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Experimental study of slow sand filtration for the treatment of various wastewaters in tropical environment

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ABSTRACT

Wastewater treatment by slow sand filtration is a biological process which consists in filtering wastewater through a porous media. The objective of this study was to evaluate the performances of this biotechnology under tropical climate. Three sand filters were monitored at ONAS (Cambérène wastewater treatment plant in Dakar, Senegal). The filters were built with local materials, and were constituted with a feeding tank of approximately 180 litters, a column (two meters high and 30-25 cm diameter). The filters were filled with sand (75 cm), gravel (25 cm) and wastewater (90 cm). The results showed that with sand of d_{10} equal to 0.58 mm and flow rate of 0.05 m/h, the filtration cycle was relatively long for the first run with pretreated wastewater. At the level of the primary settling tank, with flow a rate of 0.08 m/h, the removal rates were about 12.75%, 16.31%, 12.92%, 5.45%, 7.09% and 10.50% for TSS, COD, BOD_5, nitrogen phosphorus and faecal coliforms respectively. At the level of the clarifier, with a filtration of 0.15 m/h, the removals were 1.4% for TSS, 1.84% for COD, 1.09% for BOD_5 11.38% for nitrogen, 5.18% for phosphorus and 1.74% of faecal coliforms.
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Keywords: Flow rate; filtration cycle, removal; sand filtration; tropical climate, wastewater.

INTRODUCTION

The increasing use of raw or treated wastewater for various purposes throughout the world contributed to the development of guidelines to protect the environment and public health (WHO, 2006; Abdel Ghaffar, 2007; RSA, 2012; Bastian, 2013). In agriculture, the benefits is not only in the preservation of the environment and resource, but also in the nature of wastewater containing

nutrients (nitrogen, phosphorus and potassium, etc.) that are beneficial for crops, and can significantly increase the production (Aomar et al., 2002; Shetty, 2004). In Senegal, the field of wastewater had drawn special attention from the authorities; because the lack of adequate systems for wastewater treatment can cause serious environmental dysfunctions. According to the Director of Cambérène WWTP, only 37% wastewater are collected by the sewerage system. Because of problems related to water availability and competing uses, the reuse of raw wastewater in gardening has become a widespread practice in peri-urban areas in Senegal, as in many countries in Sahelian countries in Africa (Niang and Redwood, 2002). Then, wastewater treatment appears essential to reduce health risks associated with raw wastewater; also it participates in the improvement of people's life and contributes to environmental protection. Therefore, this study was aimed at evaluating the performances of sand filter biotechnology under tropical climate for agricultural water reuse.

MATERIALS AND METHODS
Experimental design, feeding and sampling systems

The pilot plans (Figure 1) were built based on the literature (Adin, et al., 1998; Dash, et al. 2012; Mbaye and al., 2012; Adeniran and Akanmu 2013; Amin and Mohamed, 2014). Thus, PVC pipes of 2 m high and 30-25 cm diameter were used as sand filters. The column was filled from bottom to top with 25 cm of fine and coarse gravel, 75 cm of coarse sand and 90 cm of wastewater. The sand has d_{10} of 0.58 cm and a uniformity coefficient of 1.5. Flow rates were about 0.05 to 0.15 m/h. Three barrels of 180 liters each were placed 1.5 m above each filter. They were placed close to the preliminary treatment system and the settling tanks of Camberene WWTP respectively. The influents were pumped from the preliminary treatment system or settling tanks to the barrels and arrived in the filter column (90 cm of wastewater) through a valve actuated by a float disposed laterally on the bottom of the latter. The effluents flowed by gravity into the filters. Sampling valves are drilled into the filters above the sand surface, in the water body (level 1), and at 5 cm (level 2), 15 cm (level 3), 35 cm (level 4), 55 cm (level 5), 95 cm (level 6) in the filter column under the sand surface. The valves were connected to piezometers to measure the head loss. Results of filtered wastewater at different levels are here presented in this paper.

Four experiments were conducted. In the first experiments 1 and 2, pretreated wastewater (degritted, defatted) was settled for 12 days (Experiment 1) or 1.5 days (Experiment 2) prior to filtration. Experiments 3 and 4 are related to the filtration of wastewaters from primary and secondary (clarifier) settling tanks respectively.

Sampling and analysis

Samples were collected in one liter bottles, kept in a cooler with ice and transported to the lab within one hour for analysis. The influent sludge and the treated wastewater were analyzed for TSS, COD, BOD5, nitrogen phosphorus and faecal coliforms in the laboratory at the Camberene wastewater treatment plant following specific methods described in Standard Methods (Eaton et al.; 2005).

The head losses were measured daily from piezometers by direct reading of the variations in height of the water level in the pipes. Dissolved oxygen was measured directly with Oxytops WWT apparatus.

RESULTS

Performances of settling prior to sand filtration

After twelve days of settling, the decanted wastewater gave high removal rates of about 98%, 89% and 95%, with averages initial concentrations of 602 mg/l, 1653 mg O_2/l and 1010 mg O_2/l, for TSS, COD and BOD_5 respectively. After filtration, the concentrations at the outlet were between 28 and 2 mg/l, with an average rate of 6 mg/l, showing a removal efficiency of 54% for TSS. COD content was between 164 to 19 mg O_2/l, with an average of 104 mg O_2/l and a removal efficiency of 40%.

In the second part of this study, the decantation time was reduced to 1.5 days while maintaining the filtration rate (Table 1).

The percentage reductions following the filtration were about 66, 73, 89 and 91% on average, for TSS, COD, BOD_5 and TKN, respectively.

Evaluation of the filtration efficiency
Variation of head losses

The head loss profile across the sand bed was measured by piezometers as illustrated in Figure 2. The head losses at the different sampling points were established as compared to the head loss near the sand surface. The head losses variation for the level 2, situated 5 cm below the sand surface evolved exponentially from the beginning to the end of the filtration with many fluctuations as mentioned in the literature (Adin and Rebhun, 1977; Channing et al., 2007).

Changes in oxygen content during the filtration

Changes in oxygen content in the filter close to primary settling tank are mentioned in Figure 3. This figure shows that the variation of the oxygen content in the column of the filter was highly variable. The evolution and the concentration of the oxygen content in the water body were not very different to that in the sand column (depths of 21.5 cm and 100 cm).

The concentration of dissolved oxygen contents in the filter located near the clarifier was also highly variable as shown in Figure 4. However, the amount of oxygen was higher and greater than 1 mg O_2/l in most of the time of the filtration monitoring.

Results of the filtration of the effluent of the primary settling tank and the clarifier (Experiment 3)
At the level of the primary settling tank

The results of the removal rate efficiency of the filtered wastewater sampled at the level of the primary settling tank are here presented: 63.9, 46.88, 53.23, 22.43, 8.07 and 56.19% for TSS, COD, BOD_5, TKN, TP and faecal coliforms with an average content of: 46, 362, 123, 131, 18.56 mg/l and 1015.2.103 CFU/100 ml for TSS, COD, BOD_5, TKN, TP and faecal coliforms, respectively.

The filter placed close to the secondary settling tank filter (Experiment IV)

The results shown by sand filtration of the clarified wastewater are represented in Table 3. The filtration of clarified wastewater led to removal rates of about 74.54, 34.84, 20.01, 21.13, 22 and 77.2% on average for TSS, COD, BOD5, TKN, TP and faecal coliforms. These removal rates lower than those in Experiment 1 and Experiment 2 are due to the lower pollutants contents of the clarified wastewater. Indeed, initial clarified wastewater quality characteristics expressed in mg/l were: 17.17, 116.81, 33.33, 119.46, 7.9, on average for respectively TSS, COD, BOD5, TKN and TP. The average total coliforms content was 249.10^3 CFU/100 ml.
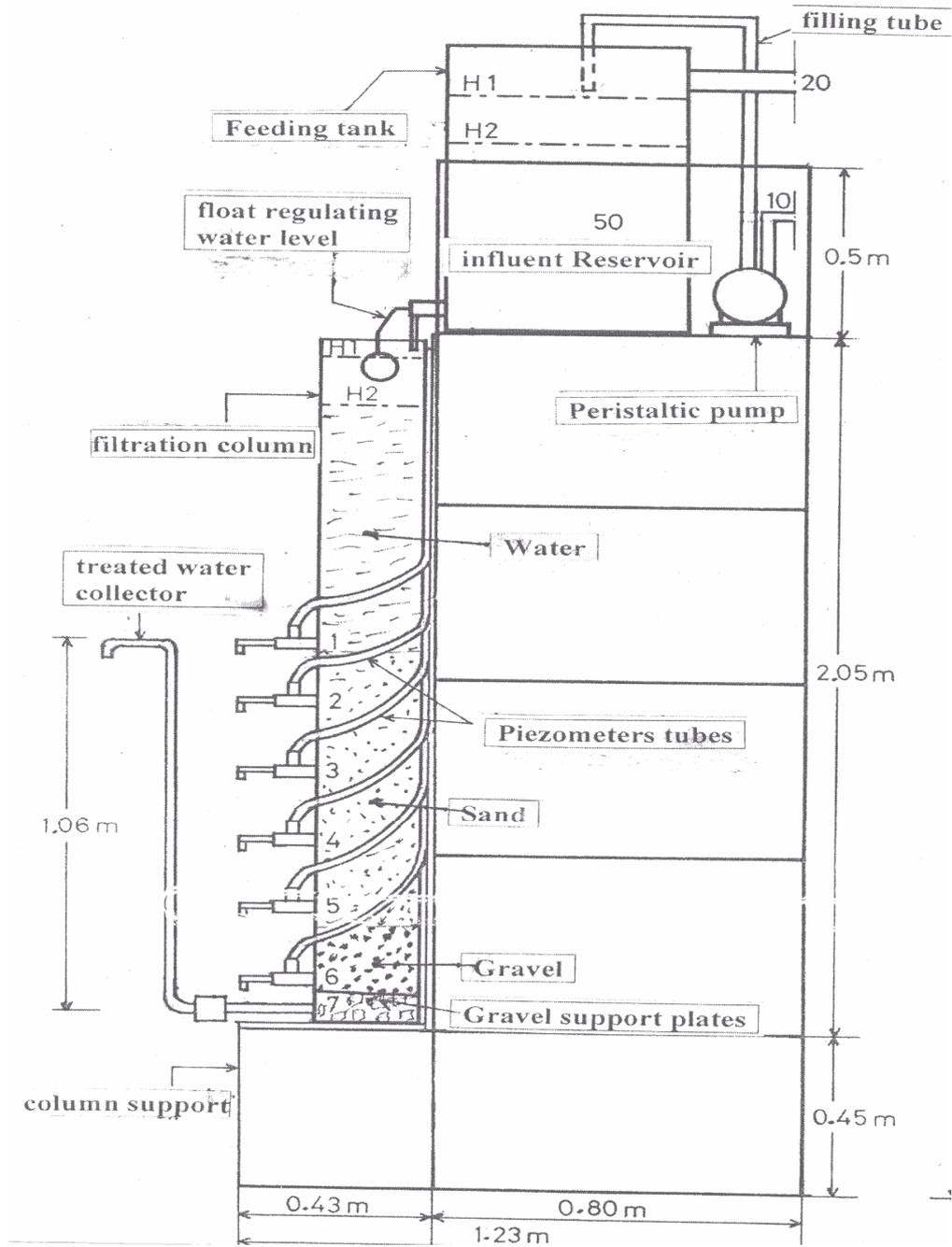
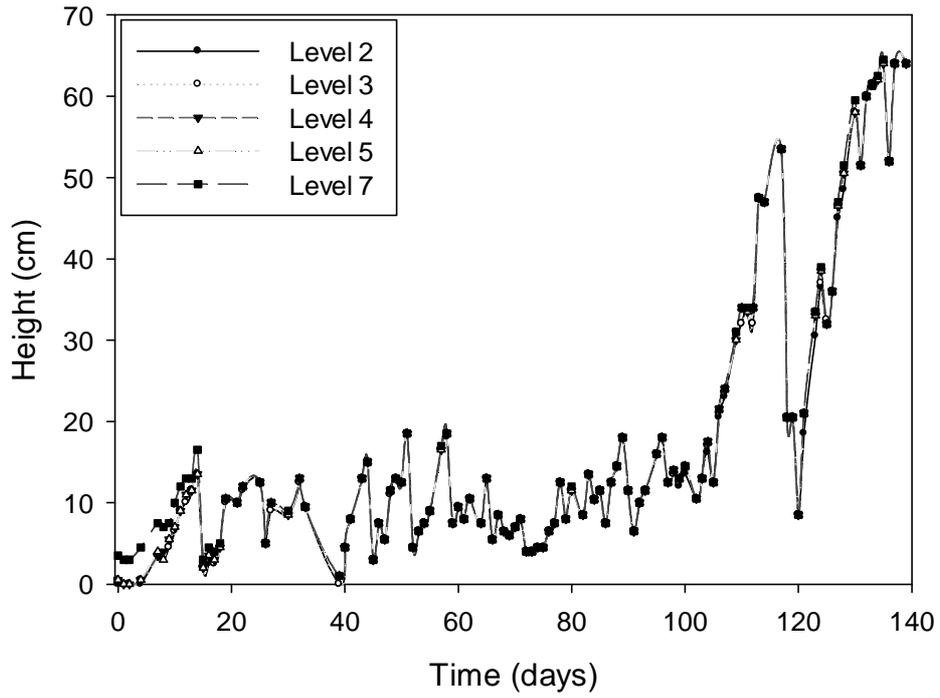**Figure 1:** Schematic of pilot plan used in slow sand filtration.

Figure 2: Evolution of head losses at different levels of the column.
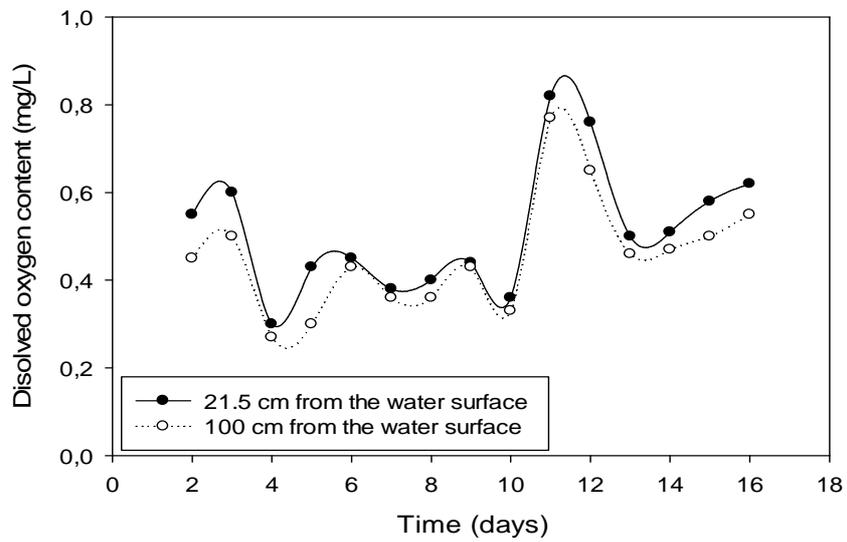

Figure 3: Changes in oxygen content in the filter close to the primary settling tank.
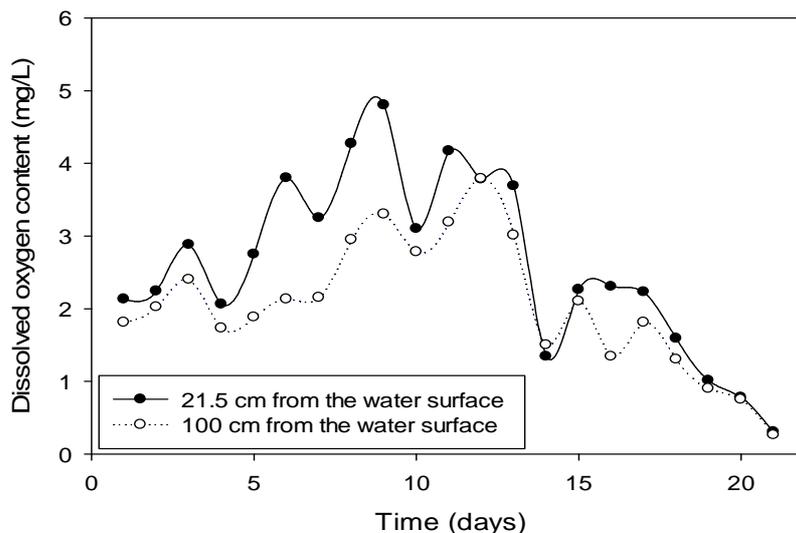
Figure 4: Variation in the oxygen content in the filter placed near the clarifier.

Table 1: Removal efficiency and average characteristics of filtered wastewater sampled after 1.5 days of settling.

		Levels			
		Inlet	**Level 1**	**Level 3**	**Outlet**
TSS	Min (mg/l)	41	38	21	4
	Max (mg/l)	90	65	58	59
	Average (mg/l)	65	48	33	22
	Removal (%)		26	49	66
COD	Min (mg/l)	753	268	217	163
	Max (mg/l)	1018	574	433	424
	Average (mg/l)	910	412	289	243
	Removal (%)		55	68	73
BOD_5	Min (mg/l)	340	180	140	35
	Max (mg/l)	500	180	200	60
	Average (mg/l)	420	180	170	47
	Removal (%)		57	59	89
TKN	Min (mg/l)	118	80	76	7
	Max (mg/l)	163	103	96	16
	Average (mg/l)	141	91	86	12
	Removal (%)		35	39	91

Min: minimum; Max: maximum; TSS: Total Suspended Solids;
COD: Chemical Oxygen Demand; BOD_5: Biochemical Oxygen Demand ;
TKN: Total Kjeldahl Nitrogen.

Table 2: Removal efficiency and average characteristics of filtered wastewater sampled at the level of the primary settling tank.

		Levels			
		Inlet	**Level 1**	**Level 2**	**Outlet**
TSS	Min (mg/l)	53	61	38	12
	Max (mg/l)	244	163	122	89
	Average (mg/l)	127.4	99.4	88.6	46
	Removal (%)		21.97	30.45	63.9
COD	Min (mg/l)	365	386	301	251
	Max (mg/l)	1068	630	698	498
	Average (mg/l)	681.6	532.8	443.8	362
	Removal (%)		21.83	34.88	46.88
BOD_5	Min (mg/l)	200	160	120	80
	Max (mg/l)	420	240	220	200
	Average (mg/l)	263	194.3	173	123
	Removal (%)		26.12	34.22	53.23
TKN	Min (mg/l)		108	111.34	116.40
	Max (mg/l)		212.40	194	155.30
	Average (mg/l)		169.3	146.39	131.32
	Removal (%)			13.53	22.43
TP	Min (mg/l)	13.7	13.4		11.64
	Max (mg/l)	32.43	34.5		31.42
	Average (mg/l)	20.19	19.17		18.56
	Removal (%)		5		8.07
Faecal coliforms	Min (CFU/100 ml)	207.10^3	80.10^3		110.10^3
	Max (CFU/100 ml)	456.10^4	432.10^4		210.10^4
	Average (CFU/100 ml)	$2317.4.10^3$	1842.10^3		$1015.2.10^3$
	Removal (%)		20.51		56.19

Min: minimum; Max: maximum; TSS: Total Suspended Solids; COD: Chemical Oxygen Demand; BOD_5: Biochemical Oxygen Demand; TKN: Total Kjeldahl Nitrogen; TP: Total Phosphorous; CFU: Colony Forming Units

Table 3: Removal efficiency and average characteristics of filtered wastewater sampled at the level of the clarifier.

		Levels			
		Inlet	**Level 1**	**Level 2**	**Outlet**
TSS	Min (mg/L)	13.6	7.4	6.2	2.2
	Max (mg/L)	22.4	14	9.8	8
	Average (mg/L)	17.13	11.06	7.5	4.36
	Removal (%)		35.4	56.21	74.54
COD	Min (mg/L)	92.8	60.4	70	48.7
	Max (mg/L)	147.9	131	97.7	103.7
	Average (mg/L)	116.81	79.26	80.01	76.11
	Removal (%)		32.14	31.50	34.84
BOD$_5$	Min (mg/L)	20	15	15	20
	Max (mg/L)	40	35	30	35
	Average (mg/L)	33.33	25	24.16	26.66
	Removal (%)		25	27.51	20.01
TKN	Min (mg/L)	79.6		82.9	62.3
	Max (mg/L)	186		121	126
	Average (mg/L)	119.46		98.43	94.21
	Removal (%)			17.60	21.13
TP	Min (mg/L)	3.9	3.7	5	4.2
	Max (mg/L)	11.8	9	8	9
	Average (mg/L)	7.93	6.30	6.65	6.61
	Removal (%)		27.16	21.33	22
Faecal coliforms	Min (CFU/100 mL)	27.10^3	135.10^3	$9.9.10^3$	$22.2.10^3$
	Max (CFU/100 mL)	75.10^4	54.10^4	20.10^4	$5.5.10^4$
	Average (CFU/100 mL)	249.10^3	248.10^3	$100.7.10^3$	33.10^3
	Removal (%)		0.003	59.5	77.2

Min: minimum, Max: maximum; TSS: Total Suspended Solids; COD: Chemical Oxygen Demand; BOD$_5$: Biochemical Oxygen Demand; TKN: Total Kjeldahl Nitrogen; TP: Total Phosphorous; CFU: Colony Forming Units

DISCUSSION

Performances of settling prior to sand filtration

In regards to the performances of settling prior to sand filtration, the BOD$_5$ concentration of pretreated and decanted wastewater was 44 mg O$_2$/L, the average removal rate was 27% (Table 1). Thus, the total removal efficiency was around 99% for TSS, 94% for COD and 97% for BOD$_5$. These higher percentages rate of reduction obtained compared with that obtained in Experiment 1 were due to the fact that the filtered wastewaters were more concentrated. The short settling time of 1.5 days did not reduce more most of the pollutants as in Experiment 1 with a longer settling time (12 days). However, the levels of total removal rates obtained, 97%, 84%, 96%, and 92% for TSS, COD, BOD$_5$ and TKN, respectively were as high as in experiment 2. These high efficiencies, independently to the settling

duration might be due to the ability of the filter media to remove the solids matters from the sludge (Kuffour et al., 2009). As reported by the literature, in the early stages, the main removal process might be due to physical filtration by the substrate due to the high proportion of particulate elements (Rousseau et al., 2004; Wang et al., 2009). On the other hand, the long decanting time did not affect the rate of depollution, because the levels of pollutants removal were close for all parameters. However, twelve days of settling have led to relatively long filtration cycle of 139 days against relatively short time of filtration of about 25 days obtained after 1.5 days of settling. This may be related to blockage of the filter pores by the TSS that had not decanted due to the short period of settling as discussed by Nakayama et al. (2007). These authors have stated that suspended materials trapped by the filter decrease the water flow rate across the filter. Then they advise that the sand media filter must be cleaned by backwashing.

These results have shown that this sand is suited for slow sand filtration after long period of settling. Largely durations of slow sand filters operations without clogging have been reported in the literature. Indeed, Rogers et al. (2011) had operated with beds for 274 and 190 days without clogging. However, it should be noted that they had worked with sand filters with depths of 0.3 mm and 0.4 m respectively.

The evaluation of the filtration efficiency showed that the variation of head losses at the different levels 3, 4, 5, 6 evolved in the same manner as the level 2. The head loss rose from 17 cm water to 55 cm water in 120 days and from 7 cm water to 64 cm in less than two weeks. In the last week of the experiment, the head loss rose by tenfold, and

64 cm water head loss was observed approximately one week later.

For the changes in oxygen content during the filtration (Figure 2), according to Trad Raïs and Xanthoulis (1999), and Barbu et al. (2011), whatever the used technology, a crucial issue in the case of aerobic wastewater treatment processes is the control of the dissolved oxygen concentration. For these authors, ensuring a satisfactory level of dissolved oxygen allows the normal development of the microbial wastewater treatment processes. However, the concentration of dissolved oxygen was less than 1 mg/L. These small amounts of oxygen content could result in the quality of the wastewater that was highly loaded in TSS. This can explain the low removal rates of COD, BOD5, TKN and TP recorded in the filter close to the primary settling tank. According to the layer depth the amount of oxygen in the porous media was less important at 100 cm than at 21.5 cm (Figure 3). The higher amounts of oxygen content at 21.5 cm could result from gas exchange between the atmosphere and the water surface. Indeed, feeding periods allow oxygen in the water body to be renewed through convection and molecular diffusion (Guilloteau et al., 1993; Mottier et al., 2000). At 100 cm photosynthetic activity and oxygen consumption in favor of the treatment are more important than exchanges between atmospheric oxygen and the environment (Figure 4).

The differences in oxygen content between the filter close to the primary settling tank and the clarifier, could explain the quality of the effluent in terms of COD, BOD_5, TKN and TP. According to Bancolé (2002) and Xu et al. (2012), the oxygen required to oxidize dissolved organic matter and nitrogen is available in the porous

medium. Oxygen is supplied to the air phase by exchanges with the atmosphere through the bed surface. Two mechanisms are mainly involved in oxygen renewal: convection and molecular diffusion.

Regarding the results of the filtration of the effluent of the primary settling tank and the clarifier (Experiment 3). At the level of the primary settling tank (Table 2), the results show that sand filtration was less effective in removing pollutants from settled wastewater than in Experiments 1 and 2 with pretreated wastewater. These low levels of pollution may be linked to the fact that these wastewaters are less concentrated than those treated in Experiments 1 and 2. Compared to the pretreated wastewater, high removals were observed. Total removals rate were about 92.79, 81.13, 88.64, 12.25, 19.30 and 91.81% for TSS, COD, BOD_5, nitrogen, phosphorus and coliforms. As observed above, pollutants removal was dependent on the depth of the sand filter bed and was increasing from sand surface with the depth. For all parameters, the rate of depollution increases with the depth of the sand layer. Thus, these values are above the permitted limits of 100-200, 40-80, 30, 10 mg/L and 2000 CFU/100 mL, respectively for COD, BOD5, the TKN, TP and fecal coliforms defined by Senegalese standard NS 05-061 relating to wastewater discharge into the environment. Only TSS with an average concentration of 46 mg/L seems to conform to this standard that defines a limit value of 40-80 mg/L. As shown by the results, slow sand filtration is not very effective for the removal of wastewater pollution indicators from the primary settling.

For the filter placed close to the secondary settling tank filter (Experiment IV), the results shown by sand filtration of the clarified wastewater are represented in Table 3. According to Haely et al. (2011), the degree

to which nutrients are deposited in a filter media depends on the applied organic loading rate. Compared to the pretreated wastewater, the average removal efficiencies achieved were 99.5, 95.55, 98.35, 57.56, 73.56 and 99.73% on for respectively TSS, COD, BOD5, TKN, TP and faecal coliforms.

Moreover, except for TSS and fecal coliform the levels of depollution for the other parameters are not influenced by the depth of the sand layer. The results of Table 3 show that the rate of removals for COD, BOD_5, TKN and TP are similar whatever the depth of the sand layer. However, the effectiveness of sand filters in removing pollutants has been reported by some authors in the literature. Thus, with coarser sands, an increased sand bed depth can contribute to better filtration. For some authors, the ideal depth is 0.40-0.70 m. It is generally accepted that bacteriological treatment efficiency is more sensitive to depth with sand of large size. But Bellamy et al. (1985) suggested that sand height could be reduced to 0.48 m with no change in bacteriological removal efficiency. However, ASCE (1991) and Muhammad et al. (1996) concluded that most of the bacteriological purification occurs within the top 0.40 m of the sand bed. Research done by Loga et al. (2001) on intermittent sand filter columns of 0.60 m sand revealed that the depth of sand was also important in removal, and became more important for coarser sands. Concerning the effect of sand depth on the removal of nitrogenous organic compounds, the research done by Muhammad et al. (1996), showed that the biochemical oxidation of nitrogenous organic compounds was found to be dependent on sufficient sand bed depth. Thus, the increased sand bed depth (0.7 m) allowed the full bacterial activity in the filter bed and produces the desired quality of water (BioSandFilter.org., 2004). Also, the reports

showed that in slow sand filtration, the vertical height of the sand bed that the water has to pass through is important in terms of filtration efficiency. The low removal of the pollutants regardless of the depth of the sand layer may be related to their low concentration in the clarified water. Thus, for TSS, the main removal process was physical filtration by the substrate, due to the high proportion of particulate elements (Rousseau et al., 2004; Wang et al., 2009). Faecal coliforms are essentially eliminated under sedimentation, Brownian diffusion and adsorption (Schmitt, 1989; Gnagne, 1996). These removals are highly dependent on the size of the pollutants, and the meshes and depth of the filter media. Trad Rais and Xanthoulis (1999) showed that the decontamination of effluents is not only determined by the depth of the water column, but also by the temperature. Indeed for depth less than 1.50 m, faecal coliform reduction of about 3 log units is observed within 8 days, when the temperature varies between 25.5 and 28 °C and when it is below 20 °C, the decontamination of water is considerably slowed. When the water temperature is between 12.5 and 18 °C, the reduction of fecal coliforms is only 3 log units after 17 days. Cleasby et al. (1984) have reported average percentages of coliforms removal over 99% using an effective sand size of 0.32 mm and sand depth of 0.94 m. The high coliforms removal efficiency achieved by slow sand filter is partly explained by the slow filtration rate and fine effective size of the sand, but is also attributed to biological processes in the layer of slime material that accumulates above the sand surface (*schmutzdecke*) and within the upper layers of the sand bed (Tyagi et al., 2009). The significant reduction in nitrogen and phosphorus suggests according to Kavanaugh et al. (1977) that these nutrients

particularly phosphorus have been heavily used during the filtration cycle.

Except for the faecal coliforms concentration, the sand flow filter beds produce filtered wastewater effluent meeting Senegalese standards (ISN, 2001). Thus, slow sand filtration can be a valuable technology for clarified wastewater processing for elimination into the environment or other uses.

Conclusions

This study of slow sand filtration for wastewater in tropical environment was performed, particularly in Senegal. It appears from the results that the experimental devices contributed to reduce the overall wastewater pollution slightly. Long settling period is important to maintain the efficiency of the system. Therefore, in such conditions, it is not an appropriate method for the treatment of wastewater highly concentrated in various pollutants. In this context, the success of such a technology will depend on external conditions, which take into account the design and operation of the filtration device. The use of such a processing device may be advantageous as a finishing treatment of wastewater for agricultural purposes in the tropical regions. Therefore, due to excellent effluent quality from the filter treating clarified wastewater, it can be said that slow sand filtration could be a promising technology for the post treatment of digested effluent in developing countries, where treated effluent can be reused for various recreational purposes i.e. gardening and irrigation, as well as for safe discharge

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