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Abstract
With decentralized treatment system development, a new concern emerges: the future of the septage. The aim of this paper is to assess the feasibility of septage treatment by SDRB, and to compare its efficiencies to those of activated sludge treatment in same conditions. The study took place on ten 2m² pilot-scales SDRB. Different designs and operation conditions have been tested on sludge treatment efficiency and will be presented as: (i) the top filtration layer (sand or compost), (ii) the load (from 30 to 50 kgSS/m^{-2}/y). After one year and half commissioning period, we focus on the results obtained at nominal loads presenting: sludge characteristic, filtration efficiency, percolate quality and sludge deposit behaviour. Although results show better filtration efficiency for activated sludge (98.4%) than for septage (87.5%), the feasibility of septage treatment with drying reed bed has been demonstrated. Sludge accumulation is about 7.9 cm/y, when fed at 50 kgSS/m^{-2}/y, and dry matter content of the sludge can reach 70% in summer period. The paper will present sludge characteristics, system efficiency, to finish on design and operation condition recommendations for SDRB treating septage.

Keywords
design recommendations; sludge drying reed beds; sludge characteristics; septage

INTRODUCTION

In developing countries as well as in industrials ones, there are many urban and rural areas without any sewage coverage. These areas rely heavily on decentralized sanitation system using septic tank (Valencia *et al.,* 2009). Nowadays, septic tank facilities have a widespread distribution, providing a first treatment to household effluent consisting of a solid/liquid separation. Operation efficiency of these systems is subject to emptying frequency, ideally every 3-4 years, but usually they are emptying after 5-10 years of operation and then reduction of the treatment efficiency is registered (EPA, 1994). This generates a large amount of faecal sludge so-called septage which has to be treated. In industrials countries the two main destinations of septage are direct land application or a co-treatment with wastewater in wastewater treatment plant larger than 10,000 people equivalent (P.E). Both of these solutions present some disadvantages: direct land application display health risk and co-treatment with wastewater reveals high transport and handling cost, also it can generate biological dysfunctions (EPA, 1994). Currently, some researchers try to find low-cost and environmental solution for septage handle and disposal like co-composting with organic waste, anaerobic digestion, settling ponds, settling/thickening tanks, sludge drying bed, constructed wetland (Koottatep *et al.*, 2001, Kengne *et al.*, 2009, Valencia *et al.*, 2009, Tsalkatidou *et al.*, 2008, Troesch *et al.*, 2009). SDRB process is the one selected for this paper. Since, most of the knowledge on SDRB comes from activated sludge treatment new researches were necessary. Process performance is based, on the one hand, on ability to dewater sludge by two combined mechanisms (i) percolation through filter media (physical effect of reeds) (ii) evapotranspiration of water from sludge to atmosphere. Reeds play an important role in both mechanisms, thanks to their

roots they improve infiltration of free water and they enhance dewatering due to evapotranspiration (Koottatep *et al.,* 2005). On the other hand, organic matter mineralization occurs thanks to biological activity (microorganisms, earthworm…), which mean depending on aerobic conditions. To achieve good performance and long-time operation functioning conditions (drying mineralization) have to prevent sludge residual from growing too fast (Nielsen, 2005). Several factors can influence sludge drying reed bed efficiency such as sludge quality, climate, number of units, loading rate and loading strategies (Nielsen, 2003). With regards to septage quality (heterogeneous and highly concentrated), the feasibility of its treatment by SDRB had to be defined and optimised. According to EPA (1999), its characteristics are highly dependent on users' habits, climate, septic tank size and emptying frequency. As a consequence, the few experiences done on septage differ greatly according to geographical context. For example Koottatep *et al.* (2005) in Thailand suggest once-a-week 250 kgTS/m^2/y application as operational condition. In France Liénard *et al.* (2008) apply 50 kgTS/m^2/y loading rate, with a feeding/resting period of 3.5/17.5 days as it is done when treating activated sludge.

This article focus on the feasibility of septage treatment and disposal on SDRB, based on experiments carried out in Andancette (France) on Cemagrefs' pilot-scale units fed with septage. Results deal with : (i) septage quality and dewaterability, (ii) performance on sludge drying reed bed pilot-scale experiments fed with septage (result will be compared to those fed with activated sludge), (iii) design and operation conditions improvement in the French context.

METHODS AND MATERIALS

Pilot-scale beds

Experimental site. Experiments took place in Andancette (France) on activated sludge wastewater treatment plant (13,000 PE). 10 experimental concrete beds, 2m^2, have been built and planted by Phragmites Australis (reed) in May 2006. Details of plant set-up and media arrangement are given by Troesch et al. (2009). Note that all of beds studied have the same filtration layer characteristics, except on the top where sand or vegetal compost are assessed as substrate. Both pilots conception have been evaluated according to the sludge quality (septage, activated sludge) and the annual load (30, 50 kgSS/m^2/y). To a better comparison SS has been preferentially used than TS to not take into account the dissolved salts that pass through the system.

Operating conditions. Pilots were fed directly from the aeration tank for activated sludge, and from a storage tank, daily filled, for septage. After 1.5 year of commissioning period (Troesch et al., 2009), pilots started their nominal load during 1.5 years, simulating a 6 beds configuration: 5 days feeding/24 days resting.

Pilots monitoring

Regular analysis were done (see table 1) according to French standard methods (AFNOR, 2005) to follow the system efficiency. Besides, biosolids growth accumulation was measured, at the end of the resting period. Statistic data analysis was done by R statistic program.

Table 1. Chemical analysis

	Frequency	Analysis (AFNOR 2005)										
	Each	DM*	SS* (mg/L)	VS* (%DM)	VSS* (%SS)	COD (mg/L)	NH_4^+-N (mg/L)	NO_3^--N (mg/L)	KN (mg/L)	TP (mg/L)	PO_4^--P (mg/L)	Cond (µS/cm)
Sludge	Load	**X** (mg/L)	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
Effluent	**2 load**		**X**		**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
Biosolid	**cycle**	**X** (g/g)		**X**								

*DM dry matter; SS suspended solids; VS volatile solids; VSS volatile suspended solids.

Influent characteristics

On top of the chemical analysis presented in table 1, specific measurements were done to characterize sludge dewaterability. Sludge from different WWTP or septic tanks were collected to measure CST, particle size distribution (laser granulometry with a CILAS 1190 instrument) as well as analysis of fats, proteins and polysaccharides content, which are implied in sludge dewaterability.

Fats were determined by a gravimetric method after chloroform extraction (solvent evaporation/drying and weight) when sample concentration were higher than 20 mg/L (Canler *et al*., 2001), and using COD measure when concentration sample is between 20 mg/L and 1 mg/L. Polysaccharides were determined by measuring sugar by colorimetric method (Dubois *et al.,* 1956); results are expressed in glucose equivalent. Proteins measurement was done by a Micro BSA method (Avella *et al.,* 2010) and by measuring nitrogen forms and supposing that *[protein] = [KN-N]-[NH_4^+-N]*.

Recirculation test

Recirculation test has been implemented to define in what extent effluent quality can be improved. It has been done on a pilot fed at 50 kgSS/m^2/y (May 2010). During feeding period effluent is stored, and recirculation occurred during resting period time using a mixing pump to homogenise effluent. Effluent were recirculated by batch and refrigerated samples were collected each batch. Infiltration rate as well as drainage flow were recording continuously. SS and NH_4^+-N content are analysed for each sample.

RESULTS AND DISCUSSION

Influent sludge quality and characterization

Table 2 summarises septage and activated sludge quality. The first comment refers to the high pollutants content of septage compared to activated sludge. Moreover, septage exhibits highest standard deviation for all parameters. This is due to septage production which is dependant on users' habits, dimension and type of septic tank and emptying frequency. On the contrary, activated sludge is more stable due to the control of operating condition in wastewater treatment plant.

Table 2. Septage and activated sludge physico-chemical characteristics over all the feeding cycle (June 2007 - May 2010)

	Septage					Activated sludge				
	mean	Std	min	max	nb values	**mean**	Std	min	max	nb values
CST (s)	**360**	142	151	842	134	**7**	1	4	13	139
DM (g/L)	**30**	10.6	7.5	99	155	**2.4**	0.6	1.3	8.8	171
SS (g/L)	**23**	8.6	2.5	64	172	**1.7**	0.3	1.1	2.8	187
VS (%DM)	**71%**	7%	51%	81%	84	**59%**	7%	44%	86%	96
COD (g/L)	**42**	13	13	87	38	**2,4**	2,4	1,5	15	31
KN (mg/L)	**1423**	435	522	2462	24	**1,9**	3,1	0,0	13	30
NH_4^+-N (mg/L)	**287**	76	24	441	39	**117**	14	93	139	17
NO_3^--N (mg/L)			0	0	0	**1,1**	1.0	0.2	3.3	7
PO_4^{3-}-P (mg/L)	**49**	19.9	25	98	10	**12,8**	4.4	6.3	20	8
TP (mg/L)	**517**	438	27	1894	14	**45**	11	21	59	12

High CST values measured for septage indicate a low dewaterability, compared to activated sludge. In the literature, particle size, SS concentration and sludge composition number among factors which are supposed to influence CST measure (Jin *et al.*, 2004). Figure 1 shows the fine characteristics of septage particle size as well as the wide spread of the curve. The d_{90}/d_{10} ratios, representing the homogeneity of the particle size distribution, are 21.6 ± 2.86 and 7.64 ± 0.09 for septage and activated sludge respectively. Low ratio and standard deviation for activated sludge confirms its homogeneity in terms of particle size, whereas septage is more heterogeneous. Indeed, fine particles (1 to 100 µm) present in septage can explain high CST values, these particles are supposed to retain more water due to their high specific surface (Nellenschulte, Kayser, 1997).

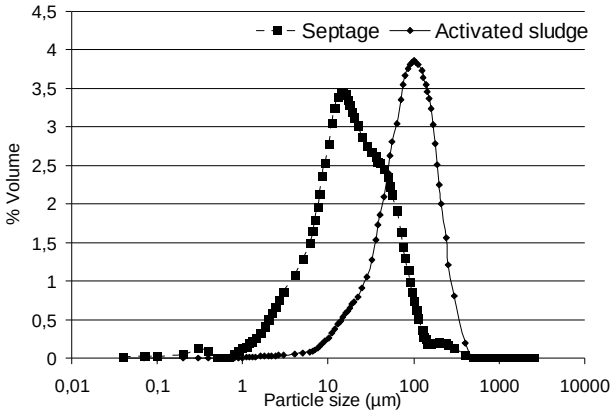

Figure 1. Influents size distribution.

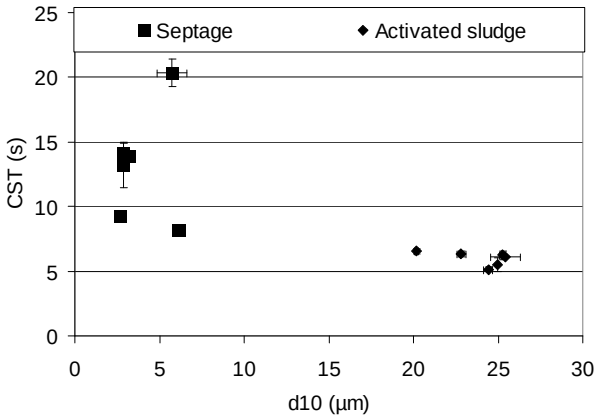

Figure 2. Influents CST measure versus d_{10}.

Parallel CST test and d_{10} measure have been done on several sludge samples, at equal SS content, to only assess particle size impact onto CST measure (Figure 2). The results outline the impact of fine particles on CST measure: as it can be seen, CST values raise with d_{10} decrease. But, in septage case, at equal $d_{10,}$ CST measures can be very different; these differences can be due to septage composition variability. Fat, protein and polysaccharide contents acting a part in ability of sludge to dewater (Shao *et al.*, 2009); these contents have been quantified in this work (Table 3).

Table 3. Influent sludge characterization

	Septage					Activated sludge				
	mean	std	min	max	nb values	**mean**	std	min	max	nb values
Fats (mg/L)	**81890**	3169	548	10192	8	**93**	47	49	142	3
Polysaccharides (mg/L)	**2421**	2578	221	5259	3	**538**	479	199	876	2
Proteins (mg/L)	**4699**	2206	788	7525	8	**876**	495	584	1448	3

One more time septage exhibits highest standard deviation. To compare the results, COD equivalents have been calculated for each fraction (COD_{fats}*=[fats]*2.3,* COD_{poly} *= [polysaccharides]*1.067,* COD_{prot}*= [proteins]*1.2)*. For septage, the most important part of COD is represented by fats whereas, in activated sludge, proteins are predominant: fats COD equivalent represent 46% ± 6% and 9.5% ± 2.8% of total COD for septage and activated sludge respectively. This large part of fats can contribute to large CST value in septage.

Nevertheless, to interrelate sludge characterization with CST measures, complementary values are needed; our further works will focus on sludge dewaterability according to its quality.

Septage effluent and biosolids quality

Results presented here focus on septage feeding pilots; to discuss them activated sludge pilots result will be given as comparison.

Substrate selection. Before presenting results on SDRB efficiency, discussion about substrate selection has to be done, within statistical test. Effluent SS and biosolid DM content have been chosen as they represent good criteria to evaluate the SDBRs' performance. As the two populations are not under normal law, an un-parametric test has been used to compare both substrates (wilcoxon.test).

Table 4. Wilcoxon test results, and mean value of septage effluent SS content and biosolid DM content for both substrate (May 2008 - May 2010).

	30 kgSS/m^2/y			**50 kgSS/m^2/y**		
	Compost	Sand	Wilcoxon test	Compost	Sand	Wilcoxon test
Effluent SS (mg/L)	2678	2105	p-value=0.813 W=866	2970	2139	p-value=0.1162 W=1010
Biosolid DM (%)	34.6%	33.50%	p-value=0.8122 W=498	34.3%	33.9%	p-value=0.6588 W=217

Table 4 exhibits p-value > 0.05 which indicates that no significant difference between sand and compost is observed in terms of effluent and biosolid quality. These results are in accordance with those of Troesch *et al.* (2009) who studied same system during commissioning period. Vegetal compost is recommended due to their positive impact on the speed growth of reeds. The lower effluent quality observed during commissioning period (Troesch *el al.*, 2009) when using compost is next improved with the bed maturing process. Indeed, sludge deposit acts as a new filtration media (Nielsen, 2005). Based on these observations following part will only present compost substrate beds results.

Effluent quality for different loads. Average of effluent quality coming from septage pilots with compost substrate are summarized on table 5. Results refer to nominal period which starts at the end of Springer 2008 after 1.5 year of commissioning period. Compared to the commissioning period effluent, quality improvement of about 6 % (SS) and 15 % (NH_4^+-N) is observed. This phenomenon can be explained by: (i) the sludge deposit increase, (ii) limitation of the sludge deposit cracking due to drying.

Table 5. Effluent quality for both testing load (June 2008 - May 2010)

	30 kgSS/m²/y					**50 kgSS/m²/y**				
	mean	std	min	max	nb values	**mean**	std	min	max	nb values
COD (g/L)	**4.5**	6.3	0.1	31	23	**5.9**	4.0	0.3	15	23
SS (g/L)	**2.7**	4.2	0.05	21	42	**3.0**	2.5	0.2	14	42
NH_4^+-N (mg/L)	**25**	22.3	0.48	68.2	23	**53**	41	3.2	140	23
NO_3^--N (mg/L)	**207**	294.0	4.05	904.4	8	**199**	231	0.5	520	5
NK-N(mgL)	**258**	371.7	47.3	1092	7	**229**	73	88	294	7
TP (mg/L)	**69**	125.5	5.8	353	7	**48**	26	8.3	72	7
PO_4^{3-}-P (mg/L)	**14**	13.1	1.9	38.4	7	**15**	16.2	3.6	43	5
cond	**4003**	1680	1720	6760	7	**3271**	1093	1680	4630	7

If pollutant contents are still high, good removal efficiency are obtained. Removal rates are 92.9% ± 7.1% for SS and 90.5% ± 14.3% for NH_4^+-N at 30 kgSS/m²/y. When loaded at 50 kgSS/m²/y removals are 87.0±11.3% (SS) and 81.9±15.6% (NH_4^+ -N). It can be specified that these values are obtained at pilot-scale (2m²) with some shortcuts; these shortcuts can be avoided in large scale and so higher removal efficiency are expected.

The results obtained argue in favour of this system technology to treat septage. The question of the design load to be applied is of importance. No important differences are observed on effluent quality between the two loads tested (Wilcoxon test: p-value > 0.05) but, in both cases, a complementary treatment is needed to enhance effluent quality. Let's note that if SDRB systems are not affected by the organic load increase, low organic load (30 kgSS/m²/y) can induce water stress during summer.

Biosolids quality. Figure 3 presents dry matter content at the end of the resting period (before feeding) during a whole season. Results display important DM values with equal evolution whatever the load tested. DM content is still always upper than 23% in winter and can reach up to 70% in summer after only 24 days of rest. Thanks to lower hydraulic load, about 3.43 ± 0.9 cm/m²/load (against 35.2 ± 8.2 cm/m²/load for activated sludge) sludge can dry intensively to reach higher value than the one obtained with activated sludge in same conditions. Comparison, between septage and activated sludge, are presented in term of mean DM content according to the absence/presence of reeds. They are of 33/53% and 28/46%, respectively for 30 and 50 kgSS/m²/y for septage and 20/31% and 15/22% respectively for 30 and 50 kgSS/m²/y for activated sludge. If septage treatment by SDRB appears to be very efficient in term of DM of residual biosolid, sludge accumulation rate allow a septage storage time longer than the one of activated sludge. At 50 kgSS/m²/y septage biosolid accumulation rate is about 7.9 cm/y against 12.2 cm/y with activated sludge. At equal load Nielsen (2003) get growth value about 11 cm/y. This low biosolid accumulation can be referred to high loss of dry mass of septage.

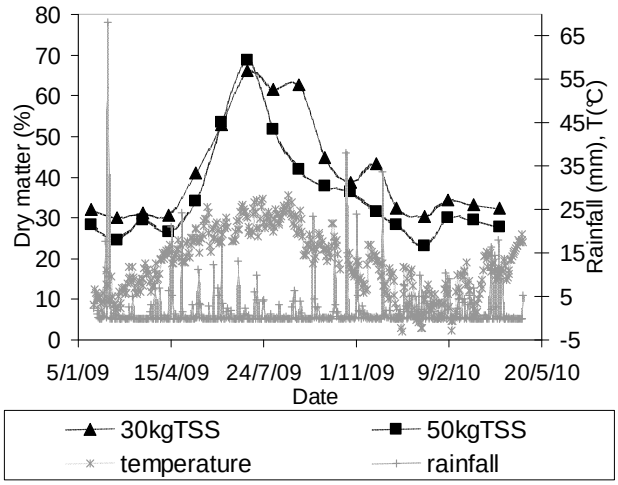

Figure 3. Biosolid final DM content evolution.

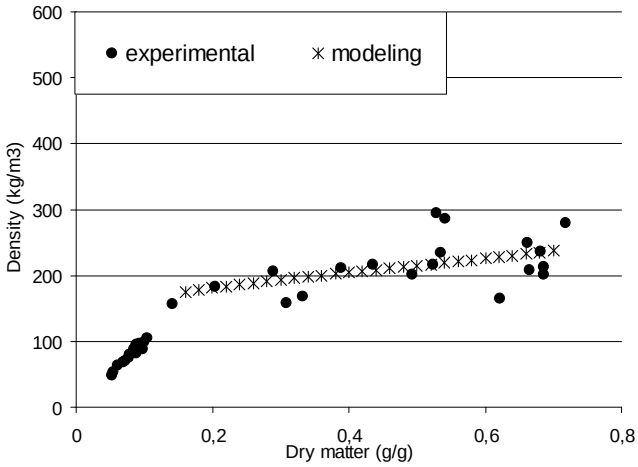

Figure 4. Apparent solid density vs DM.

Figure 4 represents the apparent solid density (ratio solid mass on total volume) versus DM (ratio solid mass on total mass). We observe first a linearity of the apparent solid density with DM, which demonstrates that the apparent total density (ratio total mass on total volume) is constant until a DM value of approximately 0.16 g/g. This constant apparent density is closed to 1000 kg/m^3 and corresponds to a saturated deposit.

Beyond this value, the deposit becomes triphasic (solid, water and air) and so is unsaturated. In this condition of unsaturation, experimental evolution can be perfectly described by the theoretical model developed by Rondet *et al*. (2010) for unsaturated granular media, where:

$$\text{Apparent solid density} = \frac{\text{solid density}}{1+\frac{\text{solid density}}{\text{water density}}\times\left(\frac{1-\text{DM}_{\text{unsat}}}{\text{DM}_{\text{unsat}}}\right)^{1-n}\times\left(\frac{1-\text{DM}}{\text{DM}}\right)^{n}} \qquad \text{Equation 1}$$

With solid density = 1439 kg/m^3 (Ruiz *et al.*, 2006), water density = 1000 kg/m^3, DM_{unsat} = 0.16 and n = 0.856.

Let's note that at high DM values, apparent solid density tends to a value closed to 250 kg/m^3.

Stored biosolid mass was calculated knowing the deposit volume (bed surface x deposit height) and its solid density. Equation 2 permits to balance the dry mass fluxes (kg_{Solids}/m^2) into the system:

$$\text{Solids}_{\text{stored}} = \text{Solids}_{\text{inlet}} - \text{Solids}_{\text{outlet}} + \text{Solids}_{\text{reeds}} \qquad \text{Equation 2}$$

Figure 5 and 6 present theoretical (calculated from equation 2) and measured biosolids accumulation according to the organic load. Reed biomass (i.e. $Solids_{reeds}$ in equation 2) is supposed equal to 2 kg_{solids}/m^2 for young reeds (Tanner, 1996) and 5 kg_{solids}/m^2 for mature vegetal fed with primary sludge (Meuleman *et al.*, 2002). The figures underline sludge reduction; both curves come off. In fact, after six month of accumulation, reduction occurs at any load. Experimental curves have several slopes, whereas theoretical ones increase gradually. Changing slope matches with season: in winter the slope increases, whereas in spring it decreases. Then, sludge reduction appears in spring when biological activity starts, whereas only accumulation occurs in winter. Accumulation time depends also to the organic load, higher it is longer accumulation is. Volatile matter ratio also reveal different mineralization rate according to the load,

it's about 18.6% ± 8.7%, 14.3% ± 6.3% for 30 and 50 kgSS/m^2/y respectively. While activated sludge results in same conditions, display fewer rates: 13.1% ± 8.7%, 9.7 ± 11.7%. Thus, for both sludge types mineralization rate decreases from about 4 units, as organic load increases. Nevertheless, these rates are fewer than those on figure 5 and 6:48.0% and 43.4% respectively.

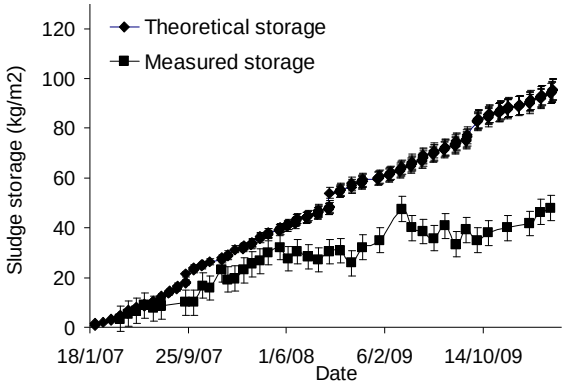

Figure 5. Evolution of biosolid accumulation at 30 kgSS/m^2/y.

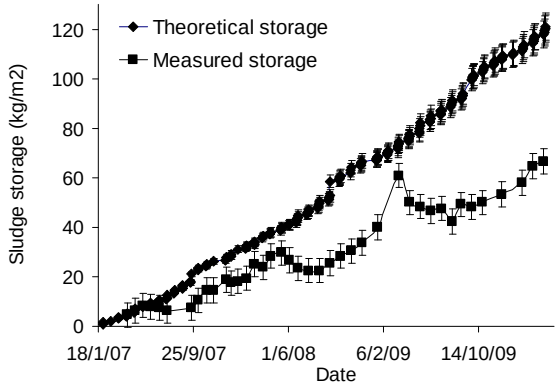

Figure 6. Evolution of biosolid accumulation at 50 kgSS/m^2/y .

Recirculation test

Effluent had been recirculated 26 times throughout the resting period. Results reveal a quality enhancement, NH_4^+-N as well as SS measure decrease gradually from 3.2 g/L to 0.3 g/L and from 60.5 mg/L to 0.7 mg/L, for SS and NH_4^+-N respectively. These quality improvements can be due to the infiltration rate reduction, which drops away from $2.4.10^{-6}$ m/s to $5.6.10^{-7}$ m/s. Thus, recirculation allows higher effluent retention time within the bed, and generates better quality effluent as classic system. This way can be an alternative to solve septage effluent issue.

CONCLUSION

With the development of decentralized sanitation systems in rural area and developing countries, a growing involvement in septage treatment is observed. Since the successful advances of SDRB system for activated sludge treatment, these 20 last years, question of septage treatment onto those system have to be asked. This work focuses on the feasibility of septage treatment and disposal on SDRB, based on experiments carried out in pilot.

This study first focuses onto septage composition, with regards to its ability to dewater. Results show important CST values, fine particles and fats content; typical of low dewaterering sludge. Next, this paper summarizes 1.5 year of operation for two specific loads: 30 and 50 kgSS/m2/y. According to system performance, feasibility of septage treatment is demonstrated. In fact, no clogging phenomena is observed, sludge deposit presents high DM content for both loads with values upper than 20% all over the year. However, percolate quality has to be improved, even if good filtration efficiencies (> 80%) are registered for SS and NH_4^+-N. From this point, complementary treatment is needed. Recirculation experiment results announce effluent quality improvement, but more experience is needed to fix the number and the volume of the recirculation batches. Through this experiment on septage treatment with SDRB some design and operation condition recommendations can be gave: (i) vegetable compost layer can be used with success, (ii) 50 kgSS/m^2/y can be recommended as specific load after a commissioning period at 30 kgSS/m^2/y, (iii) effluent recirculation is possible, to ameliorate its quality.

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