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HORIZONTAL SUBSURFACE FLOW PHYTOTREATMENT FOR DOMESTIC WASTEWATER TREATMENT: NITRIFICATION-DENITRIFICATION EFFICIENCY TESTED ON BERTALIA-UNIBO PILOT PLANT

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Abstract

Climate change and environmental crises have a very big impact on water cycle in terms of water availability. The scarcity of water impacts agricultural production, while its quality influences the safety of agricultural products and consequently public health. A sustainable way to supplement agricultural production and industrial water needs stands in the reuse of wastewater. Moreover, it is so necessary to develop smart, sustainable and efficient wastewater treatment technologies in terms of construction and management cost for small communities. Natural wastewater treatment systems represent a cost-effective treatment, already tested and implemented all around the world.

In this context, this study focuses on horizontal sub-surface flow phytotreatment systems implementation with the aim to understand the processes and features involved to optimize both design and technical management phases. This work is a continuation and extension of previous studies conducted by the authors and focuses on nitrification and denitrification processes.

To this aim, a pilot plant located on Bertalia-UNIBO campus in Bologna was monitored to evaluate the nitrification-denitrification efficiencies related to seasonal variation of Temperature, dissolved oxygen at different hydraulic retention time. The pilot plant was charged with a domestic wastewater and the emergent macrophytes were *Phragmites australis*. The tests show good nitrification efficiencies in summer (from 78% to 91%) at HRT more than 12 h and the resulting data were stable at 30h. Winter nitrification efficiencies are lower than summer (44%, 66%) at HRT more than 12 h. As expected, dissolved oxygen was greater in winter than summer. Denitrification efficiency were in the range 40% - 75%, increasing with HRT. Results also show that full scale implementations need HRT equal 30h in order to reach significant nitrification rates.

Key words: denitrification, nitrification, small plants, SFS-H phytotreatment, wastewater reuse

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1. Introduction

Climate change together with population growth and urbanization have a huge impact on water cycle in terms of water quality and availability. In the last years, many countries suffer from drought. Indeed, the number and duration of droughts have increased by 29% since 2000, as compared to the two previous decades (UNDRR, 2021). Hence, more than 2.3 billion people already face water stress, especially in developing countries. The scarcity of water impacts agricultural production, while its quality influences the safety of agricultural products such as fresh fruits or vegetables and consequently public health (FAO, 2017).

A sustainable way to supplement agricultural production and industrial water needs stands in the reuse of wastewater. Thus, on the one hand, research

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and development in wastewater treatment must focus on the improvement of water quality in water bodies, where treated sewage is discharged, to reach adequate sanitary quality standards. On the other hand, it is necessary to develop smart, sustainable and efficient wastewater treatment technologies in terms of construction and management cost, with a direct impact on the treatment processes adopted. Natural wastewater treatment systems represent a cost-effective treatment, thoroughly tested and implemented all around the world (Barjoveanu et. Al., 2010; Kadlec and Wallace, 2009) which interest is still very high (Jiang and May Chui, 2022).

Processes involved in those systems are related to several natural parameters: plant growth, soil substrate and atmospheric parameters (such as Temperature, solar irradiation, wind). Consequently, it is a low-cost technology in terms of construction and maintenance (very low or even zero energy consumption), minimal hands-on maintenance (Kadlec et al., 2000; Vymazal, 2014). In the last years many studies have been conducted on efficiency of those systems mainly related on the HRT under different process conditions: influent sewage, previous treatments, soil media, plants and obviously different climatic zones and countries.

Ghosh and Gopal (2010) studied the efficiency of a subsurface flow constructed wetlands (CWs) used as tertiary treatment showing a good removal efficiency at 4 days HRT. The study also showed removal efficiency at lower HRT even if the system was not as stable. In subtropical climate Merino-Solís et al. (2015) set al studied the performance of a pilot plant for urban wastewater treatment consisting of anaerobic filter followed by a horizontal subsurface constructed wetland showing the real possibility to implement those systems in subtropical climate zones. According to the Italian environmental law, natural wastewater treatment systems are suitable and recommended for urban discharges of towns under 2000 population equivalent (PE) (DLGS, 2006). In wider terms, natural wastewater treatment plants are well suitable for small communities, less than 10000 PE (García et al., 2001; Garfí et al., 2017). In larger agglomeration, it would be arduous to achieve the legal discharge thresholds as the plant design and technical management is much complicated. Design difficulties are mainly related to the Nitrogen removal from wastewater while technical management difficulties are related to transient inlet loading, high wet weather flows due to runoff, primary treatment adequate management. Instead, the implementation of natural wastewater treatment plants for water reuse is a smart solution especially in small communities (like farmhouses, holiday parks) as reused water needs are close-range from the treatment facilities.

In this context, it is necessary to deepen the hydraulic behavior and the efficiency of natural treatment systems implemented in the specific climatic conditions of Northern Italy. To this aim this study focuses on Horizontal Sub-Surface flow (SFS-H) phytotreatment systems implementation with the aim to understand the processes and features involved to optimize both design and technical management phases.

This work is a continuation and extension of previous studies conducted by the authors Fiorentino and Mancini, (2020) and Mancini (2004), and focuses on nitrification and denitrification processes in Horizontal Sub-Surface flow (SFS-H). A pilot plant located on Bertalia-UNIBO campus in Bologna was monitored to measure and evaluate the nitrification-denitrification efficiency related to seasonal variation due to Temperature, Dissolved Oxygen (DO) at different Hydraulic Retention Time (HRT), from 1.5 to 30 hours. Seasonal monitoring also considers the vegetation state of plants (*Phragmites australis*). The pilot plant was charged with a domestic wastewater coming from bathrooms and bar activities of the Bertalia Engineering Campus. The measurement campaigns were performed over twelve months, to compare summer and winter conditions, considering the following parameters that affect the nitrification-denitrification processes such as: pH, Dissolved Oxygen (DO), Ammonia (NH_4^+-N) and Total Nitrogen (TN) concentrations.

2. Materials and methods

For this study, experimentations were conducted on the existing pilot plant scale located in Bertalia campus of the University of Bologna (School of Engineering) (Fig. 1a).

The experimental unit of the pilot plant consisting in a sedimentation tank followed by the Horizontal Sub-Surface flow tank called “SFS H-1” containing sand (diameter = 2-4 mm) in which were planted *Phragmites australis* (Fig. 1b). The pilot plant is fed by the raw sewage from the campus sewage system coming from toilets, canteen service and bar.

The sedimentation tank aims to avoid that suspended solids could clog the following SFS-H tank gravel bed, as often happens in biofiltering beds when the path from discharge point is short (Fig. 2). Eight monitoring campaigns were conducted in one year, in different seasonal conditions (five in summer and three in winter) setting three Hydraulic Retention times (HRT): 1.5, 12 and 30 hours. After an acclimatization time of the bed, the tests were done at HRT equal to 1.5 and 12 hours in order to have a complete and exhaustive timeline and to see the hydraulic steady state conditions (Fiorentino and Mancini, 2020). HRT equal to 30 hours, after the acclimatization time, is the minimum limit above which the system starts to be interesting in efficiency terms. During each monitoring campaign were measured: Ammonium Nitrogen (NH_4^+-N); Total Nitrogen (TN); Dissolved Oxygen (DO), Temperature (T). Ammonium nitrogen, dissolved oxygen, pH and temperature were measured on site using the Ion Selective Electrod Crison 9663C (NH_4^+-N) and the multiparameter system YSI 556 (DO, pH and T) in probe tubes specifically positioned at the beginning and the end of the SFS H-1 tank.

Fig. 1. (a) Bertalia campus of the University of Bologna (School of Engineering) - pilot plant location marked with black circle (44°30'50.4''N – 11°19'16.5''E); (b) pilot plant front view

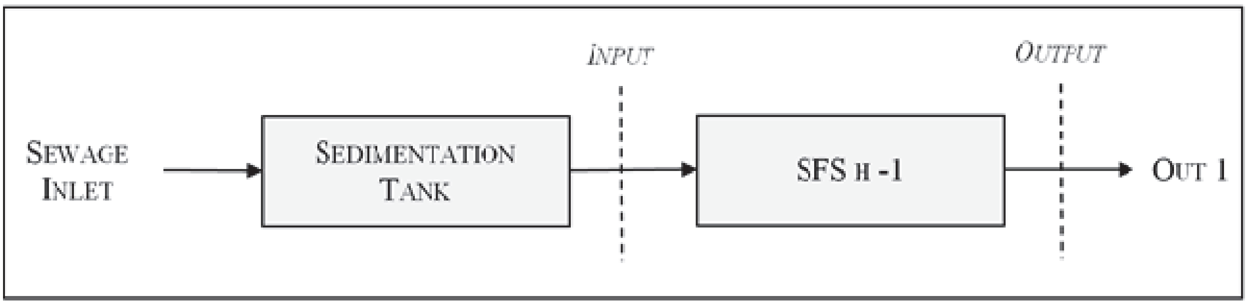

Fig. 2. Pilot plant flow scheme with sampling sections (Input and Output)

Simultaneously, samples were collected in the same tubes for TN analysis. TN was determined according to the 4500-N C. Persulphate Method from APHA Methods for water and wastewater (APHA, 1998). According to this method, TN concentration is determined by alkaline oxidation of all nitrogen compounds to nitrate at 100 to 110°C. The digestion reagent is potassium persulfate ($K_2S_2O_8$). Spectrophotometric measurement permits to obtain the Nitrate concentration, resulting from the oxidation, reading the absorbance against distilled water at the wavelength of 220 nm.

However, organic matter may also absorb at 220 nm and a second measure must be done at the wavelength of 275 nm to correct the nitrate value, as it does not absorb at this wavelength. The implementation of this method is more appropriate than Kjeldahl method in our case, because it hasbeen shown more precision and accuracy to determine TN in aqueous samples (Smart et al., 1981).

3. Results and discussion

Table 1 shows the results of experimentation in terms of Ammonium nitrogen (NH_4^+-N) and Total Nitrogen (TN), Dissolved Oxygen (DO) and Temperature (T) at different HRT in summer and winter. Nitrification and denitrification efficiency have been calculated from NH_4^+-N and TN monitoring results and reported in columns five and eight. During the monitoring campaigns M6-M7-M8 was not possible to measure TN and consequently the denitrification efficiency ("-" in Table 1). Each measurement campaign has been called "M" with progressive number from 1 to 8 followed by "Summer" or "Winter", depending on the monitoring season. DO and T is reported in the last two columns of Table 1 and discussed to understand the process conditions in each monitoring campaign.

We observe that nitrification efficiency increase with HRT in winter, from 16% to 66% with similar NH_4^+-N inlet concentrations. Summer nitrification efficiency in M2, M3 (HRT=12h) M4 and M5 (HRT = 30h) is higher than M1 (HRT=1.5h), in accordance with winter results but we don't observe a marked increase with higher HRT even if the value is very similar. This could be due to the NH_4^+-N inlet concentrations variation, from 22.12 mgN/L to 57.66 mgN/L, and in particular in M4 we observe a good removal efficiency (81%) with input concentration very high (57.66 mgN/L) showing that nitrification process is stable and efficient at this HRT.

The consideration made above is even more clearer in Fig. 3 where we reported the NH_4^+-N results for each measurement campaign and we observe that vertical line corresponding to M4 is the biggest meaning that is the biggest NH_4^+-N decrease.

Concerning the denitrification process, the data shown a TN removal efficiency increase with HRT, from 40% to 75% with Input form 26.54 mgN/L to 69.19 mgN/L. Also in this case in M4 we observe (Fig.

4) the best removal efficiency (75%) with the higher Input concentration (69.19 mgN/L).

DO concentration measured in the tank gravel bed is greater than 2 mg/L, lower limit below which oxi-nitrification process may not operate. In general terms, Oxygen inlet in the system occurs both in winter and summer but, as expected, DO concentrations are higher in winter than summer due to due to the higher oxygen saturation concentration at lower temperatures. Temperature measures follows seasonal variation and directly affects the degradation kinetics: lower. Temperature correspond to lower nitrification efficiencies. The nitrification efficiency variations between summer and winter also depends on the photosynthetic activity of the plants, *Phragmites australis* in this case, which is responsible of the oxygen concentration near the roots. Oxigen supply near the roots is maximum in summer when the plants are in the vegetative stage (Wang et al., 2019).

4. Conclusions

The study focuses Horizontal Sub-Surface flow (SFS-H) implementation for small communities and wastewater reuse. To this aim, the efficiency of nitrification and denitrification processes in SFS-H have been tested in Bertalia-UNIBO pilot plant conducting eight monitoring campaigns at different Hydraulic Retention Rates, in summer and winter. The tests show good nitrification efficiencies at HRT more than 12 h even if the data start to be stable at HRT equal to 30h.

It is possible to consider that HRT more than 30h, realist for full scale implementations, this process is even more stable. In any case, it is important to point out that, removal efficiency is strictly connected to treated sewage and in this it comes case from the Bertalia Campus facilities (toilets, canteen service and bar) that was already oxygenated.

Table 1. NH_4^+-N, TN, DO and T monitoring data in INPUT and OUTPUT sections, in summer and winter measurement campaigns in different Hydraulic Retention Time (HRT)

Measurement Campaign	*HRT (h)*	*NH_4^+-N (mgN/L)*	*NH_4^+-N (mgN/L)*	*Nitrification efficiency (%)*	*TN (mgN/L)*	*TN (mgN/L)*	*Denitrification efficiency (%)*	*DO (mg/L)*	*T (°C)*
		Input	***Output***		***Input***	***Output***			
M1 - Summer	1.5	30.11	19.48	35	36.13	21.79	40	1.56	20.2
M2 - Summer	12	24.60	2.30	91	29.52	10.88	63	2.92	19.5
M3 - Summer	12	22.12	2.95	87	26.54	13.38	50	2.44	21.5
M4 - Summer	30	57.66	11.18	81	69.19	17.18	75	2.39	28.2
M5 - Summer	30	29.18	6.36	78	35.02	12.70	64	1.99	22.0
M6 - Winter	1.5	35.39	29.72	16	-	-	-	4.03	6.5
M7 - Winter	12	33.45	18.86	44	-	-	-	4.24	3.9
M8 - Winter	30	32.21	11.02	66	-	-	-	4.14	6.1

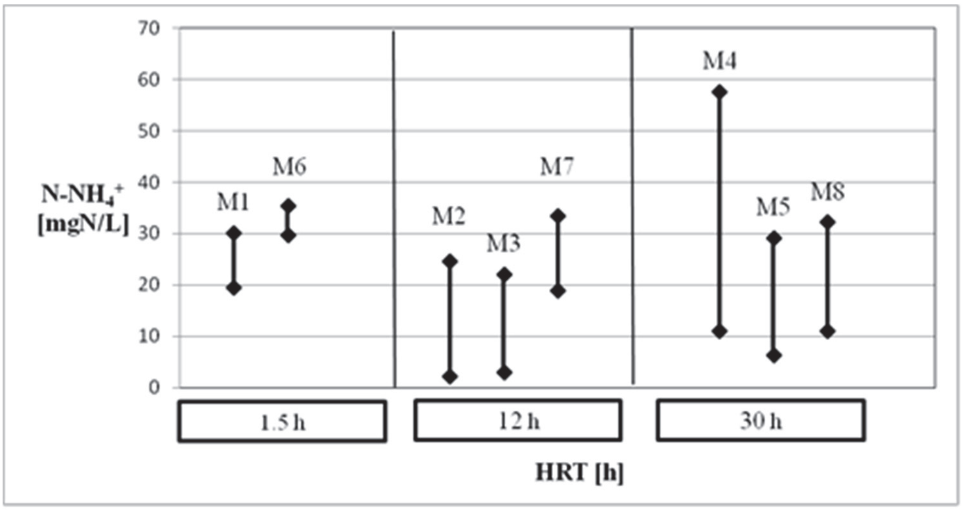

Fig. 3. Ammonium concentration in INPUT and OUTPUT sampling points in summer (M1, M2, M3, M4 and M5) and winter (M6, M7 and M8) related to each HRT

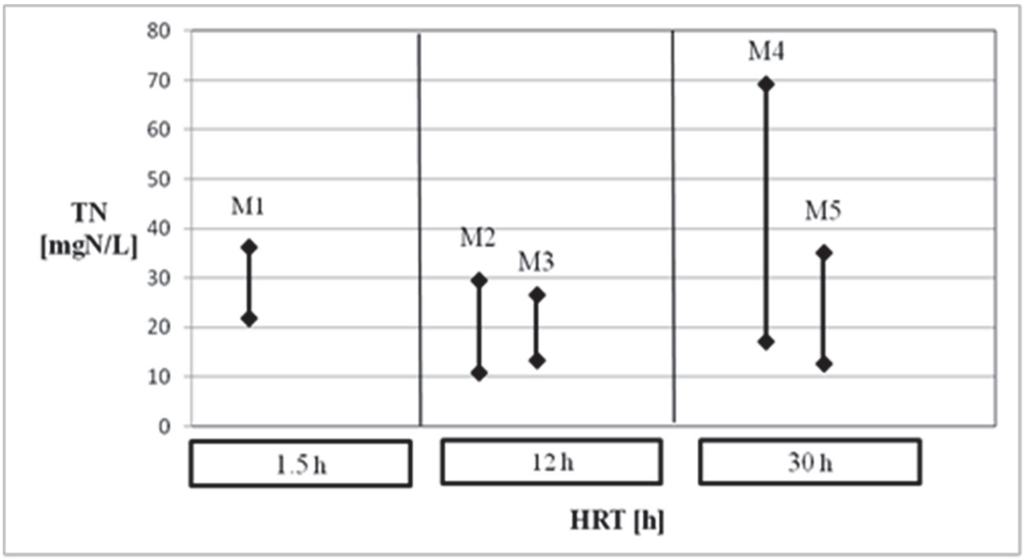

Fig. 4. Total Nitrogen concentration in INPUT and OUTPUT sampling points in summer (M1, M2, M3, M4 and M5) and winter (M6, M7 and M8) related to each HRT

Denitrification efficiency was evaluated only in summer and the values were in the range 40% - 75%, increasing with HRT. Hence, the data shown that denitrification process in those systems may have good efficiencies due to the presence of anoxic areas in the gravel bed. Denitrification efficiency also depends on nitrification in terms of ammonia concentration as well as organic matter.

As expected, Dissolved Oxygen values, measured in the tank gravel bed, are greater in winter than summer but they show the proper functioning of the system in terms of oxi-nitrification as all values are greater than 2 mg/L.

It has been confirmed that full scale implementations need HRT equal 30h in order to reach significant and reasonable nitrification rates. HRT more than 30 h should be tested in future.

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