

## Effect of hydraulic loading on the performance of unplanted drying beds treating low-concentrated faecal sludge

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### ABSTRACT

To optimize faecal sludge (FS) treatment plants in operation in Dakar (Senegal), this study was conducted to test the effectiveness of the solid/liquid separation on unplanted drying beds under different loading rates and two operation strategies (one or two feedings per campaign). Clogging, purification performances, dryness and hygienic quality were monitored. Results have shown that the load fractionation has reduced the clogging. Only removals of total solids (TS) and slightly those of total Kjeldahl nitrogen and chemical oxygen demand are influenced by the loading rate and the feeding mode. The reduction of faecal coliforms (FC) and helminth eggs (HE) in leachates is, respectively, 1 log unit and 100%. Two to nine days were sufficient to obtain a dryness higher than 80% TS with nominal loads of 13.7–122 kg/m<sup>2</sup>\*year. Concentrations of the dried sludge in FC and HE were, respectively, about 7.10<sup>4</sup> FCU/100 g and 46 eggs/g with a reduction of 3 log unit after 15 days of drying and 32% in the sludge stored during 30 days. Unplanted beds are not effective for the treatment of low concentrated FS. The use of other technologies such as planted drying beds could be advisable in these types of sludge.

**Key words** | clogging, dryness, load fractioning, loading rate, purification performance, unplanted drying beds

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### INTRODUCTION

The quantity of faecal sludge (FS) is becoming more and more important since most developing countries have chosen on-site sanitation systems to achieve the MDGs. In Senegal, about 217,740 m<sup>3</sup>/year of FS are produced in Dakar (ONAS 2011). The management of these large volumes of sludge produced annually has become very problematic from the point of view of the environment and human health protection. This therefore raises the need for FS treatment and has prompted the Senegalese National Sanitation Utility (ONAS) to establish, since 2006, under a long-term water programme, low-cost faecal sludge treatment plants (FSTPs). Settling/thickening tanks and unplanted drying beds have been constructed and are in operation at Cambérène, Rufisque and Pikine (Dakar-Senegal).

Unplanted drying beds are equipped with a sand filter and a drainage system. Raw sludge or pre-thickened sludge is loaded onto the bed. The majority of the water therein is discharged through the filter by infiltration or by evaporation. Most solids are retained on the top of the filter layer. Sludge dewatering depends on the initial content of total volatile solids (TVS) and total suspended solids (TSS), the loading rate, and the loading frequency. Indeed, the drainage is highly dependent on the volume of sludge applied and the concentration of the sludge on suspended solids that influence the formation and characteristics of the sludge cake that settles on top of the drying bed (Kopp & Dichtl 2000; Langergraber 2005; Molle *et al.* 2006; Dominiak *et al.* 2011a, 2011b).

The amount of sludge to be loaded in beds is calculated from the solid content of the sludge to be treated. Thus, low-concentrated sludge will be applied with large volumes, while highly concentrated sludge will be made with low volumes of sludge. According to Dominiak *et al.* (2011b), if a large amount of sludge is applied onto a bed, the drainage will proceed very slowly or stop in extreme cases thus leading to clogging. Therefore, ONAS has adopted systems, currently in operation, to thicken sludge before processing onto the drying beds.

Thickening and settling tanks are posing serious problems in terms of implementation and operation. They are very expensive in terms of investment, require monthly cleaning and need an efficient pumping system. All these parameters lead to an increase of operating costs. The cleaning cost of settling/thickening tanks was about 14,972.79 USD per year representing 52.37% of the total operating cost of the FSTP of Cambérène (Gning 2009). These problems reduce the popularization possibilities of this technology although adapted to warm climates and also raises the need to explore some other operational mode as the fractionation of the load which, according to Molle *et al.* (2006), enhances the drainage of beds. This study was initiated in that context with the aim to test the effect of the sludge loading rate and loading frequency on the drainage, drying process, purification performances of unplanted drying beds treating lightly concentrated FS. The hygienic quality of leachates and biosolids was also investigated.

## MATERIALS AND METHODS

### Experimental setup

The experimental device consists of three beds of 4 m<sup>2</sup>. Each bed has a depth of 85 cm occupied from bottom to top with 5 cm of coarse gravel sized 10–40 mm, 10 cm of fine gravel sized 5–10 mm and 30 cm of beach sand (Figure 1). The sand consists of rounded grains mixed with small fragments of mollusc shells.

This sand is clean and based on silica. It has no dust, no organic matter and no clay. It has heterogeneous grain sizes without a fine fraction. The sand has a  $d_{10}$  of 0.35 cm, a  $d_{50}$

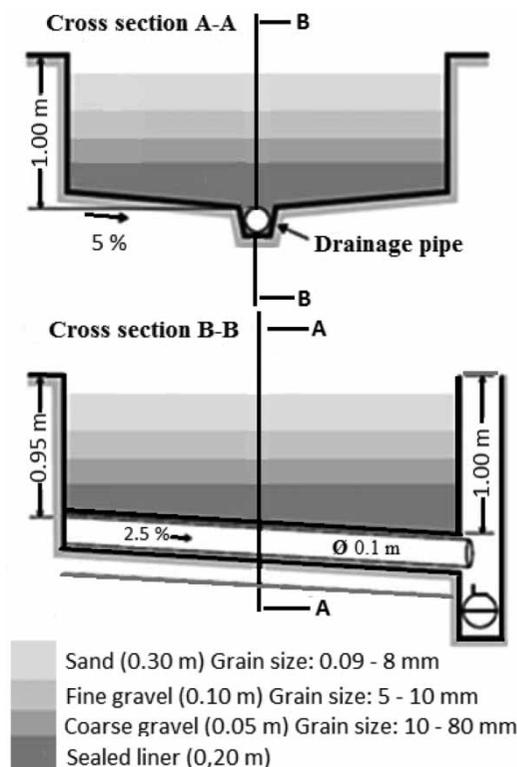


Figure 1 | Diagram of a drying bed.

of 0.55 cm, a  $d_{60}$  of 0.75 and a uniformity coefficient of 2.14 cm.

### Experimental procedure

The experiments were carried out during five campaigns between November 2007 and February 2008. The beds were fed by two different feeding modes (continuous and intermittent feeding). Owing to the high variability of the sludge, hydraulic loads have been used. Loading rates were 0.8, 1.6, 2.4 and 4.8 m<sup>3</sup>. Loads 1.6 and 2.4 m<sup>3</sup> were also made by intermittent supply with fractionation of the load in two identical loading rates, the second loading being applied after a day of rest. Other loading rates were only made by continuous feeding. The duration of the pumping was 10–30 min depending on the volume applied. The mass load, calculated based on concentrations of total solids (TS) in the sludge, from these hydraulic loads were, respectively, 13 kg/m<sup>2</sup>/year, 61.4 kg/m<sup>2</sup>/year, 100 kg/m<sup>2</sup>/year and 122 kg/m<sup>2</sup>/year. The areal loads according to the number of cycles per year (calculated based on the duration

of each cycle of each loading rate) were 0.65, 3.2, 6.6 and 13.5 kg/m<sup>2</sup>. The length of cycles was, respectively, about 18, 19, 24 and 40 days.

### Determination of drainage capacity

The drainage capacity of the beds was followed through the percolation rate, the concentration of TVS in the sand layer after each feeding and the dryness of the accumulated sludge. The percolation rate was evaluated by measuring the volume of leachate collected at the outlet of the bed for 1 min at regular time intervals of 30 min until the end of the percolation. The amount of TVS in the sand was evaluated by differential weighing consisting of the weight loss between the raw sand sample dried at 105 °C and the sand sample ignited at 550 °C for 3 h in a furnace (APHA 2005). The dryness of biosolids was measured throughout a 15 day drying period. It was evaluated by differential weighing after oven drying at 105 °C for 24 h (APHA 2005).

### Determination of purification performances

The performance was assessed by comparing average values of inputs (raw sludge) and outputs (effluent). The physico-chemical parameters studied are: TS, TSS, TVS, chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN) and pH. TS, TVS, TSS, COD and TKN were analysed in triplicate through conventional methods in accordance with procedures outlined in the *Standard Methods for the Examination of Water and Wastewater* (APHA 2005). The pH was measured directly with specific probes of Hach HQ 40 d multi pH-conductivity meter.

### Determination of health parameters

Microbiological (faecal coliforms (FC)) and parasitological (helminth eggs (HG)) parameters were determined in the incoming sludge, leachate and drying sludge. Microbiological parameters were analysed according to the guidebook of water quality analyses (Savary 2003). Helminth eggs were analysed at the laboratory of wastewater treatment of the Institut Fondamental d'Afrique Noire of the university of Cheikh Anta Diop of Dakar (Senegal) according to the Ritchie method.

### Characteristics of sludge used

The characteristics of the sludge from septic tanks, used in this study, are listed in Table 1.

For all parameters, the FS of Dakar varied widely with very distant values between the maximum and minimum. High variability is reported in the literature. For example, in Yaounde, Cameroon, where the majority of the city is also served by septic tanks, observed TS ranged from 3,000 to 127,000 mg/L, and all characteristics had a variation coefficient greater than 20 (Kengne *et al.* 2008).

## RESULTS AND DISCUSSION

### Influence of the loading rate and the load fractioning on the drainage capacity

As shown in Figure 2(a), the infiltration has evolved similarly unlike the loading rate. However, the percolation rate was higher at the beginning on beds fed with a load of 6.5 kg/m<sup>2</sup>.

Two days after feeding the percolation rate is still the same and is very low (less than 200 mL/min) for these two loading rates indicating the beginning of clogging. However, with these high loading rates (6.5 kg/m<sup>2</sup>), the clogging was delayed by the load fractioning (Figure 2(b)). Indeed, the beds loaded twice began to show signs of clogging after 9 days unlike those fed at once that started to clog 2 days after feeding. These results showed that the load fractioning has delayed the clogging of beds through the degradation of the biofilm, ammonia, organic nitrogen and COD accumulated in the filter (Makni 1995; Ménoret 2001). The mentioned authors have shown that the resting time reduced the occurrence of the blockage of beds by inducing the creation of cracks or macropores during drying periods.

Figure 2(c) shows a close relationship between the settling of TSS and the infiltration showing that TSS settling is the main factor influencing clogging. However, the amount of TVS in the sand obtained in this study is very low and varies between 0.16 and 0.55%. Thus it cannot be an influential factor in the clogging of beds since Kuffour *et al.* (2009, 2013) ran six treatment cycles on unplanted beds without experiencing any clogging despite TVS

**Table 1** | Characteristics of raw sludge

Parameters	TS (mg/L)	TSS (mg/L)	TVS (mg/L)	TKN (mg/L)	COD (mg O <sub>2</sub> /l)	pH	CF (UFC/100 mL)	HE (Nb/L)
Raw sludge	3,488* (1,036–7,776)**	2,130 (585–6,290)	1,571 (350–5,620)	442 (5.8–2,444)	3,853 (1,180–10,560)	7.28	3.6.10 <sup>8</sup>	1,006 (218–1,453)
Number of samples	36	42	35	30	50	11	6	66

\*Average value calculated based on the number of samples.

\*\*(Minimum value–maximum value).

values of about 1–1.55% in the sand. All these results are consistent with the work of several authors. Indeed, after a wastewater loading, TSS will settle and form a cake which induces resistance to the filtration of water (Dominiak *et al.* 2011a, Dominiak *et al.* 2011b). The specific cake resistance increases with the volumetric load (Christensen & Keiding 2012). When the load increases, the hydrostatic pressure increases on the cake formed and, due to the compression of the cake, the resistance increases (Dominiak *et al.* 2011a). If a large amount of sludge is applied on a bed, the drainage will proceed very slowly or stop in extreme cases (Dominiak *et al.* 2011b) thus leading to clogging. Dominiak *et al.* (2011b) also stated that smaller and more frequent wastewater sludge loadings reduced clogging.

## Treatment performance

### Influence of the load and load frequency on the treatment performance

As shown in Figure 3, TSS, TVS and COD are removed with almost similar depollution rates more than 85% whatever the loading rate and the load frequency. The removal of these pollutants appears not to be dependent on the loading rate and the loading frequency. These removal efficiencies are similar to those founded by Cofie *et al.* (2006).

This efficiency might be due to the ability of the filter media to remove the solids from the sludge (Kuffour *et al.* 2009). The main removal process was physical filtration by the substrate due to the high proportion of particulate elements in the sludge (Rousseau *et al.* 2004; Wang *et al.* 2009). The COD removal is related to the fact that, according to Walker (2008), particulate COD represents 93% of the total COD in the sludge discharged at the FSTP of Rufisque (Dakar-Senegal). This removal of organic matter regardless of the load and the supply frequency is believed to cause the high removal of TVS. TVS removal is above 80% regardless of the load and the loading frequency.

TS and TKN removal seems to be influenced by the loading rate and the loading frequency. TS removal is, meanwhile, lower than values found in the literature of about 75–85% (Kuffour *et al.* 2013). TKN removal is about 50–70%. Removal rates of these two pollutants are lower in high loading rates and in beds fed twice. In beds fed with higher

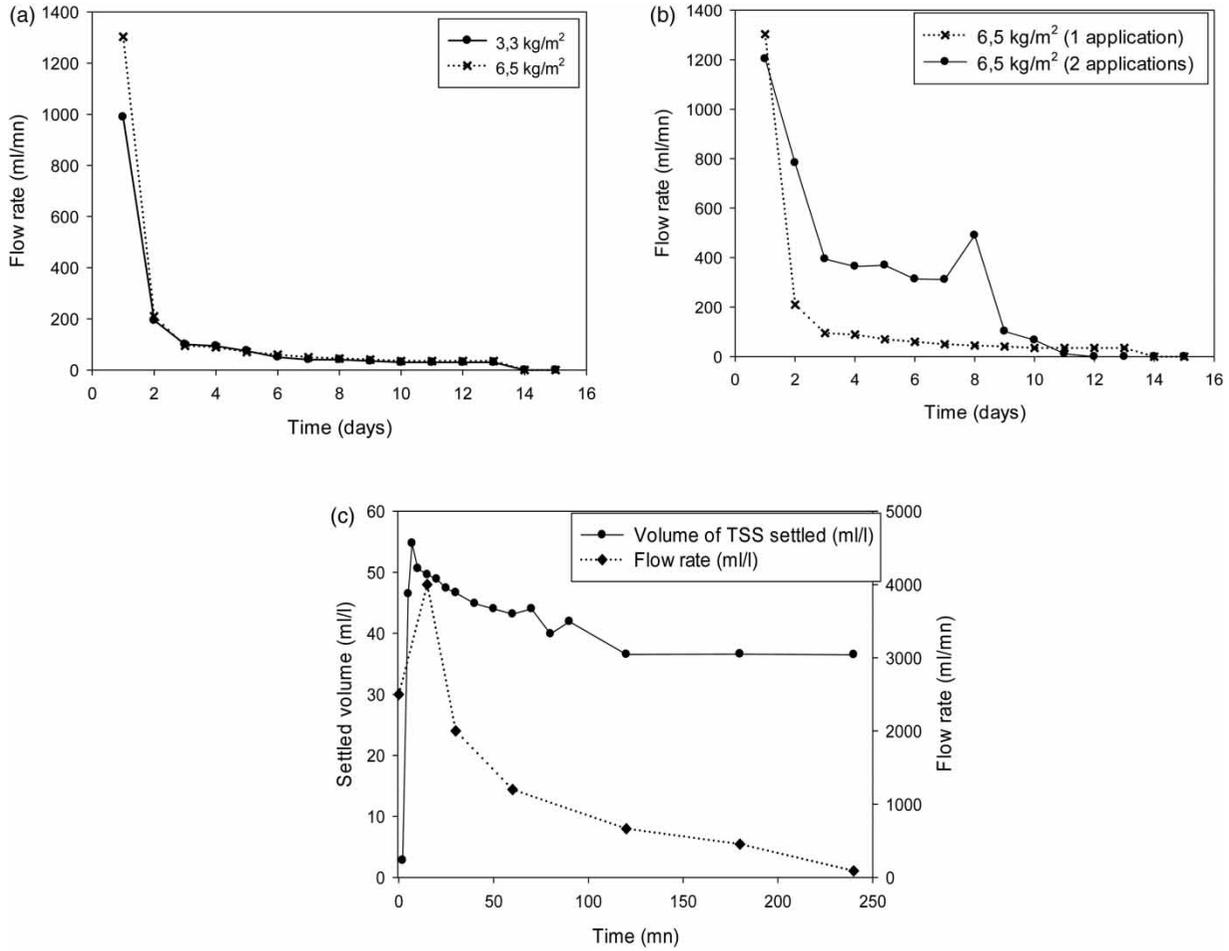


Figure 2 | Percolation speed according to loading rate (a), the loading frequency (b) and in comparison with settling flow rate of solids (c).

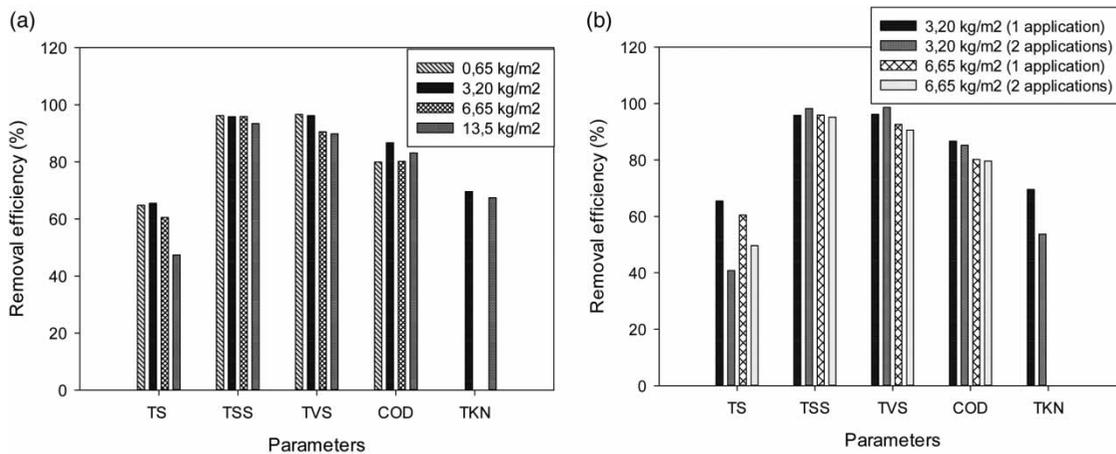


Figure 3 | Purification performance of beds as a function of the loading rate (a) and the load fractioning (b).

loading and those fed twice, the highest removal of TS can be linked to the longer time of drainage, as stated by Kuffour et al. (2013). According to these authors, as dewatering time increases, particles have enough time to settle and therefore removal of solids improves. The highest TKN removal in low sludge loading rates in comparison with higher sludge loading rates or between beds loaded once in comparison with those loaded twice are the results of organic nitrogen removal together with TVS and subsequent mineralization (Kuffour et al. 2013).

### Physico-chemical quality of leachate

Despite these high rates of reduction, leachate collected is only consistent with Senegalese Standard NS 05-061 for TSS. Indeed, the average concentrations of TSS, COD and TKN were 73 mg/L, 538 mg/L, 131 mg/L in leachate while the standards limit values for these different pollutants are, respectively, 80–40 mg/L, 200–100 mg/L and 10 mg/L.

The average bacterial load was  $1.7 \cdot 10^7$  with reduction rates of, on average, 1.25 log unit. These 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.

The raw sludge analysed in this study has relatively low concentrations of parasite eggs. This charge, albeit weak, should be taken with great caution, understanding that only six samples were analysed. Indeed, Kengne et al. (2009b) found concentrations of 10.409 eggs/L in FSs in

Cameroon. However, the residual concentration of HG in biosolids depends on the prevalence and the intensity of the infection in the population from which the sludge or wastewater was collected (Koné et al. 2007). Nevertheless, the reduction confirms the results reported in the literature of 100% reduction in leachates (Kengne et al. 2009b). HG are stopped in the first centimetres of the filter (Schmitt 1989).

### Dryness and hygienic quality of the accumulated sludge

#### Influence of the loading rate and the load fractioning on the sludge dryness

The dryness (solids contents) of the accumulated sludge according to the loading rate and the loading frequency is shown in Figure 4. The dryness was followed for the duration of the 2 week campaign.

Figure 4 shows that the dryness was greater than 80% TS at the end of the campaign regardless of the loading rate and the loading frequency. Moreover, these results have shown that the greater the loading rate the lower is the speed of drying (Figure 4(a)). Otherwise, the maximum dryness is reached almost at the same time regardless of the feeding frequency for each pair of the same loading rates but applied differently. These results show that the influence of the feeding mode on the dryness is not significant (Figure 4(b)). They are in accordance with the findings of Lienard et al. (1995), who have shown a definite influence of the load on dryness.

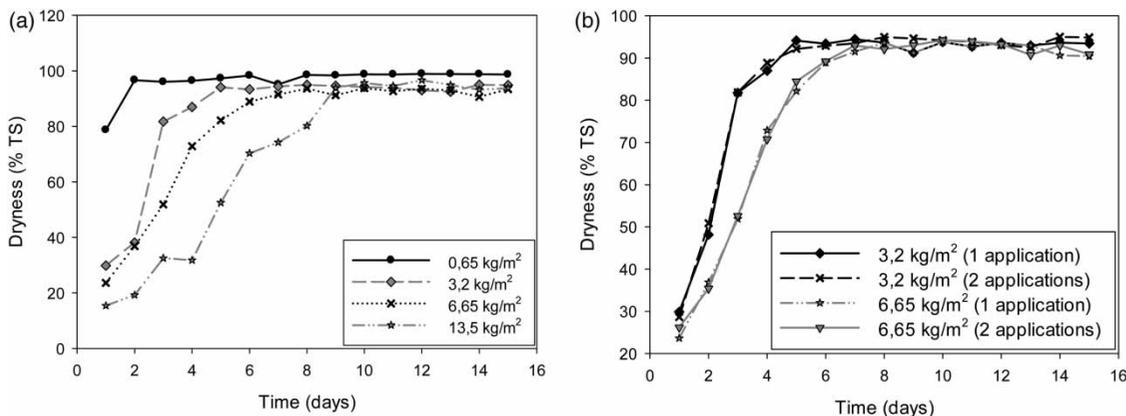


Figure 4 | Dryness of accumulated sludge based on the loading rate (a) and the loading frequency (b).

## Evolution of microbiological and parasitological parameters

The concentrations on FC were  $8.73 \cdot 10^7$  at the first day of drying and  $6.83 \cdot 10^4$  after 15 days of drying with a reduction of 2.97 log unit. The number of HG is about 68 eggs/g TS at the first day of drying and 46 eggs/g TS after 30 days of storage, showing an inactivation of about 32%. The concentration of helminths depends on both the prevalence and intensity of the infection through the population from which the sludge or wastewater were collected as well as other factors (temperature, drought, UV) influencing the survival of parasites (Koné *et al.* 2007).

FC contents were above the value of  $10^5$  UFC/100 g TS established for restricted reuse in agriculture (WHO 2006). Also, the storage period of 30 days is not sufficient to remove HG. Storage time was considered by several authors as a very important factor in the elimination of parasite eggs. Indeed, several studies documented by Strauss *et al.* (2003) show that *Ascaris* eggs can survive in the environment for 2–3 years in a temperate climate where the average temperature varies from 10 to 15 °C and for 10–12 months in a tropical climate, with average temperatures ranging between 20 and 30 °C. Recent studies by Kengne *et al.* (2009a) have shown high inactivation rates of HG complying with WHO recommendations (<1 viable egg/g MS) after 6 months of maturation (storage) on planted drying beds. This sludge must then be stored longer or co-composted.

## CONCLUSION

This study showed that in the case of low-concentrated sludge, such as in Dakar, the load fractioning can be used as an alternative to reduce the clogging of the beds. However, to deal with higher loading rates, the limits of fractionation can be seen because the volumes to be applied can be very large in the case of low-concentrated sludge. One of the most economical options may be the use of other low-cost technologies like planted drying beds. These have the triple advantages of clogging less frequently, removing at a high rate all pollutants and providing stable and hygienic biosolids.

## REFERENCES

- APHA 2005 *Standards Methods for Examination of Water and Wastewater*. American Public Health Association, American Water Work Association, Water Environmental Federation.
- Christensen, M. L. & Keiding, K. 2012 Numerical model of gravity drainage of compressible organic slurries. *Powder Technol.* **217**, 189–198.
- Cofie, O. O., Agbottah, S., Strauss, M., Esseku, H., Montangero, A., Awuah, E. & Kone, D. 2006 Solid-liquid separation of faecal sludge using drying beds in Ghana: Implications for nutrient recycling in urban agriculture. *Water Res.* **40** (1), 75–82.
- Dominiak, D., Christensen, M., Keiding, K. & Nielsen, P. H. 2010a Gravity drainage of activated sludge: new experimental method and considerations of settling velocity, specific cake resistance and cake compressibility. *Water Res.* **45** (5), 1941–1950.
- Dominiak, D., Christensen, M. L., Keiding, K. & Nielsen, P. H. 2010b Sludge quality aspects of full-scale reed bed drainage. *Water Res.* **45** (19), 6453–6460.
- Gnagne, T. 1996 Épuration par infiltration d'eaux usées à forte charge organique en milieu tropical. *Thèse de Doctorat en Sciences de l'Eau dans l'Environnement Continental Université de Montpellier II*. 171. [Purification by infiltration of high organic concentration wastewater in the tropical areas. PhD in Water Sciences in the Environment Continental, University of Montpellier II].
- Gning, J. B. 2009 Évaluation socio économique de la filière des boues de vidange à dakar. *DEA en Sciences de l'Environnement*, Université Cheikh Anta Diop de Dakar, p. 116. [Socio economic evaluation of the faecal sludge management chain in Dakar. Master in Environmental Sciences, University Cheikh Anta Diop – Dakar-Senegal].
- Kengne, I. M., Akoa, A., Soh, E. K., Tsama, V., Ngoutane, M. M., Dodane, P. H. & Koné, D. 2008 Effects of faecal sludge application on growth characteristics and chemical composition of *Echinochloa pyramidalis* (Lam.) Hitch. and Chase and *Cyperus papyrus* L. *Ecol. Eng.* **34** (3), 233–242.
- Kengne, I. M., Akoa, A. & Koné, D. 2009a Recovery of biosolids from constructed wetlands used for faecal sludge dewatering in tropical regions. *Environ. Sci. Technol.* **43** (17), 6816–6821.
- Kengne, I. M., Dodane, P. H., Akoa, A. & Koné, D. 2009b Vertical-flow constructed wetlands as sustainable sanitation approach for faecal sludge dewatering in developing countries. *Desalination* **248** (1–3), 291–297.
- Koné, D., Cofie, O., Zurbrügg, C., Gallizzi, K., Moser, D., Drescher, S. & Strauss, M. 2007 Helminth eggs inactivation efficiency by faecal sludge dewatering and co-composting in tropical climates. *Water Res.* **41** (19), 4397–4402.
- Kopp, J. & Dichtl, N. 2000 Prediction of full-scale dewatering results by determining the water distribution of sewage sludges. *Water Sci. Technol.* **42** (9), 141–149.

- Kuffour, A. R., Awuah, E., Anyemedu, F. O. K., Strauss, M., Koné, D. & Cofie, O. 2009 [Effect of using different particle sizes of sand as filter media for dewatering faecal sludge](#). *Desalination* **248** (1–3), 308–314.
- Kuffour, A. R., Awuah, E., Sarpong, D., Anyemedu, F. O. K. & Koné, D. 2013 Effects of different solid loading rates of faecal sludge on the dewatering performances of unplanted filter bed. *Civil Environ. Res.* **3** (4), 39–48.
- Langergraber, G. 2003 Simulation of subsurface flow constructed wetlands – results and further research needs. *Water Sci. Technol.* **48** (5), 157–166.
- Lienard, A., Duchene, P. & Gorini, D. 1995 [A study of activated sludge dewatering in experimental reed-planted or unplanted sludge drying beds](#). *Water Sci. Technol.* **32** (3), 251–261.
- Makni, M. H. 1995 L'oxydation et la décontamination en infiltration percolation. *Thèse de Doctorat*, Université de Montpellier II. [Oxidation and decontamination in infiltration-percolation. PhD Thesis, University Montpellier II].
- Ménoret, C. 2001 Traitement d'effluents concentrés par cultures fixées sur gravier ou pouzzolane. *Thèse de Doctorat*, Université de Montpellier II. [Treatment of concentrated effluents by fixed cultures on gravel or pozzolan. PhD Thesis, University Montpellier II].
- Molle, P., Lienard, A., Grasmick, A. & Iwema, A. 2006 [Effect of reeds and feeding operations on hydraulic behaviour of vertical flow constructed wetlands under hydraulic overloads](#). *Water Res.* **40**, 606–612.
- ONAS 2011 *Program for the structuring of the fecal sludge market for the benefit of poor households in Dakar*. Office National de l'Assainissement du Sénégal (ONAS), Ministère de l'Hydraulique et de l'Assainissement (MHA), Dakar, p. 56.
- Rousseau, D. P. L., Vanrolleghem, P. A. & De Pauw, N. 2004 [Constructed wetlands in Flanders: a performance analysis](#). *Ecol. Eng.* **23** (3), 151–163.
- Savary, P. 2003 *Guide des Analyses de la Qualité de l'Eau – Technique [Guide to the Analysis of Water Quality]*. 3rd edn, Edition TechniCités, Voiron (Isère), p. 284.
- Schmitt, A. 1989 Modélisation de l'épuration par infiltration. *Thèse de Doctorat*, Spécialité Hydrologie, Sciences de l'Eau et Aménagement, Université de Montpellier II, 297. [Modeling of the purification by the infiltration process. PhD Thesis, Hydrology, Specialty, Water Sciences and Planning, University Montpellier II].
- Strauss, M., Drescher, S., Zurbrügg, C., Montangero, A., Cofie, O. & Drechsel, P. 2003 *Co-composting of Faecal Sludge and Municipal Organic Waste: A Literature and State-of-Knowledge Review*. Swiss Federal Institute of Environmental Science and Technology, Zurich.
- Walker, M. 2008 *Performances of the FSTP of Rufisque and its impact on the WSP*. Internship report Eawag/Sandec, Swiss Federal Institute of Technology, Zurich, p. 42.
- Wang, R., Korboulewsky, N., Prudent, P., Baldy, V. & Bonin, G. 2009 [Can vertical-flow wetland systems treat high concentrated sludge from a food industry? A mesocosm experiment testing three plant species](#). *Ecol. Eng.* **35** (2), 230–237.
- WHO 2006 *Guidelines for the Safe Use of Wastewater, Excreta and Greywater*. World Health Organization, Geneva. Vol. 4, p. 182.

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