Abstract

Natural wastewater treatment systems can represent a smart solution in small communities (50-2000 Population Equivalent) as they are very low-cost technologies in terms of energy consumption and maintenance. Moreover, those systems could be implemented as clean processes for wastewater reuse in the frame of circular economy applications. In this context the present study examines the main features of Subsurface Flow System - horizontal (SFS-H) phyto-treatment process. To this aim a pilot plant was built at University of Bologna in School of Engineering campus. The plant was equipped with an inlet water storage tank and two SFS-H tanks in parallel. Tanks are filled with the same sand/gravel medium while only one is equipped by Phragmites australis, commonly used in phyto-treatment applications. The study was developed in two main phases: firstly, we analysed the hydraulic behaviours, Hydraulic Retention Time (HRT) and conductivity, in steady state conditions and secondly, we focused on the treatment capacity in various HRT conditions. Measurement campaigns were conducted over around one year in order to compare Summer and Winter conditions. Results show an interesting ammonium removal efficiency (66%) when HRT is 30h, also in worst weather conditions during winter. Finally, we evaluated organic matter and nitrogen compounds removal capacity comparing the Oxygen Consumption Rate (OCR) with similar pilot treatment plants in wetland literature. OCR values result consistent, anyway we noted that they are strongly influenced by initial transitory time (around 3h).

Key words: irrigation, nitrification, SFS-H phyto-treatment, small plants, wastewater reuse

1. Introduction

The increasing use of natural wastewater treatment systems in the last years is mainly due to their features: no energy and chemicals consumption or it is very low. Indeed, those systems represent an interesting solution for sewage treatment coming from small communities (50-2000 Population Equivalent). In the last years their use is increasing as clean processes for wastewater reuse, in the frame of circular economy applications. Wastewater reuse has a key role within the wider context of water reuse that becomes increasingly necessary due to water resources scarcity. Moreover, smart implementation of natural wastewater systems in association with agricultural uses could be a very interesting solution in the near future as the agricultural sector is responsible for about 70% of annual global freshwater withdrawals (BIO by Deloitte, 2015) (Sanz and Bernd, 2014).

From a regulatory perspective, a specific directive for wastewater reuse has not been implemented yet at European level. There are several European environmental directives and member states and regional regulations. This regulations heterogeneity, in terms of uses and permitted threshold values, represents one of the barriers to wastewater reuse development at European level. To overcome this barrier the European Commission (EC) is discussing about a Regulation proposal on minimum requirements for water reuse (EC, 2018). Table 1 shows the legal thresholds values for water reuse in
related toxic NH$_3$–N equilibrium phase, can limit
and agro-industrial wastewater treatment. The full-
treatments have also been implemented for industrial
challenge in the near future. Moreover, natural
adaptation to irrigation reuse will be an important
for discharge in natural water bodies so their
(WWTPs) have been designed to respect the threshold
Total Suspended Solids (TSS).

neighbouring reuse. High values of NH$_4^+$-N, due to the
in output, nitrogen values which guarantee onsite and
with the aim to test design criteria in order to obtain,
appropriate system” by the Italian Laws on discharge,
flow phyto-treatment bed, defined “natural
studied the oxidization performance in a submerged
features of SFS-H phyto-treatment processes. We
increase TN removal by denitrification. We study
order to permit higher Hydraulic Retention Time
oxygen transfer capability of roots to filtering bed in
reach steady oxygen concentration.

The final aim of the study is to evaluate the oxygen transfer capability of roots to filtering bed in order to permit higher Hydraulic Retention Time (HRT) able to force nitrification and consequently to increase TN removal by denitrification. We study more particularly real HRT permitted by the filtering flow within the bed in function of very different steady-state alimentation conditions and we have paid attention to transitory times required to balance oxygen demand and rate transfer to the bed and to reach steady oxygen concentration.

A pilot plant has been designed and realised in
“Bertalia campus” area of Engineering School of Bologna University. The main features of the SFS-H phyto-treatment process have
developed during the first phase.

2. Material and methods

Experimentations have been carried out in existing pilot plant located in “Bertalia campus” of Engineering School of Bologna University. The main features of the SFS-H phyto-treatment process have been examined (Fig. 1). The pilot plant is fed by clean water and raw sewage from campus sewage system and is divided into two lines, named 0 and 1, consisting in two SFS-H tanks (Fig. 2). The tanks contain the same filling of sand (diameter = 2-4 mm), the first is used as blank (SFSh - 0) and in the second were planted Phragmites australis (SFSh - 1).

A sedimentation tank is placed before the tanks because the path is short and, as often happens in biofiltering beds, suspended solids could clog the following tanks gravel bed, after this pre-treatment phase the sewage is directly sent to the two (0,1) SFS-h tanks (Fig. 2).

The study was developed in two main phases:

- Phase A: Hydraulic steady state conditions: HRT and conductivity;
- Phase B: Process steady conditions: balance of oxygen and nitrification rate.

2.1. Phase A: Hydraulic steady state conditions: HRT and conductivity

The first phase was necessary to set the experimental plant looking for HRT, Hydraulic conductivity (K) in different plant configurations as they were comparable to similar real plants. Measurements have been executed using clean water in tests conducted from 25 May 2016 to 24 June 2017. Steady flow conditions were reached and controlled by calibration of valves openness which regulate input and output flow rates. In/out flow rates and openness degree of valves were compared until the achievement of each test condition. Three HRT conditions were studied: HRT = 1.5h-12h-30h (Fig. 3).

<table>
<thead>
<tr>
<th>BOD (mg/L)</th>
<th>COD (mg/L)</th>
<th>NH$_4^+$ (mgN/L)</th>
<th>TN (mgN/L)</th>
<th>TP (mgP/L)</th>
<th>TSS (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Italy (DM, 2003)</td>
<td>20</td>
<td>100</td>
<td>2</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>France (AM, 2014)</td>
<td>-</td>
<td>60*</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Spain (RD, 2007)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>10*</td>
<td>2*</td>
</tr>
<tr>
<td>Greece (CMD, 2011)</td>
<td>10-25*</td>
<td>-</td>
<td>-</td>
<td>30*</td>
<td>1-2*</td>
</tr>
<tr>
<td>EC Regulation proposal (EC, 2018)</td>
<td>10-25*</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*The limit is referred to several uses
We measured input and output flow rate until the values were similar so it means that steady flow conditions were established. Experimental conditions were verified with the equation for SFS-h systems by Çakir et al., 2015 (Eq. 1) in each HRT condition:

\[ HRT = \frac{L \cdot W \cdot n \cdot d}{Q} \]  

where: \( HRT \) = Hydraulic Retention Time (h), \( L \) = bed length (cm) = 75 cm, \( W \) = bed width (cm) = 45 cm, \( n \) = porosity (-) = 30\%, \( d \) = filling high (cm) = 27 cm, \( Q \) = flow rate (l/min).

Therefore, we calculate \( k \) using the usual formulation by Darcy Law (Eq. 2) in three flow rate conditions established before:

\[ v = k \cdot i \]  

where: \( v \) = velocity (cm/h), \( i \) = hydraulic gradient (-)

The hydraulic gradient \( i \) in hydraulic head has been verified by controls of water level within the sampling tubes (shown in Fig. 3b) inserted inside the filtering bed in correspondence to input/output sections.

2.2. Phase B: Process steady conditions: balance of oxygen and nitrification rate

During the second phase Dissolved Oxygen (DO), pH and Ammonium Nitrogen (NH4+-N) were measured in each tank in the different hydraulic conditions, investigated during the first phase, using the multiparameter system YSI 556, for DO and pH, and the Ion Selective Electrode Crison 9663C, for NH4+-N. Data have been collected during measurement campaigns conducted from 26 June 2016 to 24 July 2017.

DO, pH, NH4+-N and NO3-N were monitored by time step varying from 30 to 180 min in each scenario (HRT = 1.5h - 12h - 30h) (Fig. 4).

Second phase aims to study the aerobic conditions in the system as oxygen allows to remove organic matter and nitrogen compounds. More in details, we will compare oxygen trends with nitrification/denitrification capacity of the system with different HRT values, in order to obtain the output concentration respecting the legal thresholds.

In this context, oxygen transfer is one of the main rate-limiting processes in subsurface-flow treatment wetlands.
The prominent pathways of oxygen transfer in subsurface flow treatment wetlands are atmospheric diffusion, plant-mediated oxygen transfer, and convective flow of air within the pore space of the media (Nivala et al., 2013).

3. Results and discussion

3.1. Phase A: Hydraulic steady state conditions: HRT and conductivity

Experimental results reported in Table 2 represent the ingoing and outgoing flow rate calibration required to obtain and maintain steady flow conditions. Flow parameters into the biofiltering bed are reported in Table 3. Hydraulic conductivity resulting from Darcy law implementation and flow parameters into the biofiltering bed, in each HRT condition, are reported in Table 3.

<table>
<thead>
<tr>
<th>HRT (h)</th>
<th>Q (l/min)</th>
<th>Hydraulic Valve Openness (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>0.267</td>
<td>10 (without flow reducer)</td>
</tr>
<tr>
<td>12</td>
<td>0.038</td>
<td>50 (with flow reducer)</td>
</tr>
<tr>
<td>30</td>
<td>0.016</td>
<td>10 (with flow reducer)</td>
</tr>
<tr>
<td>OUT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>0.300</td>
<td>20 (without flow reducer)</td>
</tr>
<tr>
<td>12</td>
<td>0.036</td>
<td>90 (with flow reducer)</td>
</tr>
<tr>
<td>30</td>
<td>0.016</td>
<td>20 (with flow reducer)</td>
</tr>
</tbody>
</table>

### Table 3. Hydraulic parameters of the flow internal to the filtering bed related to each HRT condition

<table>
<thead>
<tr>
<th>HRT (h)</th>
<th>Q (cm³/min)</th>
<th>v (cm/h)</th>
<th>ΔH (cm)</th>
<th>i (-)</th>
<th>K (cm/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>300</td>
<td>37.04</td>
<td>1.1</td>
<td>0.0141</td>
<td>2626.74</td>
</tr>
<tr>
<td>12.65</td>
<td>36</td>
<td>4.44</td>
<td>0.10</td>
<td>0.0016</td>
<td>2629.85</td>
</tr>
<tr>
<td>29.53</td>
<td>16</td>
<td>1.98</td>
<td>0.05</td>
<td>0.0007</td>
<td>2645.50</td>
</tr>
</tbody>
</table>

Fig. 3. Pilot plant scheme with flow rate measurements points identified with blue arrows (a). SFSh-0 and SFSh-1 tanks view from the output (b). Detail of the regulation valves (c).

3.2. Phase B: Process steady conditions: balance of oxygen and nitrification rate

The following graphs (Figs. 5-10) represent the initial transitory for DO, NH₄⁺-N and NO₃⁻-N parameters respectively for HRT= 1.5 h, HRT= 12 h, HRT= 30 h.

Data in Fig. 5 show as not completely outraced the transitory from the initial conditions. It’s detectable a clear oxygenation effect by roots of plants. The input rate in water maintains the DO level higher than the one measured in the reference bed without plants around 1 mg/L.

The registered trends of NH₄⁺-N and NO₃⁻-N concentrations, as traced in Fig. 6, indicates as not outraced the initial transient phase for both parameters. The final efficiency in Ammonium Nitrogen removal, evaluable around 15 %, attests a very limited nitrification effect. As reported in Fig. 7, at the beginning of the test, it has been noted an oxygen consumption rate prevalent on the rate of
SFS-H phytotreatment oxi-nitro rate tested in steady-state on engineering-UNIBO PILOT plant

The phenomenon is due to the kinetic of carbonaceous BOD and to the conditions of the medium at starting of flow, which initially presents high oxygen demand for the release to the sewage of organic substances cumulated during the time of out-of-service. This transient phase appears to be limited to around two hours from start. The final steady condition shows a DO level equal to e 5.5 mg/L (about 2 mg/L higher than the not planted bed) and it is reached approximately after 10 h.

The transitory trend of the outlet concentration of ammonium nitrogen is complementary to that of dissolved oxygen and the regime condition, equally reached after about 10 hours, reveals an ammonium concentration of 19.5 mg/L (about 15 mg/L less than that of the not planted bed). The nitrification efficiency, after 12 hour of retention time, is evaluated around 43% (Fig. 8).

Fig. 5. HRT = 1.5 h - Dissolved Oxygen concentrations measured by YSI probe in S2 sampling tubes with plants (blue line) and without plants (red line)

Fig. 6. HRT = 1.5 h - Ammonium (green line) and Nitrate (black line) concentrations in samples from S2 tubes

Fig. 7. HRT = 12 h - DO concentration measured by YSI probe in S2 sampling tubes with plants (blue line) and without plants (red line). *day after

The graph in Fig. 9 shows that the regime condition for dissolved oxygen is reached after about 24 h and is characterized by a concentration of about 5 mg/L (also in this case about 2 mg/L higher than that of the not planted bed). The initial transient phase of oxygen demand due to the bed is included within the initial 3 hours.

Fig. 8. HRT = 12 h - Ammonium concentration (NH₄⁺-N) analysed in samples from S2 sampling tubes without plants (green line) and with plants (grey line). *day after

Also, the steady condition for nitrification is reached after about 24 h and it is characterized by an initial stretch with high slope during around 6 hours from start. The output regimen NH₄⁺-N concentration becomes around 11 mg/L (in this case 20 mg/L less than not planted bed NH₄⁺-N concentration).

Results of measurements carried out with HRT equal to 30 h show an interesting NH₄⁺-N removal efficiency (66%)(Fig. 10).

Fig. 9. HRT = 30 h - DO measured by YSI probe in S2 sampling tubes with plants (blue line) and without plants (red line). *day after

Fig. 10. HRT = 30 h - Ammonium concentration (NH₄⁺-N) analysed in samples from S2 sampling tubes without plants (green line) and with plants (grey line). *day after
Anyway, ammonium output concentration does not guarantee yet the respect of the Italian legal threshold for reuse in irrigation (2 mg/L). To estimate the oxygen consumption in relationship with pollutants degradation in wetland processes the approach based on Oxygen Consumption Rate (OCR) estimation is commonly used. The equations proposed in wetland literature for OCR are related to surface of bio-filtering bed and estimation generally include: mass removed for a specific parameter as Biochemical Oxygen Demand, Chemical Oxygen Demand, NH4+-N and Total Kjeldahl Nitrogen (TKN) calculated by flow rate and input/output concentration.

In this study we consider the equation proposed by (Kadlec and Wallace, 2009) that takes into account the ratio between BOD and TKN mass removed and surface area. Implementing the data collected in our case, the OCR values result 12.8 g/m²-d and 7.6 g/m²-d with HTR equal to 12 h and 30 h respectively.

Moreover, OCR values are around 55 g/m²-d during a transitory initial period (3h) when the process behaviour is transitory and appear more similar to a vertical flow wetland system. Consequently the final OCR values are strongly influenced by this transitory time so we recalculate the values excluding the transitory initial time, founding values equal to 1.9 g/m²-d and 4.4 g/m²-d with HTR equal to 12 h e 30 h respectively.

The higher value, in HRT=12 hours test, represents OCR conditions still affected by the transitional oxy/nitro phase. Those OCR values are consistent with literature values in wetland treatment of urban wastewater. In the hypothesized test conditions: HRT = 1.5h - 12h - 30h the experimentations show removal efficiency (66%) but output concentration of ammonium doesn’t guarantee yet the respect of bounds of 2 mg/L of the Italian legal threshold for reuse in irrigation. For this further experiment is forecasted and planned with HRT 36-48 h.

It’s possible to conclude that results obtained operating with HRT equal to 30 h show an interesting removal efficiency (66%) but output concentration of ammonium doesn’t guarantee yet the respect of bounds of 2 mg/L of the Italian legal threshold for reuse in irrigation. For this further experiment is forecasted and planned with HRT 36-48 h.

Finally, the organic matter and nitrogen compounds removal capacity was evaluated comparing the OCR with similar pilot treatment plants in wetland literature. OCR values result 1.9 g/m²-d and 4.4 g/m²-d with HTR equal to 12h e 30h respectively.

Anyway, we noted that it is strongly influenced by initial transitory time (around 3h).

4. Conclusions

This study deals with the possibility to adopt, for reuse in irrigation, SFS phyto-treatment systems for wastewater treatment of small communities or for finishing treated effluents from WWTPs. The measurements campaigns have been carried out in order to obtain information about applicability and design criteria with reference to the legal thresholds from the Italian regulation for wastewater reuse.

The operating conditions of a SFS-h phyto-treatment pilot plant have been studied in different HRT and Flow Rate scenarios aiming to verify the operational conditions of a real scale plant working in steady state. In the hypothesized test conditions: HRT =1.5h - 12h - 30h the experimentations show hydraulic conductivity values around 2600 cm/h in accordance with the references available in scientific literature.

In terms of oxygen balance and oxidation capability, in a transient phase limited to the first two/three hours it has been noted a decreasing trend for DO probably due to the kinetic of carbonaceous BOD and to the conditions of the medium at starting of flow, enriched of organic substances cumulated during the time of out-of-service.

Good values of DO within the filtration flow (around 5 mg/L) are guaranteed in all test conditions and steady process conditions are reached both with HRT=12 and with HRT =30. In the first case, nitrification rate brings the concentration of ammonium nitrogen to 19.5 mg/L with a nitrification efficiency around to 43 % . In the second case (HRT=30 h), the output regimen concentration of NH4+-N decrease to 11 mg/L (20 mg/L less than that of the not planted bed).

It’s possible to conclude that results obtained operating with HRT equal to 30 h show an interesting removal efficiency (66%) but output concentration of ammonium doesn’t guarantee yet the respect of bounds of 2 mg/L of the Italian legal threshold for reuse in irrigation. For this further experiment is forecasted and planned with HRT 36-48 h.

Finally, the organic matter and nitrogen compounds removal capacity was evaluated comparing the OCR with similar pilot treatment plants in wetland literature. OCR values result 1.9 g/m²-d and 4.4 g/m²-d with HTR equal to 12h e 30h respectively, and they are consistent compared to similar pilot plants. Anyway, we noted that it is strongly influenced by initial transitory time (around 3h).

References


