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SOLID WASTE MIXTURES AS CONSTRUCTED WETLANDS FILLING: EFFECT OF HYDRAULIC LOADING RATE ON NUTRIENT REMOVAL FROM WASTEWATER

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Abstract

This study aims to contribute to constructed wetlands' (CWs) eco-efficiency by applying the concepts of circular economy and waste to treat waste. Five sets of lab-scale CWs with different combinations of filling materials were evaluated and the effect of the hydraulic loading rate (HLR) on the nutrient removal efficiencies was studied. Each CW set consisted of two, duplicate, plastic pots with solid waste filling supporting *Phragmites australis* macrophyte plants. The filling materials were layer combinations of limestone rock fragments, a waste from construction activities, and one of four other solid wastes: cork granulates from the cork industry (LCG); snail shells from the food and catering industry (LSS); coal slag from coal power plants (LCS); and clay brick fragments from construction activities (LBF). A reference set (LO) was filled only with limestone fragments. The CWs were operated using a low-strength wastewater in successive fill-and-drain cycles with a retention time of one to eight days and a one-day rest. Their removal efficiency was evaluated for COD, total phosphorus (TP) and total nitrogen (TN). All four CWs with mixed filling showed COD removal efficiencies higher than the reference CW and above 79%. The highest removal efficiency was achieved by the LCS CW (91 to 97%). The reference LO CW showed the highest TP removal efficiency. With exception of the LSS CW, the mixed filling CWs showed removal efficiencies close to the reference CW (above 55%). All but the LSS CW showed higher TN removal efficiencies than the reference CW (above 51%). The observed effect of HLR depends on the type of CW. The effect on COD, TP and TN removal efficiencies averaged 9%, 15% and 20%, respectively, for a range of HLR from 0.005 to 0.087 m/day. From this study it can be concluded that all tested layer-packed mixed solid waste fillings are adequate substrate combinations for nutrient removal from wastewater. Moreover, high nutrient removal efficiencies were maintained over a wide range of hydraulic loading rates. This innovative combination of waste materials can improve the CW adaptability to specific types of wastewater and contribute to reducing solid waste disposal in landfills.

Keywords: Circular economy, Eco-efficiency, Waste reuse, Wastewater treatment

1 INTRODUCTION

Constructed wetlands (CWs) are a green technology for wastewater remediation, engineered to simulate natural wetlands with an improved control over the treatment capabilities (Kadlec and Wallace, 2009). CWs have efficiently been used to treat diverse types of wastewater in the last few decades, but are still the object of intense research (Mateus et al., 2016; Wang et al., 2017; Wu et al., 2014; Wu, et al, 2015a; Wu, et al., 2015c). Despite representing a lower-energy and less-operational requirements alternative to the conventional wastewater treatment systems, CWs are land-intensive and it is consensual that their sustainability remains a challenge.

Sub-surface flow CWs consist of two basic structural and one biota components: (i) A basin lined with a geomembrane and provided with drains for wastewater inlet and treated water collection, which serves as a container to the filling medium; (ii) A granular filler medium to support the growth of macrophyte plants and microbial biofilms; (iii) Macrophyte plants and microbial community. CWs treat wastewater trough combined physicochemical and biological processes by the action of both the filling medium and biota components.

Design and operation factors such as plants and filling medium selection, hydraulic loading rate (HLR), hydraulic retention time (HRT), and feeding mode are crucial to achieve a sustainable treatment performance (Wu, et al., 2015b). In general, batch tidal flow operation (fill-and-drain operation) can result in better performance than continuous operation by promoting more oxidized conditions, with the advantage of lower capital and operation costs than aerated systems (Zhang et al., 2012).

The optimal design of HLR and HRT plays an important role in the removal efficiency of CWs and significantly influences investment costs. High hydraulic loads promote the faster passage of wastewater through the filling medium, thus reducing the ideal contact time. On the contrary, longer HRT allow an adequate contact time for the contaminant removal processes but require higher areas (Wu et al., 2015b).

A possible strategy to enhance CW performance for sustainable wastewater treatment consists in the use of low-cost materials as filling medium. Several works focused in the capabilities of sub products and waste solids as sorbent for water pollutants (Vohla et al., 2011; Wang et al., 2013; Westholm et al., 2014). However, most works deal only with bench scale sorption experiments and mainly for phosphate or phosphorous compounds sorption. The potentiality of such materials as CW wetlands fillers should be assessed at larger scale, on real CW operating conditions, and with multicomponent polluted waters.

This study aims to contribute to the development of an eco-efficient design through the concept of circular economy and the use of waste to treat waste. To achieve that goal, five combinations of waste solids were evaluated as CW fillers, evaluating the organic matter and nutrients removal rates from wastewater in lab-scale but real operative CWs, under tidal flow operation and for variable HLR.

2 METHODS

Combinations of five solid wastes were evaluated as filling materials for CWs used for wastewater treatment: cork granulates resulting from the cork industry; snail shells resulting from the food and catering industry; coal slag resulting from power plants; clay brick fragments and limestone rock fragments, both resulting from construction activities. To evaluate the combined capability of the waste materials to treat wastewater, five sets of lab-scale CWs were established. They were located indoors, at an average daily temperature of 17.7 ± 1.0 °C, and consisted of truncated cone pots in black opaque plastic with 35.0 cm x 31.5 cm x 39.0 cm in height, lower and upper diameter (Figure 1). A reference set was filled only with limestone fragments, already shown to be a good CW substrate (Mateus et al., 2012). The remaining four sets were filled with three layers, a 7 cm bottom layer and a 7 cm top layer of limestone fragments and a 15 cm inner layer of each of the evaluated waste materials. This combination of materials was intended to increase the CWs' removal of organic and nitrogen compounds from the wastewater, limestone had particularly been shown to remove phosphorous compounds (Mateus et al., 2012). The water level was maintained 3 cm below the surface of the top layer to avoid contact with the atmosphere, as is usual in subsurface CWs. All CWs were planted with two shoots of the reed *Phragmites australis*.

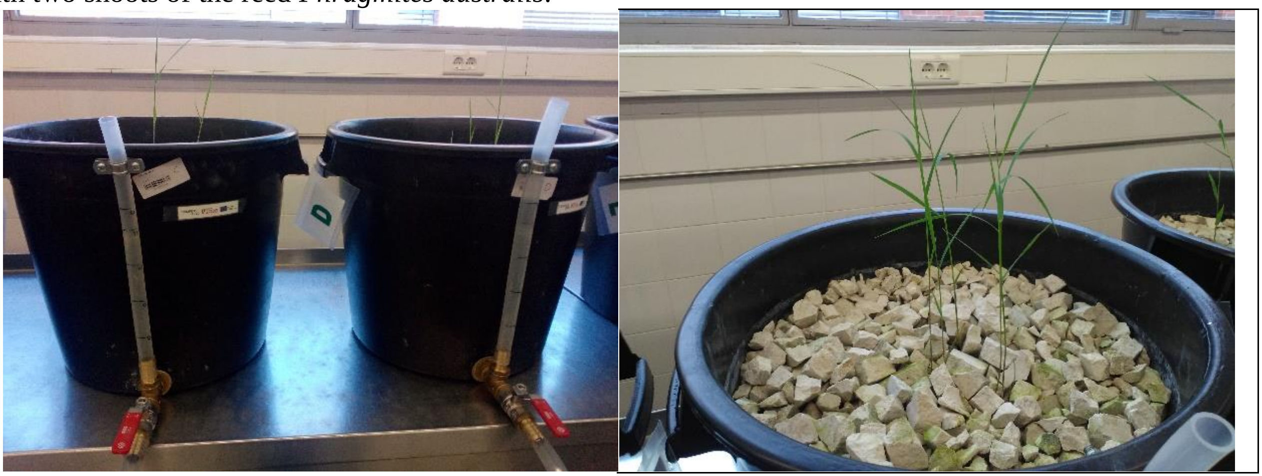

Figure 1 – Photographs of the experimental lab-scale constructed wetlands setup

The CWs were operated in a discontinuous mode for successive fill-and-drain cycles with variable flooded time (corresponding to HRT of 0.5, 1, 2, 4, 6 and 8 days) and a one-day drained time. In two preliminary cycles, the CWs were fed with effluent from a well-established pilot-scale tertiary-treatment CW to enhance the establishment of a microbial community. For the following cycles, the CWs were fed with a synthetic low-strength wastewater prepared from tap water (COD=261±29 mg_{O2}/L; total P=2.23±0.06 mg_P/L and total N=17.63±0.88 mg_N/L; pH=7.61±0.03).

The particle size distribution of the studied waste solids was examined using standard sieve analysis techniques and the values of d_{10} and d_{60} were determined (EN 933-1:2012). The pycnometer method was used to evaluate the true density of the solids, according to European Standards (EN 1097-6:2013). The loose bulk density and voids were determined, also following European Standards (EN 1097-3:1998). The CWs' working bulk porosity was evaluated measuring the required water volume to flood the pots filled with the different waste material combinations. Total phosphorous (TP), total nitrogen (TN) and chemical oxygen demand (COD) analysis were performed with reagent kits from Hanna Instruments. A COD heat block (HI-839800, Hanna Instruments) was used to perform the required digestions and a photometer (HI-83399, Hanna Instruments) was used to perform the analysis. At least two replicates were made for all assays and measurements.

3 RESULTS

Table 1 shows the physical properties of the five tested materials. Table 2 shows the three layer combinations and the mixed-filler working porosity of the five lab-scale CW sets.

Table 1. Physical properties of the individual waste solids

Solid waste	Density (Mg/m^3)	Bulk density (Mg/m^3)	d_{10} (mm)	d_{60} (mm)	d_{60}/d_{10}
Clay brick fragments	2.67 ± 0.03	1.069 ± 0.003	1.9	6.5	3.4
Coal slags	2.10 ± 0.05	0.880 ± 0.004	0.06	1.2	19
Cork granulates	0.15 ± 0.01	0.072 ± 0.001	2.2	3.6	1.6
Limestone fragments	2.69 ± 0.01	1.309 ± 0.001	7.2	11.2	1.6
Snail shells	2.56 ± 0.06	0.130 ± 0.001	11.2	14.8	1.3

Table 2. Identification of the lab-scale CWs' waste solids combinations and bulk porosity

CW	Bottom and top layers	Middle layer	Porosity
LBF	Limestone fragments	Clay brick fragments	0.371 ± 0.013
LCG	Limestone fragments	Cork granulates	0.404 ± 0.006
LCS	Limestone fragments	Coal slags	0.186 ± 0.008
LO	Limestone fragments	Limestone fragments	0.388 ± 0.007
LSS	Limestone fragments	Snail shells	0.442 ± 0.017

The d_{10} and d_{60} are the diameters corresponding to 10% and 60% finer in the particle size distribution, by weight, respectively. The ratio d_{60}/d_{10} is the uniformity coefficient, which should be less than 4 to prevent the risk of water flow clogging (Arias et al., 2001). Materials with a coefficient of uniformity higher than 4 are not recommended for use in CW unless they are mixed with other materials. This was the case for the coal slags.

Figures 2 to 4 show the nutrient removal rates from wastewater for the five lab-scale CWs plotted against HLR, corresponding to the different flood times investigated. Due to the differences in CW porosity (Table 2), the same HRT correspond to different HLR for CWs with different solid waste combinations.

4 DISCUSSION

All four CWs with mixed filling showed COD removal efficiencies higher than the reference CW and above 79%. The highest COD removal rates were obtained for the LCS CW and the lowest for the control LO CW. COD removal rates were not significantly affected by the increase in HLR in the experimental range. The average variation between the lowest and highest removal rate was 9%. The LO CW showed the highest variation, from 70.3% at the highest HLR to 86.1% at the lower HLR. The LCS CW showed the lowest dependence of COD removal rate on the HLR, with a small fluctuation between 91.0% and 96.6% and with an average of 93.7%. All observed COD removal rates were higher than 70%, which indicates that all the waste materials tested are good CW filling materials for the removal of oxidable compounds.

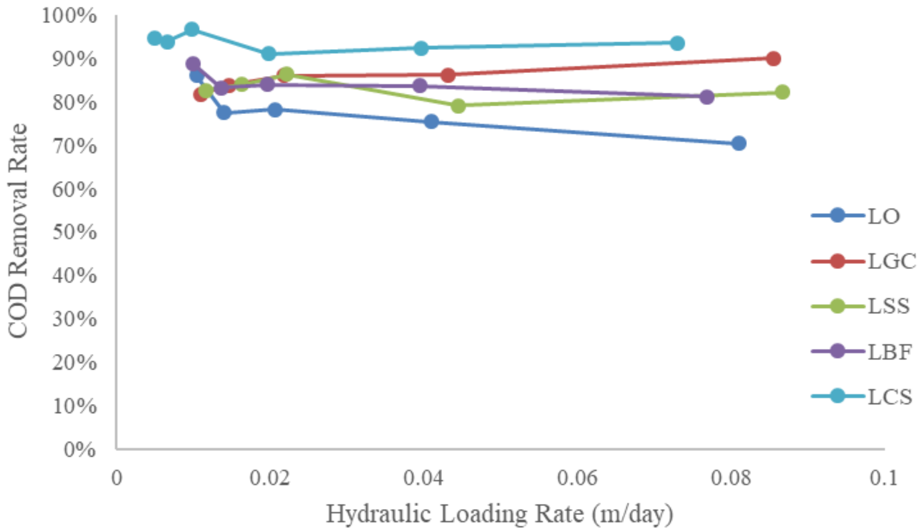

Figure 2. COD removal rate from wastewater for the five lab-scale CWs

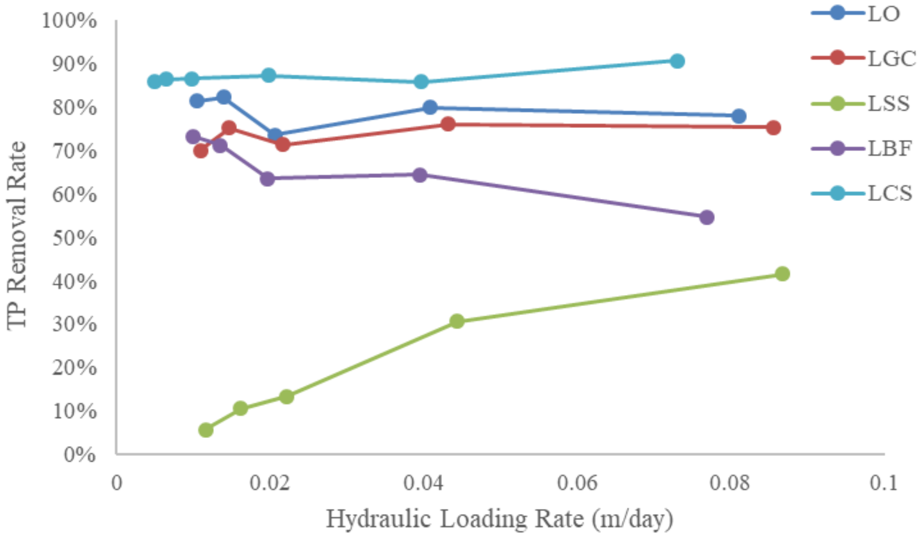

Figure 3. TP removal rate from wastewater for the five lab-scale CWs

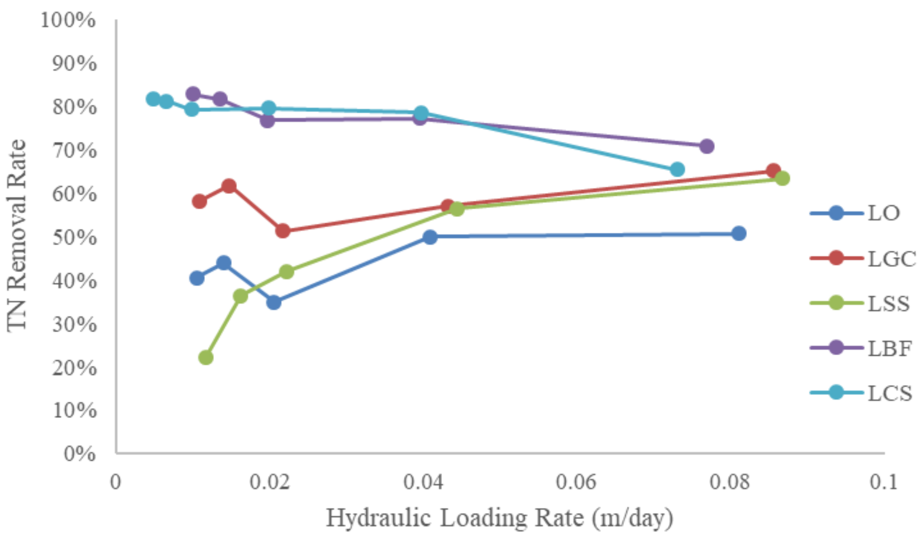

Figure 4. TN removal rate from wastewater for the five lab-scale CWs

Analogous to COD removal, the TP removal rates showed to be only slightly affected by the increase in HLR, with exception for the LSS CW. Surprisingly, for that CW the TP removal rate was positively affected by increasing the HLR. This observation may be due to the release of snail shell organic residual matter in the first operation cycles. Although the LSS CW showed TP removal rates lower than the obtained for the others CWs, future work should try to clarify this phenomenon. The highest TP removal rates were obtained for the LCS CW, in the range of 85.7% to 90.7%, and with very little variation with the increase in HLR. The average variation of the TP removal rate with HLR was 14.8%, but this was strongly affected by the LSS CW results. Excluding this CW, the variation of TP removal was 9.6%. All but the LSS CW showed to be good alternatives for TP removal from wastewater, with removal rates above 55%.

The removal percentages for total nitrogen were strongly affected by the HLR. No clear trend was observed, however. LCS and LBF CWs showed superior TN removal rates and a small decrease as HLR increased. The other CWs showed a slight increase in removal rate as the HLR increased. LSS CW showed an unexpected TN removal rate increase with HLR increase, the justification for which could be the same proposed for the TP removal rate variation. The average TN removal rate variation was 19.8%. Excluding the LSS CW, which had a variation of 41.3%, the average variation was 14.5%. The observed average TN removal rates range from 44.1% for the lower performer CW (LO) and 80.1% for the LCS CW.

CW performance depends on many factors, other than the filling properties, including wastewater type, temperature conditions, HRT, HLR, and the operation and maintenance procedures. Consequently, the range of pollutants removal rates reported in the literature is very wide. Nevertheless, the obtained ranges of COD and nutrient removal rates are within or above the reported value ranges for simple filling materials tidal-operated CWs (Wu et al., 2015a).

The expected negative effect of HLR increase on the removal rates due the corresponding lower HRT was not observed. This result suggests a robust response of the tested CW combination fillings to hydraulic peaks, which are frequent in wastewater treatment plants. In the present batch experiments, variation in the HLR was operated through variations in the flood/drain ratio. Higher HLR rates corresponded to lower flood/drain ratios, that contribute to higher oxygenation of the biofilms and may increase the biological uptake of water pollutants, explaining the observed behaviour.

The global results showed that all tested waste material combinations are adequate filling for nutrient and COD removal from wastewater by CWs. At the highest HLR tested, near 0.08 m/day, the lowest removal rates were approximately 70%, 41% and 51%, respectively for COD, TP and TN.

The LCS CW, which combines limestone fragments and coal slags as filling matrix, showed to be the most stable CW, with average removal rates approximately of 94%, 86% and 80%, respectively for COD, TP and TN, only slightly affected by the HRL variation. The LCG CW, which combines limestone fragments and cork granulates showed to be an acceptable alternative, with average removal rates approximately of 86%, 74% and 59%, respectively for COD, TP and TN, also only slightly affected by the HRL variation.

Future work should be directed at strengthening the results obtained and at clarifying the trends observed in the LSS CW.

5 CONCLUSIONS

Many studies have been published evaluating low-cost materials as filling medium for treatment wetlands. In the present work, five solid wastes were combined with the objective of improving CWs' capability to simultaneously remove COD, TP and TN from wastewater.

Besides the valorisation of the solid wastes, other strategies for CW sustainability and efficiency improvement were evaluated: tidal flow operation; hydraulic loading rate variation; and solid waste combinations, including combinations of organic and inorganic wastes.

The evaluated solid wastes were clay brick fragments, coal slags, cork granulates, limestone fragments and snail shells. It was shown that these layer-packed solid waste combination fillings are adequate in improving COD removal in limestone based CWs, and that all but the limestone-snail shells filling combination have a very good performance for total nitrogen and total phosphorus removal from wastewater.

The snail shells based CW presented the lower nutrient removal but showed a removal rate increase with operation time, which justifies future work to evaluate the long-term efficiency. All the other CWs showed to be adequate alternatives, but the limestone-coal slags and limestone-cork granulates combinations showed the highest potential as mixed fillers for CWs designed to remove COD and nutrients from wastewater.

This innovative combination of different waste materials can be tuned to improve CW performance for specific types of wastewater, while simultaneously contributing to the valorisation of solid waste.

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