Organic matter removal during pilot-scale soil aquifer treatment for domestic wastewater in the tropics

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ABSTRACT

The potential of enhancing water uses using soil aquifer treatment (SAT) is an interesting alternative for tropical regions, limited only by lack of knowledge on its performance in local conditions and the feasibility of adapting this technology. A SAT pilot study was conducted to analyze the phenomena associated with the transformation of organic matter (OM) from domestic wastewater. Chemically enhanced primary effluent collected at the Cañaveralejo wastewater treatment plant (Cali, Colombia) was used to feed pilot-scale SAT units at a rate of 1.25 m.d^{-1}. Dissolved organic carbon (DOC) removal in a 5.0 m length and 0.1 m diameter column packed with sand was 64.4%, while a similar column packed with a Mollisol soil from Valle del Cauca region yielded 56.2%. Oxygen availability was an important factor in OM degradation, given that the sand column degraded OM aerobically and the soil column degraded OM under oxic as well as anoxic conditions. SAT acted as a reliable barrier for DOC in tropical conditions. Nevertheless, operational problems such as clogging indicated that probably Mollisol soil may not be the suitable for SAT or that this particular effluent requires further pre-treatment before SAT.

Key words | chemically enhanced primary effluent, dissolved organic carbon, organic matter, soil aquifer treatment, tropical environment

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INTRODUCTION

The use of ecosystem services from fresh water resources evidently exceeds the current worldwide water demand (WRI 2005). Additionally, projections indicate that the water demand will increase in future years at an annual rate of 0.65% (IWRA 2002; Gleick 2008). The main impacts of this increased stress on aquatic ecosystems include the increase of water bodies' deterioration, excessive water extraction and pollution.

In the southwestern region of Colombia, the Cauca river valley constitutes the axis of development for different socioeconomic activities (energy generation, construction materials and water supply). Consequently, the Cauca River becomes the receiver of all the discharges generated by these activities; the main impacts of this are dissolved oxygen depletion, loss of aquatic biodiversity in the main water stream and water quality deterioration.

In this scenario and considering the high costs of operation and maintenance of conventional methods for wastewater treatment, the implementation of large-scale natural treatment systems becomes a viable alternative for this region, taking advantage of the tropical conditions that can enhance performance efficiency.

Several studies worldwide have demonstrated the advantages of implementing soil aquifer treatment (SAT) for primary, secondary and tertiary wastewater effluents. Experiences developed in Israel, Chile, USA, South Korea, Iraq and India highlight the importance of these natural methods to reduce the pollutant load from wastewater, making it suitable for aquifer recharge (Nema *et al.* 2001; Idelovitch *et al.* 2003; Lee *et al.* 2004; Cha *et al.* 2006; Akber *et al.* 2009).

SAT is a land treatment system in which treated wastewater is incorporated into soil to simulate a process of natural infiltration, initially conceived as an economical method commonly used for groundwater recharge, in which reclaimed wastewater percolates through the unsaturated zone where a series of biological and physicochemical interactions occur, removing suspended solids, biodegradable materials, pathogens and also reducing nitrogen, phosphorus and heavy metals (Li *et al.* 2000; Hussen 2009; Sharma *et al.* 2011).

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SAT is also referred to as a managed aquifer recharge or artificial recharge, which is considered a natural, robust and cost-effective treatment or pre-treatment technology for reducing bulk organic matter (OM), pathogens and wastewater-derived organic micropollutants (Maeng *et al.* 2012a), so that its receiving water body is protected and its potential for safe drinking water supply is preserved.

SAT, however, is site- and influent wastewater quality-specific and requires detailed site investigations and pilot studies to assess its feasibility under local conditions (Sharma *et al.* 2008). Therefore, this research was aimed at studying the performance of a pilot-scale SAT system for a domestic primary effluent under tropical conditions, in order to get a better insight into the processes involved in OM transformation.

MATERIALS AND METHODS

Wastewater used in this research consisted of a chemically enhanced primary effluent (CEPE) collected from Cañaveralejo wastewater treatment plant (C-WTP) in Santiago de Cali, Colombia, which uses ferric chloride as coagulant to aid pollutants removal. This facility serves almost 2.3 million people, in a city with a mixture of different types of discharges, combining domestic, industrial and rainwater in the same sewer system. C-WTP has average removal efficiency of approximately 40 and 60% for biochemical oxygen demand (BOD) and total suspended solids (TSS), respectively, providing a primarily treated effluent with an average of 60 mg.L^{-1} of TSS, 99 mg.L^{-1} of BOD_5 and 224 mg.L^{-1} of chemical oxygen demand (COD) during 2011.

Experimental units consisted of PVC pipes of 100 mm diameter, packed with two different filter media that allowed infiltration across a matrix of 5.0 m height, in agreement with the average water table in soils of Valle del Cauca department (CVC 2010). Each column had two sampling ports with valves at 1.0 and 2.0 m depth, filled with plastic nets to ensure flow through them and avoid matrix losses (Figure 1).

Each SAT column was fed by a 0.04 m^3 tank and inlet flow was controlled using stop valves. Columns were fed by gravity with the CEPE that was collected in C-WTP. Prior to feeding the experimental units, CEPE was filtered

Figure 1 | Pilot-scale SAT experimental set-up used.

using a geotextile (PAVCO NT 1800, pore size = 180 μm) and allowed to settle for 1 hour, in order to retain large solids from CEPE and avoid clogging of each matrix (Maeng *et al.* 2012b). The construction of the experimental set-up was done by connecting two columns of 2.5 m height in series, obtaining a total height of 5.0 m. Columns were connected using dark plastic hoses to avoid biological within-hose growth.

Two types of matrix were studied: the first one consisted of pre-washed river sand from Cauca River with a uniformity coefficient of 2.36 (SC1). The second one consisted of soil/sand (SC2), which was obtained by drilling and extracting a 1.0 m sample from a sugarcane field, from the order Mollisol, since it is the most representative soil type in Valle del Cauca region (Cenicaña 2008). This 1.0 m column of soil was put on top of 4.0 m of sand to obtain a whole 5.0 m SAT column. The following procedure was carried out for conducting soil column experiments.

1. Infiltrating matrixes were ripened over 50 days with CEPE until stabilization was achieved with respect to dissolved organic carbon (DOC) removal (Maeng *et al.* 2012b), which was monitored twice a week and stabilization was considered to be reached when the last four collected values of efficiency displayed a coefficient of variation (CV) below 15%.
2. After this steadiness was reached, CEPE was applied continuously at the fixed flow rate (1.25 $m.d^{-1}$) for 3 weeks.
3. Then, samples were collected twice a week for 3 weeks at the influent (0.0 m), effluent (5.0 m) and through the sampling ports (1.0 and 2.0 m), completing a total of six runs (R1 to R6).
4. Adjustment of flow rate was required and maintained to keep a constant infiltration rate throughout the experiment.

Measured parameters included *in situ* monitoring using a Symphony multi-parameter meter for pH, redox potential (ORP), dissolved oxygen (DO) and electrical conductivity (EC); laboratory parameters included TSS, COD and BOD_5, which were carried out according to *Standard Methods for the Examination of Water and Wastewater* (2005). DOC was measured with a Shimadzu TOC-V_{CPH} organic carbon analyzer. Samples were centrifuged and filtered through a 0.45 μm cellulose membrane. The DOC analyzer was calibrated to measure within the range 0.01 $\mu g.L^{-1}$ to 60 $mg.L^{-1}$.

DOC results were analyzed by conducting an inferential assessment in order to establish more conclusive evidence using the statistical software Minitab version 15. An analysis of variance (ANOVA) test was used by doing a joint analysis with data from both treatments. The Anderson–Darling normality test and a one sample *t*-student were used to confirm the assumptions. Finally, Barlett's test was used to determine homogeneity of variances in order to validate the results. The ANOVA test was also used to establish differences between depths along individual matrixes regarding DOC concentration variation. A post-hoc ANOVA test was used for an individual analysis, in order to establish differences within each infiltrating matrix, which consisted of comparing changes from port to port by running Tukey simultaneous tests.

The Valle del Cauca region (Colombia) and specifically Santiago de Cali (3°22′39.65″N and 76°31′56.73″W) is situated at 995 metres above sea level, with an annual average temperature of 24°C, a relative humidity of 75% and an annual rainfall of 1,050 mm bi-modally distributed. Experimental units were located indoors during the second dry season of the year, from June to August of 2012, when temperatures varied from 24 °C to 30 °C.

RESULTS AND DISCUSSION

Figure 2 shows *in situ* parameter behavior during SAT (pH, EC, DO and ORP). A noticeable pH decrease was observed on P2 (1.0 m) in SC1; nevertheless, pH was nearly steady for the remaining 4.0 m depth. In contrast, pH for SC2 stayed moderately stable along the whole 5.0 m of soil/sand column.

EC displayed larger variations for SC1 than SC2. A significant EC decrease was observed on P2 (1.0 m) of SC1; just like pH, EC was practically stable after P2. EC in SC2 was reasonably stable along the whole 5.0 m of soil/sand column, displaying a gradual reduction from port to port. This EC reduction implies the removal of total dissolved solids (TDS) from CEPE (Saleem *et al.* 2011) that may have been retained on each infiltrating matrix, showing a higher reduction on the sand matrix (SC1), probably due to surface chemistry. EC and pH results indicate that CEPE characteristics were modified in the first metre for SC1 and changes were along the whole 5.0 m column of SC2.

Reduction of TDS (salinity) was a common characteristic in both treatments (SC1 and SC2). Carollo Engineers (2010) registered a 20% reduction in EC from domestic wastewater using a full-scale SAT system for tertiary treatment, which agrees with the 19% reduction for SC1 and the 9% reduction for SC2. Similar results, although different in their magnitude, were obtained by Miranda *et al.* (2010) in

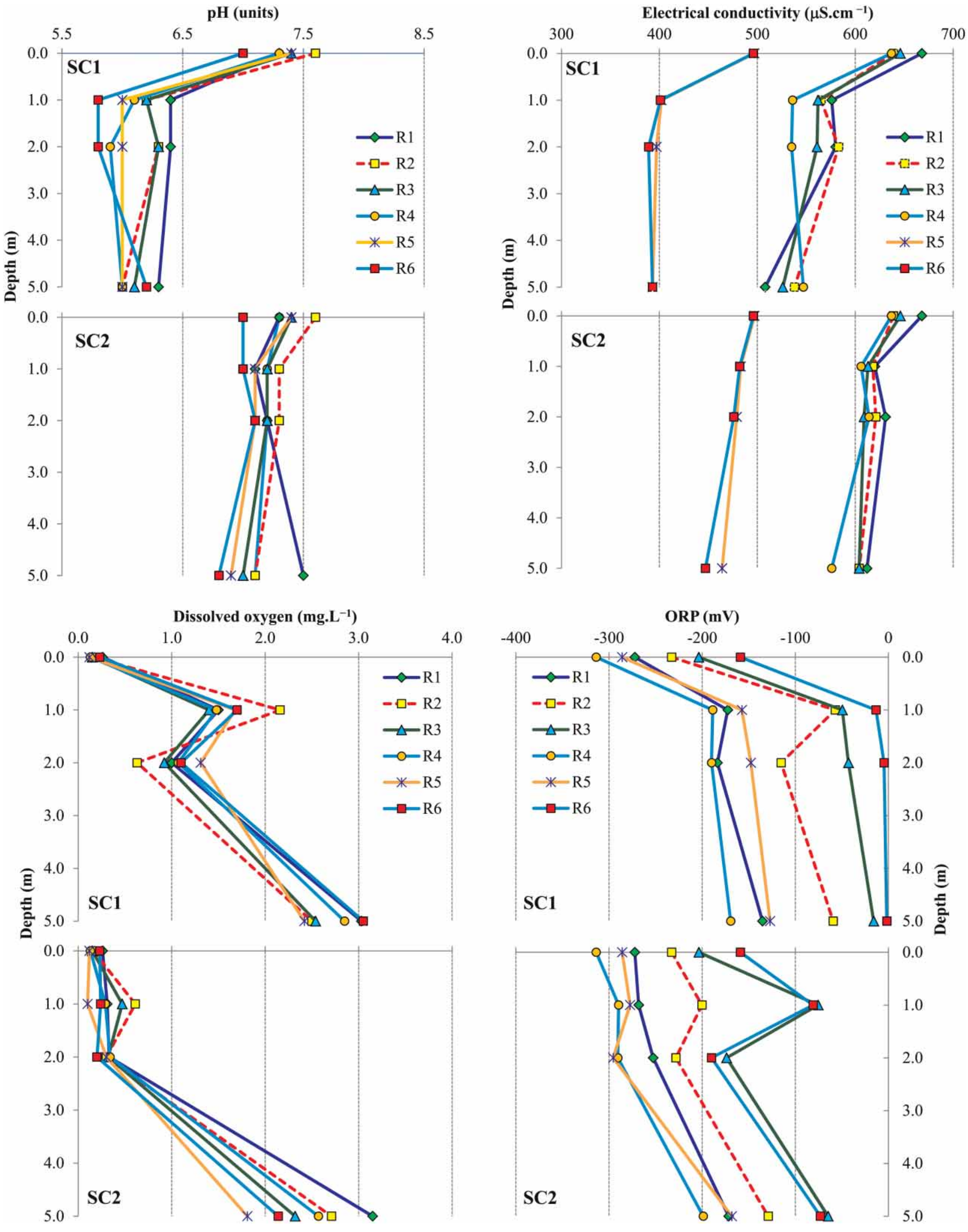

Figure 2 | *In situ* parameter behavior during SAT.

SAT column assays using brewery wastewater (~60% reduction).

A clear DO increase was observed at P2 (1.0 m) of SC1, which indicates that oxygen may have been drawn into the infiltrating matrix as CEPE flowed down; however, DO decreased when it was measured at P3 (2.0 m), suggesting that low-oxygen conditions may dominate the remaining 4.0 m of the column. The DO values for SC1 can be associated with the ORP results, which increased at P2 (1.0 m). For SC2, DO remained below 1.0 $mg.L^{-1}$ at P2 (1.0 m) and P3 (2.0 m). This could be considered as a micro aerophilic environment, which prevailed over the entire 5.0 m of the column.

This DO difference between SC1 and SC2 was expected, considering that sand would allow a higher air flow rate than the soil selected for this study with a lower pore space volume for air to flow through (Rucks *et al.* 2004). This agrees with the ORP results, which indicate a strong reductive environment in the whole soil/sand column. The DO data of both effluents were not considered in the analysis given that the sample was collected by drops, which may have caused some oxygenation of it.

Figure 3 shows the removal of DOC along the depth of the SAT columns. For SC1, there is an evident change in DOC concentration from influent to P2 (1.0 m), which implies that OM was consumed or transformed in the first metre of the sand column. From P2 until the effluent, DOC was fairly stable and its values increased over a small range. The results are in agreement with Xue *et al.* (2009), who stated that the dominating mechanism for the removal of bulk DOC during SAT is aerobic biodegradation. Considering the presence of DO at the top of the matrix, the metabolism was taking place under aerobic conditions, with the subsequent CO_2 production that may have caused the pH decrease.

Microorganisms not only consume OM but also generate some OM via intermediate metabolites and decay (Islam 2011), which would explain the small increase in DOC concentration registered on the effluent of SC1. This could also be related to effluent organic matter from the soil columns, which consists of natural OM, soluble microbial products and trace chemicals (both synthetic and natural); these substances may be inherently present in CEPE or could have been produced by biological degradation during soil passage (Maeng *et al.* 2012b).

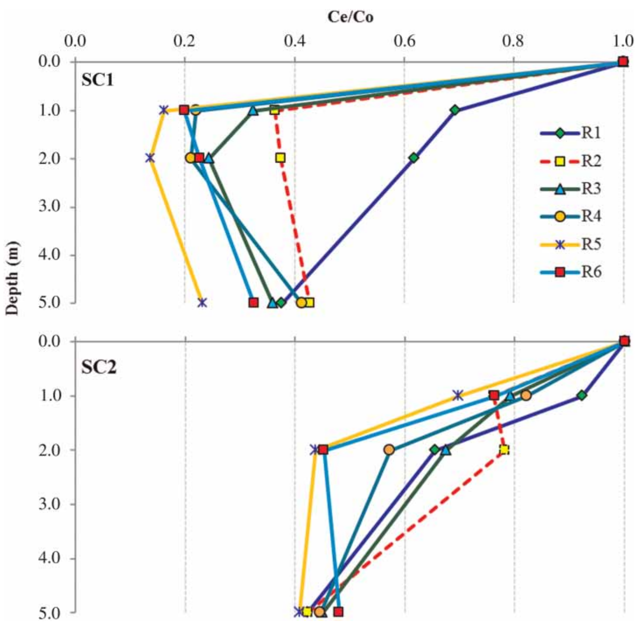

Figure 3 | DOC removal as a function of depth.

SC2 showed gradual reduction in DOC concentrations along the column depth. The lowest DOC concentration was obtained at the effluent, indicating that OM was progressively transformed along the whole 5.0 m. DO values at different depths in this matrix imply that degradation of DOC was taking place mostly under anoxic conditions, and ORP values were low as well, confirming such conditions which, added to pH stability along the whole 5.0 m depth, suggests that DOC degradation was carried out under low-oxygen conditions (Muller *et al.* 2003).

Inferential analysis confirmed that there was a definite effect of the type of matrix and depth on changes in DOC concentration, with significant differences between sampling ports and at different moments throughout the experimental period, given that the system could not be assessed for longer because of clogging problems. For both treatments, DOC concentration changed from port to port and, for SC2, significant differences were observed in time, whereas no statistically important differences were observed on SC1 throughout time.

SC1 displayed significant differences when comparing DOC concentration of P1 (0.0 m) with P2 (1.0 m), P3 (2.0 m) and P4 (5.0 m). Differences were not statistically important when comparing DOC concentration of P2 (1.0 m) with P3 (2.0 m) and P4 (5.0 m), or when comparing P3 with P4, which confirms that nearly all OM was consumed, transformed or retained in the first meter of the sand column. SC2 displayed significant differences when comparing DOC concentration among all ports, except from P3 (2.0 m) to P4 (5.0 m). This suggests that OM was consumed, transformed or retained gradually along the whole 5.0 m depth of the soil/sand column.

BOD removal was fairly constant for SC1 ($CV = 0.1\%$) while COD removal was variable ($CV = 16\%$), which implies that biodegradable OM was almost completely transformed during SAT and the non-biodegradable fraction varied, represented by discontinuous COD concentrations in the effluent; hence, a fraction of non-biodegradable OM may have passed through the sand column without being transformed or retained. Removal efficiencies displayed different behaviors for DOC, COD and BOD, indicating that OM transformation may have been affected by DO availability.

Table 1 | Removal efficiencies (%) of DOC, COD, BOD_5 and TSS during SAT

	SC1 – Sand column				SC2 – Soil/sand column			
n = 6	DOC	COD	BOD_5	TSS	DOC	COD	BOD_5	TSS
Avg. (%)	64.4	86.4	99.7	98.1	56.2	84.4	83.5	91.4
CV (%)	11	16	0.1	1	5	10	22	3

For SC2, DOC concentration in the effluent was nearly constant during the first three runs and increased for the last three runs, as BOD and COD increased as well. Removal efficiencies displayed almost parallel trends and reduced at the end of the experiment, probably related to the fact that SC2 showed signs of clogging, with a later permanent obstruction.

The effluent DOC, BOD and COD concentrations show a more steady relation for SC2 than for SC1, probably due to the fact that anoxic/anaerobic processes on soil are more stable than oxygen-dependent processes that were constrained by the aeration rate through the sand matrix, which was not controlled. Table 1 summarizes the removal efficiencies of OM and suspended solids for both treatments.

Removal efficiencies for DOC and COD show a higher variation for SC1 than for SC2, confirming that DO availability was key factor in OM transformation. Considering SC1 as oxic and SC2 as a low-oxygen medium, this outcome agrees with Maeng *et al.* (2012a, b), who found that removal efficiencies of DOC were lower under anoxic than under oxic conditions, even though their experimental set-up used silica sand as filter medium; their column study conditions were similar to those used in this research and obtained comparable removal efficiencies for DOC along the columns' depth.

BOD in both treatments showed the highest efficiencies, which entails a high microbiological activity on both matrixes; unfortunately, SC2 was not able to maintain such a trend due to hydrodynamic problems that led to clogging after a run time of approximately 90 days.

CONCLUSIONS

Pilot-scale SAT systems proved to be effective in OM removal under tropical conditions and this largely depends on the type of media used and depth. However, these findings only apply to this particular CEPE from C-WTP; thus, any projected SAT full-scale system should consider these main features when outlining such a scheme. It is likely that secondary or tertiary treatments are required before SAT under these specific tropical conditions, to reduce clogging and increase the operation time. On the other hand, shorter columns can be used for further pilot SAT studies.

The sand column (SC1) presented its most noticeable changes only in the first metre of depth, displaying aerobic/anoxic conditions in an oxidative environment, while the soil/sand column (SC2) revealed mostly anoxic conditions in a reductive environment, showing gradual modification in water quality along the column, indicating that biochemical activity took place through the entire depth of the column with local soil media, probably because the microbial community from the original soil was able to colonize the bottom layers of the column via lixiviation of microorganisms along with down-water flow.

Inferential analysis confirmed that there is a definite effect of the type of matrix (soil or sand) and its position in the column (depth) on changes in DOC for this particular CEPE. Overall DOC removal was higher for the sand matrix (64.4%) than the soil/sand matrix (56.2%), but the soil/sand matrix displayed smaller variation in its performance.

Almost all biodegradable OM was consumed during SAT on both matrixes and the difference between BOD removals derives from a hydraulic problem on the soil/sand column (clogging).

SAT technology may not be feasible for use in Mollisol soil for CEPE, considering the clogging problems observed during this study on the soil/sand matrix; hence, special considerations should be taken for additional pre-treatment if a full-scale SAT is to be implemented in the Valle del Cauca region for CEPE.

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