnel. Even though the Water Framework Directive 2000/60/EC, concerning urban wastewater treatment, forces to treat sewage, there are a lot of small and medium-sized towns without this service. In addition, many of them cannot deal with energy and maintenance costs of conventional treatment plants, making them unsustainable and uneconomic.[1]

Constructed wetlands (CWs) are engineered treatment systems for wastewater effluents up to 2000 habitant equivalents, showing a high sustainability potential when properly designed and maintained. CW systems are based on the functioning of natural ecosystems, and the treatment processes involve complex interactions between soil, water, plants and micro-organisms.[2,3] The main parts of a CW are the liner separating the wetland from the subsoil to avoid infiltration and pollution of ground water, substrate bed, vegetation, and influent distribution and effluent collecting systems.

The most used types of CWs are the surface flow or free water surface systems, the horizontal subsurface flow systems (HF) and the vertical subsurface flow systems (VF). For improving the performance and the removal of pollutants and nutrients, a combination of these systems is used, so-called hybrid systems. HF systems are usually operated in conditions of permanent water saturation which limits oxygen transfer and nitrification only occurs at a low rate. Pulsed fed VF systems are partially saturated and can provide good conditions for nitrification, but the denitrification in these systems is limited. Therefore, in hybrid systems, the strengths and weaknesses of each type of system balance each other out and in consequence, it is possible to obtain an effluent low in biological oxygen demand (BOD) and in total nitrogen (TN) concentrations.[3] Many combinations are possible, including subsurface HF followed by VF, VF followed by HF and other stages of filters including water recirculation from one stage to another.[2]

CW technology is able to treat different types of wastewater, and hybrid CW systems can reach

CONTACT M. Soto m.soto@udc.es Department of Physical Chemistry and Chemical Engineering I, University of A Coruña, Rúa da Fraga no. 10, 15008 A Coruña, Galiza, Spain

simultaneous removal of organic matter and nitrogen, but they do not reduce the large surface area demand of these systems. In order to supply the extra oxygen needed to warrant the removal efficiency, while maintaining the advantages provided by CW technology, an external supply of air can be provided.[4–6]. Thus, the concept of aerated CW systems (i.e. with artificial forced aeration) arises.

Forced aeration strategies can vary extensively from partial to total aeration in relation to time and space, and from low to high intensity. The depth of aerated HF CWs varied from 0.3 to 1 m,[6–8] but probably an efficient aeration process requires a high depth in order to reach sufficient long contact time between the supplied air and wastewater. Air pumps can be activated when the oxygen concentration in the units is lower than 0.2 mg/L and turned off when the oxygen concentrations in the CW is higher than 0.6 mg/L.[8] However, this strategy requires automated devices and, usually, continuous aeration was provided, over the overall wetland bed or only near the inlet zone.[6,7] However, a timetable for intermittent aeration or spatial segregation of aerated and non-aerated zones has been considered convenient in order to reach simultaneous nitrification and denitrification.[9–11] In an efficient aerated HF CW, nitrification occurs when the aeration system is turned on, while denitrification requires anoxic conditions which could be obtained by ceasing aeration. Denitrification also requires a carbon source which must be furnished by the influent wastewater substrate. Thus, effluent recirculation could be necessary to improve the contact between the generated nitrate, the influent organic substrate and microbial population during anoxic periods.

Two additional points of interest concerning CW construction and use are clogging prevention and phosphorus removal improvement. One of the main problems with operating subsurface HF systems is clogging of granular media. Although the clogging phenomenon is an extremely complex and not well-understood process, the influent content in suspended solids is an important factor in causing clogging. The use of anaerobic digesters as pretreatment can achieve high suspended solids removal and contribute to avoid wetland clogging problems.[12–15] On the other hand, CWs will be of great interest when combined with anaerobic digesters, as both technologies agree with the essential criteria of low cost and sustainability, including simplicity of construction, operation and maintenance.

Phosphorus removal in CWs can occur through a combination of several processes: plant uptake, microbial growth, adsorption, precipitation within substrates, etc. Among these processes, adsorption and precipitation play the largest role in phosphate removal.[16] So, to ensure efficient phosphorus removal, research should aim to identify substrates that have a high phosphorus removal capacity, and suitable properties for use as CW substrate. Particularly, there is a great interest in studying the beneficial reuse options of by-products and waste materials which can be an alternative to gravel from quarry and which can contribute to the improvement of wastewater treatment systems.

The HIGHWET project was addressed to improve the capacity and effectiveness of CWs as high-rate and sustainable wastewater treatment systems. The HIGHWET project aimed to perform and validate new approaches based on the combination of the hydrolytic up-flow sludge bed (HUSB) anaerobic digester and CWs with forced aeration for decreasing the required surface of conventional HF CWs and improving the final effluent quality. For this purpose, two demonstration plants were designed and constructed in Spain and Denmark. The first configuration (A Coruña, NW of Spain) consisted of a HUSB and HF CWs for raw municipal wastewater treatment, while the second configuration (nearby Aarhus, Denmark) consisted of a combination of a HUSB and hybrid (FV + HF) CWs for the treatment of high-load organic industrial wastewater. The effect of effluent recirculation, aeration regime, energy consumption and different phosphorus adsorbent materials was planned to be checked in both plants. The effect of HF bed depth on aeration and treatment efficiency, which has not been investigated at the moment in a side-by-side comparison at the field scale, was assessed in A Coruña plant. This work reports the first results obtained in the A Coruña HIGHWET plant.

2. Material and methods

2.1. HIGHWET pilot plant in A Coruña

The pilot plant was built at the outdoors of the Science Faculty of the University of A Coruña in A Coruña (Spain) and the start-up was carried out in July 2014. It consisted of a hydrolytic anaerobic digester (HUSB) followed by four horizontal subsurface flow (HF1, HF2, HF3 and HF4) CWs working in parallel and receiving anaerobic pretreated wastewater. Figure 1 presents the diagram of the pilot plant design. HF1, HF2 and HF3 units are fitted with forced aeration, while the HF4 is not aerated in order to be used as a control. All the HF units were provided with effluent recirculation, but different heights of gravel bed were implemented in order to compare the behaviour of the aeration operating at high organic and hydraulic load in different scenarios. The HF beds were planted with common reeds (*Phragmites australis*) at a density of 16 plants/m^2.

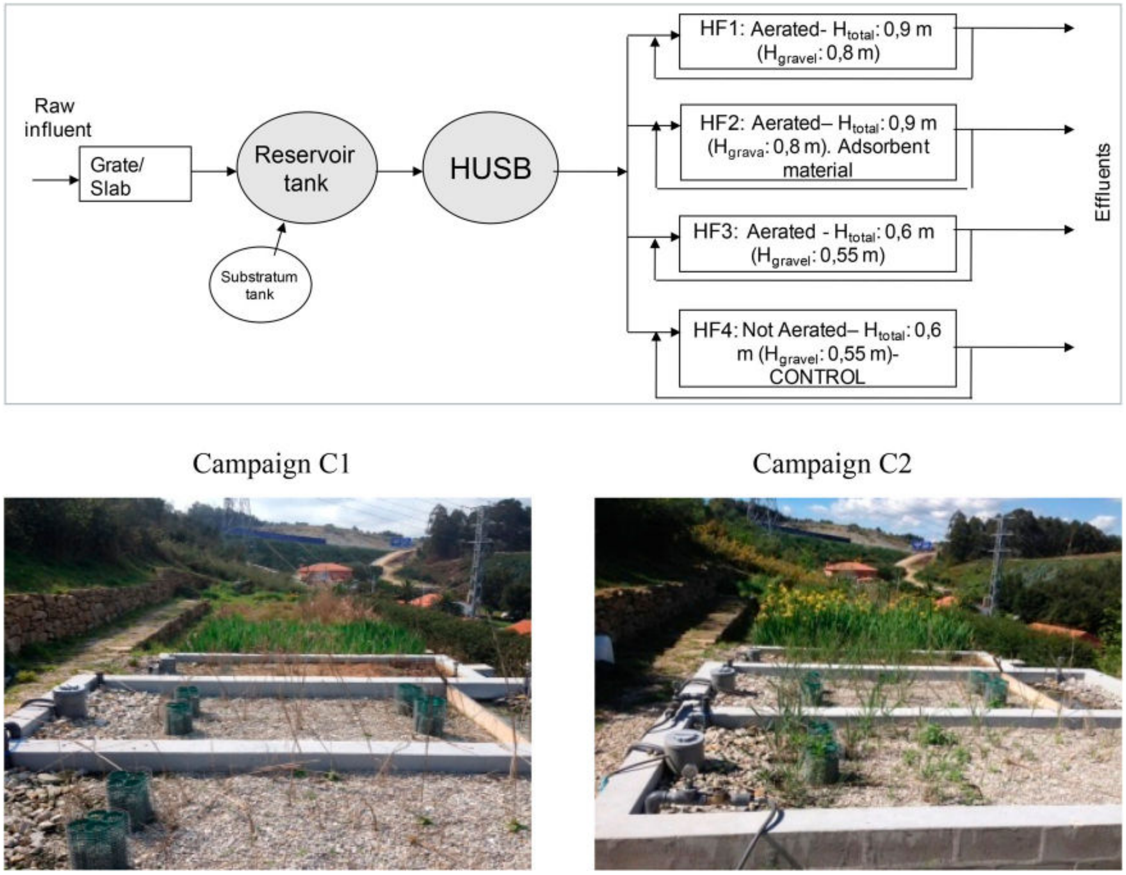

Figure 1. Configuration of the HIGHWET plant at A Coruña and plant situation during campaigns C1 and C2.

The plant was outfitted with the necessary pumps, tanks and other required devices. The raw influent wastewater flowed by gravity to the reservoir tank (volume of 1.8 m^3), after passing the coarse chamber. The coarse chamber was equipped with a mesh of 5 × 10 cm in order to remove big solids and a bypass for draining the excess flow. The concentrated synthetic wastewater was stored in the substratum tank (volume of 600 L) and pumped to the reservoir tank by using a peristaltic pump at a flow rate of 200 L/d. Submerged drain pumps were used in order to stir and homogenize the content of the substratum tank and the reservoir tank. A peristaltic pump at a flow rate of 3000 L/d was used to feed the HUSB reactor, while one three-channel peristaltic pump supplied each aerated bed (HF1, HF2 and HF3) at a flow rate of 1000 L/d and another peristaltic pump supplied the control bed (HF4) at a flow rate of 200 L/d. Finally, four timed submerged drain pumps situated in effluent collection tanks (up to 600 L of capacity) provided the independent recirculation flow to the inlet zone of each one of the HF units. Recirculation pumps operated in ON/OF cycles of 1 h being ON for approximately 10 min (HF1, HF2 and HF3) and 2.5 min (HF4).

2.2. HUSB digester

The HUSB digester consists of a concrete cylinder 0.70 m in diameter and an active height of 1.8 m (active volume of 0.69 m^3 and total height of 2.0 m). It was not provided with a gas/solid/liquid separator, since the target is to operate it at the hydrolytic stage and, therefore, biogas will not be produced or would be kept at a minimum. The design hydraulic retention time (HRT) for the HUSB was 3–7 h, while the organic loading rate (OLR) could be in the range of 0.5–4 g BOD/L·d.

2.3. HF CW units

The four HF units consisted of rectangular basins of 4 × 1.4 m (length × width), giving a total area of 5.6 m^2 for each bed. The base of the beds (with a slope of 1%) and the walls were built in concrete reinforced with iron rods and waterproofed with epoxy painting, in order to secure their isolation. The total height of the basins was 0.9 m for HF1 and HF2 units and 0.6 m for HF3 and HF4 units, while the water plate remained at 0.8 and 0.5 m, respectively. The average porosity was estimated to be 40%; thus, the void volume of each HF unit was 1.8 m^3 for HF1 and HF2 units and 1.1 m^3 for HF3 and HF4 units.

At the inlet zone of each HF unit, the influent distribution system consisted of a pipe (20 cm in diameter and 1.3 m in length) placed perpendicularly to the flow and buried in large gravel (50–60 mm) along the first 50 cm of the bed. This pipe had holes of 30 mm spaced at intervals of 25 cm along the length of the pipe. The effluent collection system was similar to the influent distribution system, but placed at the back of the bed. The water level of each bed was controlled by a pipe elbow inclined to the desired level and placed in an external tank of 40 × 40 × 80 cm. From here, the effluent was driven by a pipeline to the recirculation/final effluent tank.

As the main filtering medium, granitic gravel of 12–16 mm size was implemented for a length of 3 m on HF1 and HF3 units. In the case of the HF2 unit, the granitic gravel (12–16 mm size) was implemented for only a length of 2.5 m, while a phosphorus adsorbent material was placed along the remaining 0.5 m. Both materials in the HF2 unit were separated by perforated plywood. On the other hand, the main filtering medium in the HF4 unit was a finer granitic gravel of 6–12 mm size for a length of 3 m. The height of the filtering media was 0.85 m for HF1 and HF2 units and 0.55 m for HF3 and HF4 units.

2.4. Biomass monitoring in HF units

In order to monitor the development of biomass on the gravel, perforated cylinders of 20 cm diameter were inserted in the gravel, two at 80 cm from the inlet zone of each unit and another two at 80 cm (or at 120 cm in the case of the HF2 unit) from the end of each bed. The perforated cylinders were constructed with a steel mesh with lower mesh size than the gravel diameter and reached the bottom of each bed. Inside each cylinder, four columns of plastic mesh (8 cm in diameter) filled with gravel were placed. The columns will be manually extracted at different times of operation to analyse biomass development and solids accumulation on the gravel surface.

2.5. Aeration system

The aeration system in the HF units consists of a series of pipes installed at the bottom of the beds that will provide the necessary oxygen to the wastewater to maintain the proper concentration of dissolved oxygen (DO) while the water is being treated. The aeration lines are kept pressurized by air pumps that provide uniform distribution of air throughout the bed. The aeration can be adjusted by increasing the aeration time, switching the blowers on and off as the load is increased in the course of the development of the project, in order to adapt to the influent flow and concentration changes.

2.6. Phosphorus adsorbent material

In the HIGHWET project, it will be studied the beneficial reuse options of by-products and waste materials which can be an alternative to gravel or sand from quarry and which can contribute to the improvement of phosphorous removal in CWs. The adsorbent material selected was the scrap material from the production of specific concrete for building material worldwide. It is used for plain masonry or insulating purposes and for reinforced components such as lintels and roof/floor and wall panels.[17] The specific concrete is manufactured from silica sand, cement, lime and water. The material is processed in order to convert the minerals chemically into a strong crystal structure of tobermorite ($Ca_5Si_6O_{16}(OH)_2{\bullet}H_2O$). Tobermorite occurs in nature but is very rare. The adsorbent material based on tobermorite and with a particle size of 0.5–5.6 mm has been implemented in the last 0.5 m of the HF2 unit.

2.7. Influent wastewater

The influent to the plant comes from a local sewer receiving wastewater from one of the faculties of the University of A Coruña and surrounding houses. During the start-up period (July–October 2014), the raw wastewater presented the following characteristics (in mg/L except pH): pH 7.1 ± 0.6, total suspended solids (TSS) 64 ± 47, chemical oxygen demand (COD) 141 ± 87, BOD_5 47 ± 27, NH_4-N 24.2 ± 18.2, TN 25.3 ± 18.3, PO_4-P3.0 ± 2.0. These characteristics corresponded to a much diluted domestic wastewater, which was due to the entrance of rain water in the collection sewer. In order to use a more representative wastewater, in the present study, the raw domestic wastewater was supplemented with a concentrated synthetic substratum. A mixture of substrates (urea, trisodium phosphate, sodium acetate, starch and municipal primary sludge) was stored in the substratum tank (volume of 600 L). The concentrated substratum was formulated and renewed twice a week. This synthetic wastewater was continuously fed to the reservoir tank in order to reach the proposed TSS, BOD and total Kjeldahl nitrogen concentration.

2.8. Sampling and analysis

During the monitoring periods, the pumps were periodically calibrated and corrected to the desired flow, and the actual flow to each unit of the plant was obtained.

Sampling procedures involved taking influent and effluent composite samples (integrated over a 24-h period). Influent samples were collected using an automatic sampler type 1350 of American Sigma, while effluent samples were collected from daily accumulated volume in final tanks. This procedure was repeated once or twice a week. The obtained samples were analysed in the laboratory for total and volatile suspended solids (TSS, VSS), COD, BOD_5, ammonium, TN, nitrate, nitrite, phosphate and total phosphorus (TP). Temperature, pH, oxidation–reduction potential (ORP) and DO were determined *in situ* on the same sampling days. An integrated pH & Redox 26 Crison electrode was used for pH and ORP determination, a selective electrode (Crison 9663) for ammonium and an electrode ProODO from YSI Inc. for DO. Anions and cations were determined by ion chromatography (Metrohm 882/863). Inductively coupled plasma optical emission spectrometry (ICP-OES) was used for TP determination. Analytical methods were carried out as described in Standard Methods.[18]

3. Results and discussion

3.1. Plant operation

Available data for the start-up period (July–December 2014) indicate that the plant operated at an average volumetric loading rate (VLR) of 0.6 g BOD/L·d (HUSB digester) and surface loading rate (SLR) of approximately 20 g BOD_5/m^2 d (aerated HF units) and 4 g BOD_5/m^2 d (non-aerated HF4 unit). A high recirculation flow at the HF units of about 300% of influent flow was applied during this step. In these conditions, the aerated lines completely removed the influent organic matter, reaching TSS, COD and BOD_5 below 7 mg/L (HF1, HF2 and HF3 effluents) and removal rates higher than 98%. The non-aerated line showed slightly lower performance with removal rates of 99% TSS, 93% COD and 89% BOD_5.

Following the start-up period, two detailed monitoring campaigns were carried out in January–February (campaign C1) and March–April (campaign C2) 2015. The operation conditions for these campaigns C1 and C2 are indicated in Table 1 and the influent and effluent characteristics in Table 2. The SLR was increased to approximately 30 (C1) and 40–45 (C2) g BOD_5/m^2 d for the aerated HF units and to 8 (C1) and 14 (C2) for the non-aerated HF unit. On the other hand, the TN SLR remained approximately constant, at 5–6 g $TN/m^2 \cdot d$ for the aerated units and 1.5 g $TN/m^2 \cdot d$ for the non-aerated unit. In this way, the three aerated HF units received a similar SLR and hydraulic loading rate (HLR), but the HF3 unit operated at a lower HRT (1.2–1.5 d) as well as a higher VLR (166–239 g $BOD_5/m^3 \cdot d$), in comparison to HF1 and HF2 (2–2.9 d and 89–138 g $BOD_5/m^3 \cdot d$). On the other hand, the higher HRT (5.0–5.2 d) corresponded to the non-aerated HF4 unit. The later are typical values of conventional HF systems treating domestic wastewater. The recirculation rate ranged from 110% to 160% of influent flow for the aerated units and from 350% to 370% for the HF4 unit, substantially increasing the actual hydraulic load through the HF beds. An aeration regime of 5 h on followed by 3 h off (overall cycle of 8 h) was set at HF1, HF2 and HF3 units during campaign C1. The aeration rate was decreased to 3 h on/5 h off during campaign C2. During both campaigns, the HUSB operated at the design HRT and OLR.

The influent temperature was approximately 14°C (C1) and 19°C (C2) that decreased to about 11°C (C1) and 15.5°C (C2) at the outlet of the HF units. The DO content was low in the HUSB effluent (1.6–2.3 mg/L) and significantly increased at the outlet of the HF units. DO reached saturation levels at HF1, HF2 and HF3 units at campaign C1. At campaign C2, DO in HF1 and HF2 remained high (7–9 mg O_2/L), while the mean value for the HF3 unit was lower (3.7 mg O_2/L). This behaviour could be related to the higher SLR in the HF3 unit during campaign C2 (47 g $BOD_5/m^2 \cdot d$) in comparison to campaign C1 (33 g $BOD_5/m^2 \cdot d$) and the lower bed depth of the HF3 in comparison to HF1 and HF2 units. The lower bed depth of the HF3 unit could reduce the oxygen transfer efficiency whose effects would only be noticeable in overload conditions. On the other hand, the non-aerated unit HF4 showed moderate OD levels in the range of 4–5 mg/L. Except for the HF2 unit effluent, the pH was very stable throughout the different measurement points in the plant, with mean values ranging from 7.2 to 7.7. The HF2 unit provided with the tobermorite-enriched material showed a distinct increase in pH at the effluent, showing mean values of 8.2 (C1) and 8.3 (C2), significantly higher ($p < .01$) than those of the other HF units.

3.2. HUSB digester performance

An anaerobic digester with a similar design to the typical up-flow anaerobic sludge blanket (UASB) when it is used at hydrolytic (non-methanogenic) conditions is known as a HUSB digester.[19,20] The type of substrate, influent concentration, temperature, HRT and solid retention time are the main operational parameters that define the methanogenic or non-methanogenic conditions of an anaerobic system.[19] The HUSB reactor should minimize methanogenic activity while enhancing hydrolysis and acidification of particulate matter in order to reach high volatile fatty acid concentrations in the effluent. Therefore, a HUSB reactor is mainly used for that wastewater with a high suspended solid concentration in order

Table 1. Hydraulic and loading rate parameters applied at the HIGHWET plant treating municipal wastewater.

Parameter	HUSB	HF1	HF2	HF3	HF4
Campaign C1					
Feeding flow (L/d)	2724	879	789	897	213
HLR ($L/m^2·d$)	–	157.0	140.9	160.2	38.0
SLR ($g\ BOD_5/m^2·d$)	–	31.9	28.6	32.6	7.7
SLR ($g\ TN/m^2·d$)	–	6.1	5.5	6.2	1.5
VLR ($g\ BOD_5/m^3·d$) [a]	2116	99	89	166	39
HRT (d)	0.25	2.0	2.3	1.2	5.2
Recirculation flow (L/d)	0.0	1059	1014	1000	789
HLR with recirculation ($L/m^2·d$)	–	346.1	322.0	338.8	178.9
Aeration regime (h on/ h off)	–	5/3	5/3	5/3	0/24
Campaign C2					
Feeding flow (L/d)	2576	707	631	748	221
HLR ($L/m^2·d$)		126.3	112.7	133.6	39.5
SLR ($g\ BOD_5/m^2·d$)	–	44.3	39.6	46.9	13.9
SLR ($g\ TN/m^2·d$)	–	5.3	4.7	5.6	1.6
VLR ($g\ BOD_5/m^3·d$)[a]	2005	138	123	239	71
HRT (d)	0.27	2.5	2.9	1.5	5.0
Recirculation flow (L/d)	0	1059	1014	1000	789
HLR with recirculation ($L/m^2·d$)	–	315.4	293.8	312.1	180.4
Aeration regime (h on/ h off)	–	3/5	3/5	3/5	0/24

[a] VLR (volumetric loading rate) considering the active volume of the HUSB digester and the void volume of the HF units (see text).

to solubilize particulate matter and to increase the removal of easily biodegradable organic matter in the wastewater.

Treating municipal wastewater, the HUSB digester can operate at HRT ranging from 3 to 14 h.[19,13] In the HIGHWET plant, the HUSB was operated at approximately 6 h of HRT. As shown in Figure 2, the wastewater parameter most affected by the anaerobic treatment is the particulate organic matter. The HUSB removed 76–89% of TSS, highly reducing the influent concentration of suspended solids to the HF units. Average COD and BOD removal was 42% and 48%, respectively. Additionally, the HUSB digester removed organic nitrogen (Org. N, calculated as the difference between TN and ammonia and nitric nitrogen) at a rate ranging from 14% to 22% (Figure 2) and increased the ammonia concentration by about 35%, as can be obtained from Table 2.

During the reported period of 4-month operation, the HUSB did not require sludge purge. Available data from periodic inspections of the height and concentration of the sludge bed indicate a rate of sludge formation of approximately 2 L/d with a concentration of about 30 g VSS/L and 60 g COD/L. A COD balance indicates that the sludge bed accumulates about 6% of influent COD, which in turn is about 14% of the removed COD. Once the maximum sludge bed of about 1.2 m is reached, maintaining the steady state will require the purge of about half (or more) of the accumulated sludge at each three-month period. The purge frequency could be reduced if a larger HRT or a lower VLR is applied. However, in the case of large plants, the optimum solution may be a more intensive process and a higher purge frequency.

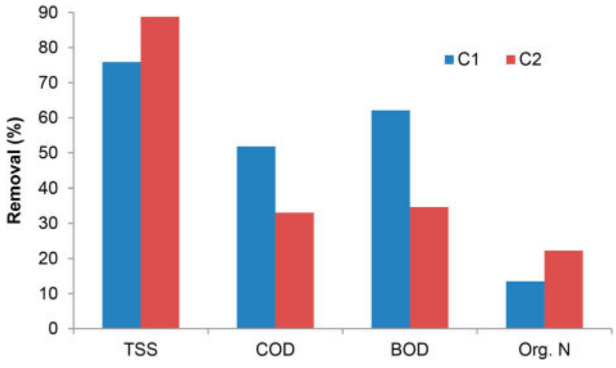

Figure 2. Efficiency of the HUSB digester in removing suspended and total organic matter and Org. N at campaigns C1 and C2.

3.3. Organic matter removal in HF units

Instead of the increase in SLR during campaigns C1 and C2 in comparison to the start-up period, the aerated lines completely removed the influent organic matter reaching very low TSS and BOD_5 (usually close to zero or below the detection limit) and COD below 23 mg/L (Table 2). Removal percentages higher than 96% were usually achieved. Only the non-aerated HF unit showed slightly lower performance with removal rates of 98% TSS, 86% COD and 91% BOD_5 during campaign C1. Thus, all the units showed sufficient capacity to remove the higher SLR applied, which ranged from 29 to 47 g $BOD_5/m^2·d$ (50–63 g $COD/m^2·d$) for the aerated units and from 8 to 14 g $BOD_5/m^2·d$ (14–19 g $COD/m^2·d$) for the non-aerated unit. Average surface removal rates (SRRs) were 37 and 10 g $BOD_5/m^2·d$ for the aerated and non-aerated units, respectively.

3.4. Nitrogen removal in HF units

Figure 3 shows the removal of and increase in several forms of nitrogen in the HF units. Nitrogen in the influent to the HF units (i.e. HUSB effluent) appeared mainly as ammonia nitrogen (71% and 85% of TN in campaigns C1 and C2, respectively), the remaining corresponding to Org. N (15–28%), while nitric (NO_3^- and NO_2^-) nitrogen accounted for less than 1% of TN. All the aerated units effectively removed TN, Org. N and NH_4^+-N at rates ranging from 47% to 100%, but differences existed mainly as a function of the unit configuration and the on/off aeration ratio.

At the higher aeration ratio (campaign C1, 5 h on/3 h off), units HF1 and HF3 completely nitrified the ammonium, which did not appear in the final effluent. A higher accumulation of NO_3-N in the deeper HF1 unit than in the HF3 unit led to a slightly higher TN removal in HF3 (61%) than in HF1 (53%). The tobermorite-enriched HF2 unit presented during campaign C1 a performance similar to that of the other aerated units, with the only difference of a slightly lower ammonia removal rate (88%) which appeared in the effluent at low concentrations. This could be due to the higher pH in this unit, probably caused by the presence of the tobermorite material that could induce partial inhibition of ammonia nitrification. In the conditions of aeration of campaign C1, the unremoved nitrogen accumulated in the effluent in the form of nitrate, indicating that denitrification was the limiting step. The non-aerated HF unit reached a much lower ammonia removal (29%) and TN (35%), accumulating ammonia but not nitrate in the effluent.

During campaign C2, the aeration regime in HF1, HF2 and HF3 units was changed to 3 h on/5 h off, thus receiving a 40% less air flow. At the same time, the organic SLR increased by about 40% and the nitrogen SLR remained nearly the same or slightly decreased. In comparison to campaign C1, during campaign C2 the percentage ammonia removal decreased in units HF1 and HF3, while it increased in the HF2 unit (Figure 3). TN removal increased in HF1 (67%) and HF2 (81%), while it decreased in HF3 (53%). The better operation of the HF2 unit during campaign C2 could be due to a higher surface area provided by the tobermorite material, once the system adapted to the effect of higher pH. Ammonia accumulated in the effluents of HF1 and mainly of HF3, but not in HF2 effluent. Thus, nitrification became the limiting step in HF1 and HF3 units. Instead of the higher BOD SLR in the non-aerated unit during campaign C2, the percentage of ammonia and TN removal slightly increased up to 41% and 43%, respectively.

A similar percentage removal of Org. N was observed in the aerated HF1 and HF3 units and in the non-aerated HF4 unit, which ranged from 47% to 66%, while the tobermorite-enriched HF2 unit reached distinctly high values of 79–87% (Figure 3). Considering that the Org.

Table 2. Characteristics of the influent and effluent from each unit of the HIGHWET plant treating municipal wastewater

	T	pH	DO	TSS	COD	BOD	TN	NH_4-N	NO_3-N	NO_2-N	PO_4-P	TP
Campaign C1 (*n* = 6)												
Storage tank[a]	12.1 ± 3.8	7.6 ± 0.9	3.2 ± 1.2	568 ± 13.9	739 ± 33	536 ± 67	33.5 ± 14.0	20.8 ± 12.2	0.1 ± 0.2	0.14 ± 0.24	11.3 ± 3.8	nd
HUSB effluent	14.2 ± 1.3	7.3 ± 0.9	2.3 ± 0.8	137 ± 7.4	356 ± 16	203 ± 25	39.0 ± 19.7	27.9 ± 14.4	0.1 ± 0.2	0.22 ± 0.31	11.6 ± 5.9	nd
HF1 effluent	10.9 ± 2.8	7.4 ± 0.5	11.2 ± 0.6	bl	11 ± 5	1.8 ± 3	18.3 ± 8.1	0.0 ± 0.1	13.8 ± 6.7	0.17 ± 0.21	12.0 ± 3.6	nd
HF2 effluent	10.7 ± 2.9	8.2 ± 0.3	10.5 ± 0.9	bl	12 ± 3	1 ± 2	17.5 ± 4.8	3.5 ± 4.3	10.5 ± 2.5	2.12 ± 1.39	4.7 ± 1.5	nd
HF3 effluent	10.8 ± 2.7	7.5 ± 0.4	10.5 ± 1.0	bl	12 ± 5	0.8 ± 0	15.3 ± 7.3	bl	11.4 ± 5.4	0.25 ± 0.19	11.8 ± 3.9	nd
HF4 effluent	10.8 ± 2.5	7.4 ± 0.3	4.9 ± 1.4	3 ± 5	50 ± 29	18.9 ± 2	25.2 ± 3.5	19.8 ± 3.4	0.2 ± 0.3	0.27 ± 0.29	9.5 ± 1.8	nd
Campaign C2 (*n* = 7)												
Storage tank[a]	16.3 ± 2.2	7.2 ± 0.4	1.7 ± 0.6	634 ± 15	699 ± 31	537 ± 67	34.3 ± 8.8	26.1 ± 9.5	bl	0.06 ± 0.17	12.7 ± 2.4	18.6 ± 3.3
HUSB effluent	19.0 ± 1.8	7.5 ± 0.3	1.6 ± 0.6	71 ± 6	468 ± 21	351 ± 44	41.6 ± 11.8	35.2 ± 10.2	bl	0.07 ± 0.17	15.3 ± 2.5	18.3 ± 8.8
HF1 effluent	15.6 ± 1.8	7.6 ± 0.1	6.8 ± 2.4	bl	9 ± 19	bl	13.6 ± 6.0	6.4 ± 7.4	4.2 ± 2.8	0.43 ± 0.32	12.5 ± 2.8	18.8 ± 3.0
HF2 effluent	15.5 ± 1.9	8.3 ± 0.5	9.2 ± 0.9	bl	4 ± 6	bl	8.0 ± 2.9	0.3 ± 0.6	6.2 ± 2.3	0.16 ± 0.26	5.0 ± 1.1	8.5 ± 2.2
HF3 effluent	15.3 ± 1.8	7.7 ± 0.2	3.7 ± 1.3	bl	23 ± 39	bl	19.7 ± 9.0	15.3 ± 8.6	0.6 ± 0.7	0.43 ± 0.39	13.6 ± 2.6	21.6 ± 2.5
HF4 effluent	15.0 ± 1.7	7.6 ± 0.1	4.6 ± 1.1	bl	6 ± 10	bl	23.9 ± 2.2	20.8 ± 2.5	0.2 ± 0.2	0.14 ± 0.19	11.8 ± 1.3	17.2 ± 1.6

[a] Wastewater in the storage tank was the sum of raw wastewater and supplemented synthetic wastewater and was used as the influent to the HUSB digester. bl, below detection limit; nd, not determined. Concentrations are in mg/L.

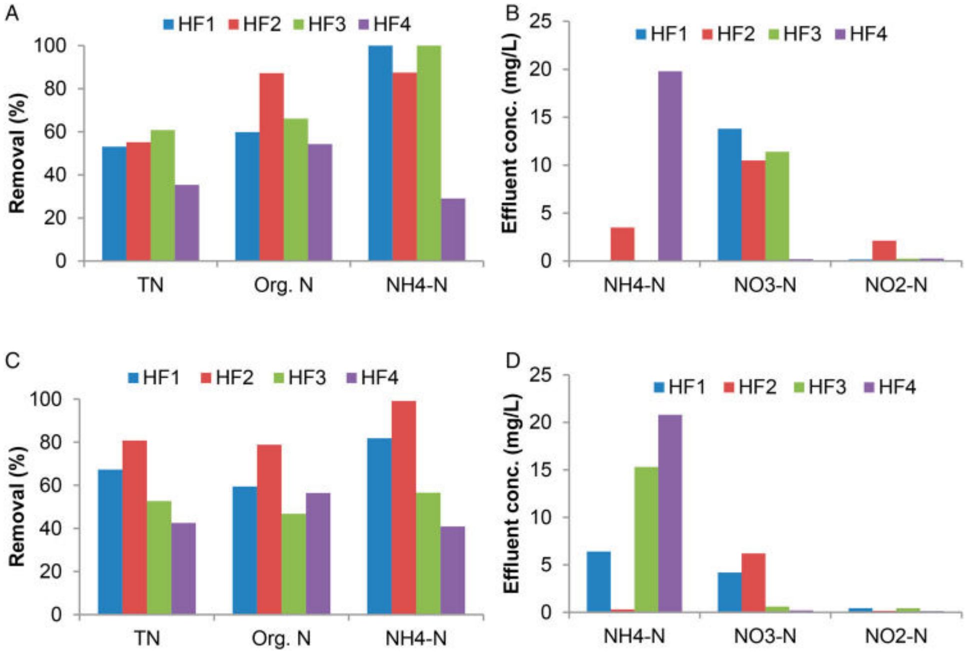

Figure 3. Percentage removal and effluent concentration for several forms of nitrogen in HF units during campaigns C1 (a and b) and C2 (c and d).

N can be removed throughout ammonification, the maximum surface nitrification rate (SNR) can be calculated. The results for maximum nitrification rate and TN removal rate are presented in Table 3. Higher nitrification rates were obtained in campaign C1, clearly decreasing in campaign C2 due to the reduction in aeration flow, particularly in the shallower unit HF3. However, TN removal rate slightly increased in HF1 and HF2 units from campaign C1 to C2. On the other hand, the volumetric nitrification rate (VNR) and particularly the volumetric TN removal rate remained higher in the HF3 unit in both campaigns.

The results in Figure 3 and Table 3 indicated that an aeration regime ranging from 5 h on/3 h off to 3 h on/5 h off may be adequate to optimize TN removal in HF CWs with forced aeration. Thus, a fifty/fifty on/off regime of aeration is recommended as the reference value. As the minimum HRT applied in the present study was 1.2 d, an aeration cycle of 8 h (on + off) may be suitable, but it may need optimization for the operation with diluted wastewater at a shorter HRT. On the other hand, aerated HF systems reached average SRR of 3.4 ± 0.4 g TN/m^2·d and volumetric removal rate (VRR) of 12.8 ± 3.7 g TN/m^3·d, which were 5.5 and 4.1 times higher than those found in the non-aerated system.

3.5. Phosphorus removal

Influent and effluent concentrations of phosphate (campaigns C1 and C2) and TP (C2) are given in Table 2, while Figure 4 shows the percentage removal for the different HF units. The HUSB digester showed a minor effect on TP, but slightly increased phosphate content in the effluent. Reduced phosphate (c. 20%) and TP (6%) removal was obtained in the non-aerated HF unit. These reduced removals are not surprising as the HF4 unit was operated with a SLR (8–14 g BOD$_5$/m^2·d) higher than the recommended design values of 5–6 and because the monitoring campaigns were carried out in winter (C1) and early spring (C2) when the planted macrophyte was still dormant. A lower effect on phosphate and TP was even found in the aerated HF1 and HF3 units, as shown in Figure 4. On the contrary, the tobermorite-enriched HF2 unit reached distinctly high values of

Table 3. Surface and volumetric nitrification and TN removal rates for HF units.

	Campaign C1 (5 h on/3 h off)				Campaign C2 (3 h on/5 h off)			
	HF1	HF2	HF3	HF4	HF1	HF2	HF3	HF4
SNR (g N/m^2·d)[a]	5.4	4.8	5.6	0.5	4.1	4.5	3.1	0.7
VNR (g N/m^3·d)[a]	16.8	14.8	28.6	2.7	12.8	14.0	15.5	3.6
SRR (g TN/m^2·d)	3.2	3.0	3.8	0.5	3.5	3.8	2.9	0.7
VRR (g TN/m^3·d)	10.1	9.4	19.3	2.7	11.0	11.8	14.9	3.6

[a] Maximum nitrification rate by accounting both the removed ammonia and the removed Org. N.

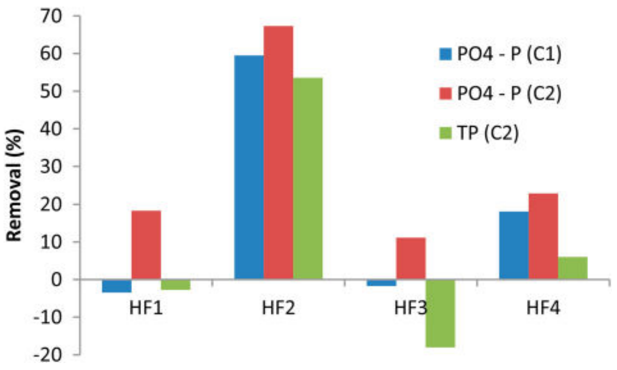

Figure 4. Percentage removal of phosphate and TP in HF units.

60–67% phosphate removal and 54% TP removal. More research is still needed to assess the sustainability of phosphorus removal by this material (lab absorption assays and long-term continuous operation) and particularly the arrangement used to place the tobermorite material in this HIGHWET plant treating domestic wastewater.

3.6. Final remarks

As extensive and passive treatment systems, CWs usually require a high footprint in the form of land surface, thus being considered suitable for the treatment of wastewater effluents below 2000 people equivalents (pe). The SLR generally recommended for secondary treatment in HF CWs is in the range of 4–6 g BOD/m^2·d.[21,22] So, the surface land required ranges from 5 to 7 m^2/pe. In these conditions, HF CWs reach current European Union (EU) targets for secondary treatment, together with a substantial nitrogen and phosphorus removal.[3,22,23] A higher SLR can be applied in HF CWs but in detriment of effluent quality and system sustainability.[13] Vymazal [3] reported that HF CWs (*n* = 213 systems) receiving a SLR of 9.7 g BOD/m^2·d reached an average effluent BOD$_5$ of 32 mg/L, which is above the EU effluent standards. Furthermore, these systems removed about 0.83 ± 6.56 g TN/m^2·d.[24]

The non-aerated control unit in the present study removed 0.5–0.7 g TN/m^2·d, while it received a SLR ranging from 8 to 14 g BOD$_5$/m^2·d, thus being comparable to the literature performance of HF systems. Compared to the non-aerated HF unit, aerated units in the present study reached 3.7 and 5.5 times higher BOD$_5$ and TN SRRs, somewhat higher than those recently reported by Zapater-Pereyra et al. [25] for aerated HF systems. Even the BOD$_5$ SRR in the aerated units was about eight times higher than the current design criteria for conventional HF units. Thus, we can conclude that the required area can be reduced by a factor of 5, which fulfils the aims of the HIGHWET project. These results could favour the extension of CW technology to serve wastewater discharges in a broad range above 2000 pe, namely in the range of populations from 2000 up to 5000 pe. In this range of application, septic tanks are not useful and HUSB digesters can clearly compete with Imhoff tanks and other wastewater pretreatments.

Three additional points of interest about the performance of HIGHWET plants which are currently being assessed are those related to substrate clogging, greenhouse gases (GHG) and energy consumption. In the present study, the plant included an anaerobic pretreatment step in order to reduce the entrance of suspended solids to HF beds and help in clogging prevention. Additionally, compared to conventional HF units, larger gravel was used in aerated units. We have taken into consideration that clogging can also be caused by biofilm development,[26] which is a risk in more intensive systems. However, clogging processes usually lasted in time and then were not assessed in this first report. On the other hand, CWs can cause an important flux of GHG, such as nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4), that could mitigate the environmental benefits of CWs. Methane emissions are higher when anaerobic conditions predominate over aerobic conditions, as occurs in conventional HF CWs.[27] Artificial aeration increases aerobic conditions and thus probably reduces CH_4 emissions.[7,28] Reduction in N_2O has been also found in some operation conditions when aeration was provided.[7] Finally, energy consumption due to forced aeration must be assessed taking into account both economic issues and its contribution to indirect GHG emissions.

4. Conclusions

The HIGHWET project combines the HUSB digester and HF CWs with forced aeration for decreasing the footprint and improving the effluent quality. The HUSB removed 76–89% of TSS, highly reducing the influent concentration of suspended solids to the HF units. The average COD and BOD removal was 42% and 48%, respectively, while surplus sludge was produced at a rate equivalent to 6% of influent COD.

HF units showed TSS, COD and BOD removal percentages higher than 96% (aerated units) and 90% (non-aerated unit) when the SLR applied ranged from 29 to 47 g BOD$_5$/m^2·d (50–63 g COD/m^2·d) for the aerated units and from 8 to 14 g BOD$_5$/m^2·d (14–19 g COD/m^2·d) for the non-aerated unit. The results obtained indicated that an aeration regime ranging from 5 h on/3 h off to 3 h on/5 h off may be adequate to optimize TN removal in HF CWs with forced aeration. In these conditions, TN removal ranged from 53% to 81%.A fifty/fifty on/off regime of aeration is recommended as the reference value. On the other hand, aerated HF systems reached average SRRs of 3.4 ± 0.4 g TN/m^2·d and VRRs of 12.8 ± 3.7 g TN/m^3·d, which were 5.5 and 4.1 times higher than those found in the non-aerated system.

A reduced phosphate (20%) and TP (6%) removal was obtained in the non-aerated HF unit. A lower effect on phosphate and TP was even found in the aerated HF1 and HF3 units. On the contrary, the tobermorite-enriched HF2 unit reached distinctly high values of 60–67% phosphate removal and 54% TP removal, being a promising approach to increased phosphorus removal in CWs.

Compared to the non-aerated HF unit, aerated units in the present study reached 3.7 and 5.5 times higher BOD_5 and TN SRRs. Even the BOD_5 SRR in the aerated units was about eight times higher than the current design criteria for conventional HF units. In conclusion, the required area may be reduced by a factor of 5 or more, which favours the extension of the CW technology to serve wastewater discharges in a broad range above 2000 pe. Three additional points of interest about the performance and sustainability of the HIGHWET plants which are currently being assessed are those related to substrate clogging, GHG and energy consumption.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding information

This work was supported by the EU’s seventh framework programme for research, technological development and demonstration under grant agreement no. [605445].

References

[1] EC. 6th commission summary on the implementation of the urban waste water treatment directive. Commission Staff Working Paper; 2011.

[2] Brix H, Arias CA. The use of vertical flow constructed wetlands for on-site treatment of domestic wastewater: new Danish guidelines. Ecol Eng. 2005;25:491–500.

[3] Vymazal J. The use constructed wetlands with horizontal sub-surface flow for various types of wastewater. Ecol Eng. 2009;35:1–17.

[4] Wallace S, Liner M, Diebold J. 2007. Degradation of aircraft deicing runoff in aerated engineered wetlands. Multi-functions of wetlands systems, June 26–29, University of Padova, Italy.

[5] Cottingham PD, Davies TH, Hart BT. Aeration to promote nitrification in constructed wetlands. Environ Technol. 1999;20:69–75. doi:10.1080/09593332008616794

[6] Nivala J, Wallace S, Headley T, et al. Oxygen transfer and consumption in subsurface flow treatment wetlands. Ecol Eng. 2013;61:544–554.

[7] Maltais-Landry G, Maranger R, Brisson J. Effect of artificial aeration and macrophyte species on nitrogen cycling and gas flux in constructed wetlands. Ecol Eng. 2009;35:221–229.

[8] Zhang L, Zhang L, Liu Y, Shen Y, Liu H, Xiong Y. Effect of limited artificial aeration on constructed wetland treatment of domestic wastewater. Desalination. 2010;250:915–920.

[9] Maltais-Landry G, Chazarenc F, Comeau Y, Troesch S, Brisson J. Effects of artificial aeration, macrophyte species, and loading rate on removal efficiency in constructed wetland mesocosms treating fish farm wastewater. J Environ Eng Sci. 2007;6:409–414.

[10] Tao W, Wang J. Effects of vegetation, limestone and aeration on nitritation, anammox and denitrification in wetland treatment systems. Ecol Eng. 2009;35:836–842.

[11] Araya F, Vera I, Sáez K, Vidal G. Effects of aeration and natural zeolite on ammonium removal during the treatment of sewage by mesocosm-scale constructed wetlands. Environ Technol. 2016;37:1811–1820.

[12] Ruiz I, Álvarez JA, Díaz MA, Serrano L, Soto M. Municipal wastewater treatment in an anaerobic digester-constructed wetland system. Environ Technol. 2008;29:1249–1256.

[13] Ruiz I, Díaz MA, Crujeiras B, García J, Soto M. Solids hydrolysis and accumulation in a hybrid anaerobic digester-constructed wetlands system. Ecol Eng. 2010;36:1007–1016.

[14] Pedescoll A, Corzo A, Álvarez E, García J, Puigagut J. The effect of primary treatment and flow regime on clogging development in horizontal subsurface flow constructed wetlands: an experimental evaluation. Water Res. 2011;45:3579–3589.

[15] de la Varga D, Díaz A, Ruiz I, Soto M. Avoiding clogging in constructed wetlands by using anaerobic digesters as pretreatment. Ecol Eng. 2013;52:262–269.

[16] Zhao YQ, Babatunde AO, Hu YS, Kumar JLG, Zhao XH. Pilot field-scale demonstration of a novel alum sludge-based constructed wetland system for enhanced wastewater treatment. Pro Biochem. 2011;46:278–283.

[17] Hellers BG, Schmidt BR. 2011. Autoclaved aerated concrete (AAC) – the story of a low-weight material. 5th International conference on autoclaved aerated concrete, Bydgoszcz, Poland, http://www.5icaac.utp.edu.pl

[18] APHA, 2005. Standard methods for the examination of water and wastewater, 21st ed. American Public Health Association/American Water Works Association/Water Environment Federation, Washington.

[19] Álvarez JA, Zapico CA, Gómez M, Presas J, Soto M. Anaerobic hydrolysis of a municipal wastewater in a pilot-scale digester. Water Sci Technol. 2003;47:223–230.

[20] Álvarez JA, Ruíz I, Soto M. Anaerobic digesters as a pretreatment for constructed wetlands. Ecol Eng. 2008;33:54–67.

[21] Akratos CS, Tsihrintzis VA. Effect of temperature, HRT, vegetation and porous media on removal efficiency of pilot-scale horizontal subsurface flow constructed wetlands. Ecol Eng. 2007;29:173–191.

[22] Carballeira T, Ruiz, I, Soto M. Effect of plants and surface loading rate on the treatment efficiency of shallow subsurface constructed wetlands. Ecol Eng. 2016;90:203–214.

[23] Barros P, Ruiz I, Soto M. Performance of an anaerobic digester-wetland system for a small community. Ecol Eng. 2008;33:142–149.

[24] Vymazal J. The use of hybrid constructed wetlands for wastewater treatment with special attention to nitrogen removal: a review of a recent development. Water Res. 2013;47:4795–4811.

[25] Zapater-Pereyra M, Gashugi E, Rousseau DPL, Alam MR, Bayansan T, Lens PNL. Effect of aeration on pollutants removal, biofilm activity and protozoan abundance in conventional and hybrid horizontal subsurface-flow constructed wetlands. Environ Technol. 2014;35:2086–2094. doi:10.1080/09593330.2014.893024

[26] Zhao L, Zhu W, Tong W. Clogging processes caused by biofilm growth and organic particle accumulation in lab-scale vertical flow constructed wetlands. J Environ Sci. 2009;21:750–757.

[27] de la Varga D, Ruiz I, Álvarez JA, Soto M. Methane and carbon dioxide emissions from constructed wetlands receiving anaerobically pretreated sewage. Sci Tot Environ. 2015;538:824–833.

[28] Maltais-Landry G, Maranger R, Brisson J, Chazarenc F. Greenhouse gas production and efficiency of planted and artificially aerated constructed wetlands. Environ Pollut. 2009;157:748–754.