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Surplus activated sludge dewatering in pilot-scale sludge drying reed beds

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ABSTRACT

A pilot-scale experiment on dewatering of surplus activated sludge (SAS) is presented, where two pilot-scale vertical flow, sludge drying reed beds (SDRBs), planted with *Phragmites australis* are used. The bottom of the beds is filled with cobbles, connected to the atmosphere through perforated PVC ventilation tubes, in order to achieve oxygen diffusion through the overlying porous medium that is colonized by roots and an abundant nitrifying biomass. Two layers of gravel, of decreasing size from bottom to top, make the drainage layer where the reeds are planted. The two beds were fed according to the following cycle: one week feeding with SAS at rates one 30 kg/m^2/year and the other 75 kg/m^2/year, and resting for three weeks. The results show that planted SDRBs can effectively dewater SAS from domestic sewage, the produced residual sludge presents a high dry weight content, the degree of volume reduction depends upon the initial SAS concentration and can be of the order of 90%, and decomposition of organic matter and high levels of mineralization can be achieved. Furthermore, the percolating water is not septic. The fertilizer value of the treated SAS, which contains no added chemicals, is comparable to that of SAS treated by other methods.

1. Introduction

The treatment of sewage leads to the production of large amounts of surplus activated sludge (SAS), whose treatment involves, among others, the removal of water to reduce volume for proper use or disposal. Sludge drying reed beds (SDRBs) for treatment of SAS are a combination of traditional sludge drying beds and vertical flow constructed wetlands. Their main advantages include low investment, reduced SAS removal costs, simplicity, and production of small volumes of well-composted residual sludge. The surplus activated sludge is fed onto the reed bed periodically, and becomes dewatered by percolation through earlier deposited layers of SAS and gravel drainage layers, transpiration by the reeds, and evaporation from the sludge surface. With slow transfer of oxygen into the sludge layer, the sludge gradually becomes oxidized/mineralized, as observed through reduction in volatile solids, increase in percentage of fixed solids and gradual loss of moisture. The percentage of total solids (TS) of the dewatered residual sludge can build up to 50% [1]. Most experience on reed bed dewatering comes from the work of Nielsen [2–4], Lienard et al. [5,6], De Maeseneer [7], Hofmann [8,9] and Edwards [10].

In this study, design, operation and results of pilot-scale experiments on dewatering of SAS under Mediterranean conditions are presented. The experimental set up comprises two similar SDRB tanks, planted with *Phragmites australis*, and operating in parallel under two different loading rates.

2. Materials and methods

2.1. Experimental set up

Two similar pilot-scale vertical flow SDRB units, with surface area of 0.53 m^2 each and height 1.50 m, were constructed on Democritus University campus, in the open space of the Laboratory of Ecological Engineering and Technology (Xanthi, Greece). For the construction of the beds, two cylindrical plastic tanks of diameter 0.82 m were used. A picture and a schematic section of the pilot-scale units are presented in Fig. 1.

Both beds were planted with common reeds (*P. australis*), transplanted from water courses in the vicinity of the experiment. The bottom of the beds was filled with cobbles (30 mm mean diameter, layer thickness d = 10 cm) which communicated with the atmosphere through four PVC ventilation tubes (50 mm in diameter), so as to avoid anaerobic conditions. Two layers of gravel were placed on top of the cobbles (4–8 mm, d = 15 cm lower layer; 2–5 mm, d = 15 cm top layer), which make the drainage media where the reeds are planted. A freeboard of 1.0 m was allowed for accumu-

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(a)

(b)

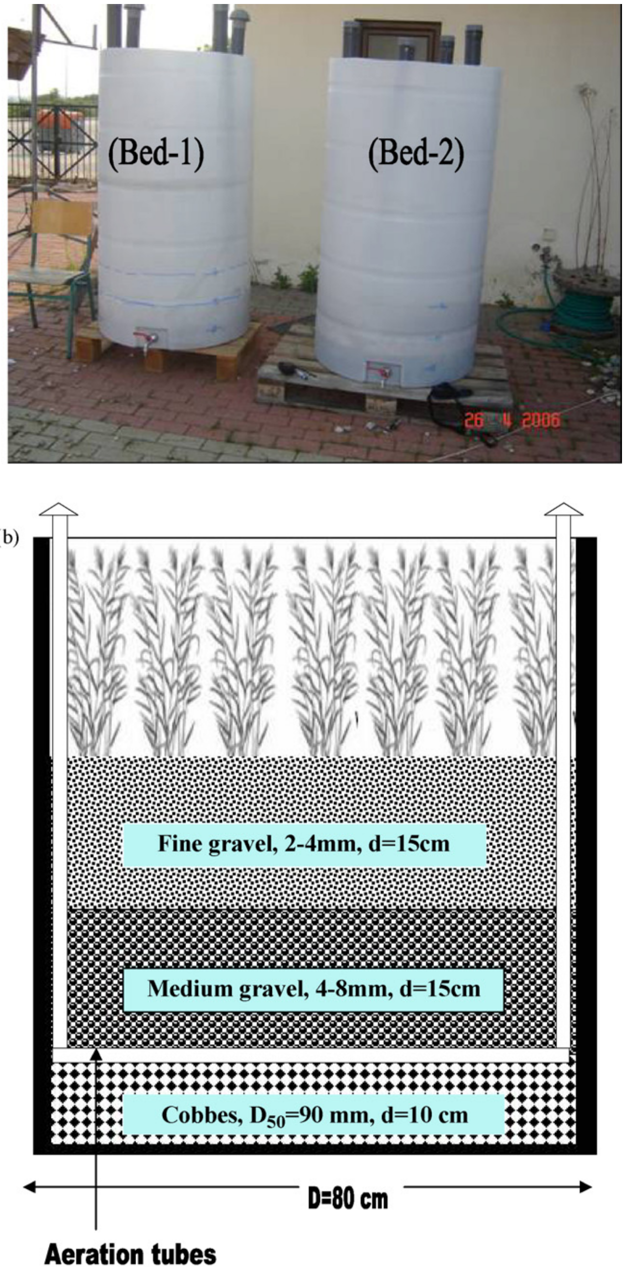

Fig. 1. (a) The experimental set up; (b) schematic section of a pilot-scale unit.

lation of the dewatered SAS. Photos from the various stages of pilot-scale unit construction are presented in Fig. 2. The drainage layer rests on a well-ventilated floor; oxygen diffuses through the voids within the granular medium, which is colonized by roots and an abundant nitrifying biomass. The presence of oxygen is fundamental to enabling the reeds to grow abundantly in an organic medium that could rapidly become fermenting, anaerobic and toxic.

The commissioning phase of the units was 6 months. During the commissioning phase the two planted beds were lightly loaded with synthetic wastewater, which greatly benefited the reed growth. The loading of the SAS for the main trials started in October 2006 and continued until December 2008. Both beds were fed with SAS, following the schedule presented in Table 1. The more frequent loading cycles were used during high values of temperature and extensive evapotranspiration in the Mediterranean climate. The loading of Bed-2 was totally stopped in June 2008 in order to test

Table 1
Timetable of loading cycles.

Time Period	Loading cycle
October 2006–28/5/2007	28 day loading cycle (i.e., 7 days of feeding followed by 21 days of resting)
29/5/2007–19/08/2007	14 day cycle (i.e., 7 days of feeding followed by 7 days of resting)
20/08/2007–1/6/2008	28 day loading cycle (i.e., 7 days of feeding followed by 21 days of resting
02/06/2008–30/6/2008	14 day cycle (i.e., 7 days of feeding followed by 7 days of resting)
1/7/2008–5/10/2008	21 day cycle (i.e., 7 days of feeding followed by 14 days of resting)
6/10/2007–1/12/2008	28 day loading cycle (i.e., 7 days of feeding followed by 21 days of resting)

progress of mineralization of the top sludge layer under no sludge loading conditions. The different degrees of mineralization could be investigated through comparison of the loaded and unloaded units.

Initially, for the first two loading cycles, the loading was carried out directly from the aeration basin (TS 0.5%) and then, for all the following cycles, after thickening (TS 3.1%). The SAS was produced at the wastewater treatment plant (WWTP) of the municipality of Komotini, Rhodope Province, Greece. Two loading rates were used: 30 kg/m^2/year (Bed-1) and 75 kg/m^2/year (Bed-2). The feeding was carried out manually, using a device which offered uniform spreading over the surface of the beds. For the entire loading period, there was continuous recording at the experimental site of air temperature, solar energy and rainfall depth. Fig. 3 presents the time series charts for air temperature, solar heat flux and rainfall depth. Air temperature varied between 0.0 and 33.5 °C. The solar energy measured on the site varied in magnitude from 1.8 to 289.3 Wh/m^2. The total rainfall depth for the period was 1435.4 mm.

2.2. Sampling and analytical methods

Surplus activated sludge samples were collected at the end of the resting phase of every cycle using a core sampler (i.e., the sampling was taking place exactly before the application of the new sludge loading). Samples were analyzed for TS (dewatering efficiency), VS (mineralization), TKN, NO_3^-–N and NO_2^-–N, and TP according to Standard Methods [11]. Samples for the characterization of the percolated fluid were also taken at the end of the feeding phase of each cycle, as follows: immediately after the loading, 10 min later, 1 h later and 1 d later. The percolated fluid samples were analyzed for pH, EC, SS, VSS, COD, NH_4^+–N and PO_4^{3-}–P according to Standard Methods [11]. Standard methods of analysis [11] were also used for the determination of total heavy metal concentrations through Flame Atomic Absorption Spectrophotometry, using external standards in the same medium as the extractant. Aqueous metal concentrations were then calculated on a dry weight basis for the solid samples.

2.3. Statistical analysis

In order to examine the correlation between the constituent concentrations (TS, VS, TKN, TP, nitrite and nitrate) with the operation parameters of the two beds (e.g., temperature, windspeed, windvane, relative humidity, rainfall, solar heat flux, barometric pressure, SAS loading rate and resting days), correlation coefficients (r) were calculated according to the following Eq. (1):

$$r = \frac{\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{N}(y_i - \bar{y})^2}} \quad (1)$$

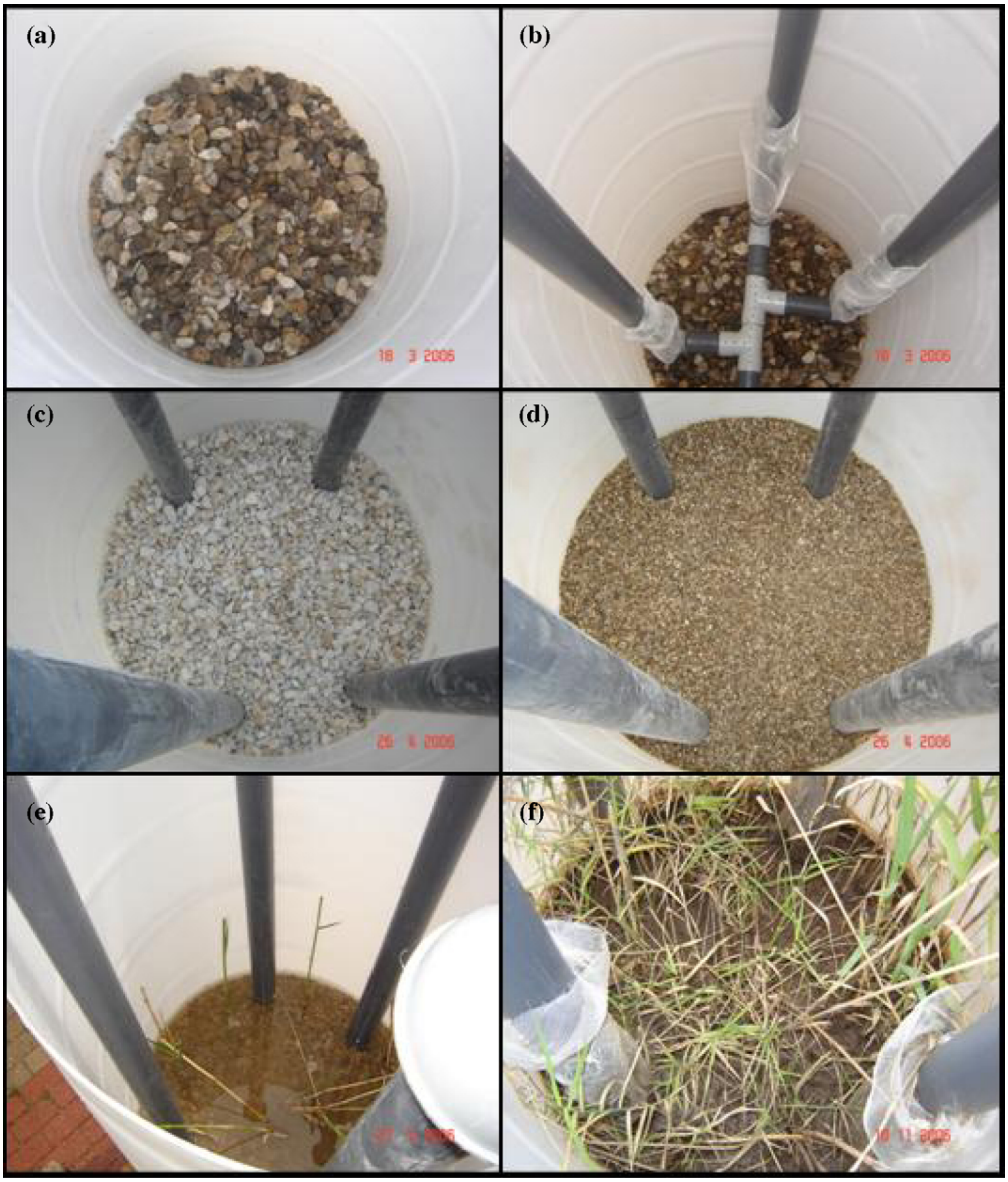

Fig. 2. Photos from the pilot-scale unit construction: (a) drainage layer; (b) aeration tube; (c) 2nd layer with medium gravel; (d) 3rd layer with fine gravel; (e) unit planted with common reed; (f) unit loaded with SAS.

where x_i and y_i the parameter values, $\bar{x}$ and $\bar{y}$ the mean values of the two parameters and N the number of measurements. Correlation coefficient values range from −1 to 1. The negative values of r indicate that the two variables have an inverse relation.

3. Results and discussion

3.1. Influent SAS quality

The wastewater treatment plant which offered the SAS is an extended aeration system with long retention time in the aeration basin and well-stabilized SAS. The retention time in the extended aeration unit, and therefore, the age of the SAS were 20 days. Table 2 presents the characteristics of the inflowing SAS to the two pilot SDRB units.

3.2. Loading rate

When experiments started (26/10/2006) and for two loading cycles, raw SAS (TS 0.50%) directly from the aeration basin was used. Starting from the third SAS application cycle, raw SAS thickened in a gravity thickener (TS ca. 3.1%) was used. The total influent liquid volumes for 31 cycles (October 2006–December 2008 operating period) were (using the mean TS concentration) for Bed-1 2.3 m^3/m^2 or about 7.1 kg d.w./m^2, and for Bed-2 3.9 m^3/m^2 or 11.2 kg d.w./m^2 (Table 3). The daily loadings were 5.86 and 14.64 L for Bed-1 and Bed-2 (feeding of Bed-2 was stopped in June 2008), respectively.

Table 2
Mean values of the influent SAS characteristics.

Parameter	SAS from thickener
TS [%]	3.1
VS [% TS]	71.6
TSS [g/L]	22.5
VSS [g/L]	16.6
pH	6.19
TKN [mg/g d.w.]	54.85
TP [mg/g d.w.]	9.29
$(NO_2^-{-}N)+(NO_3^-{-}N)$ [μg/g d.w.]	699.20

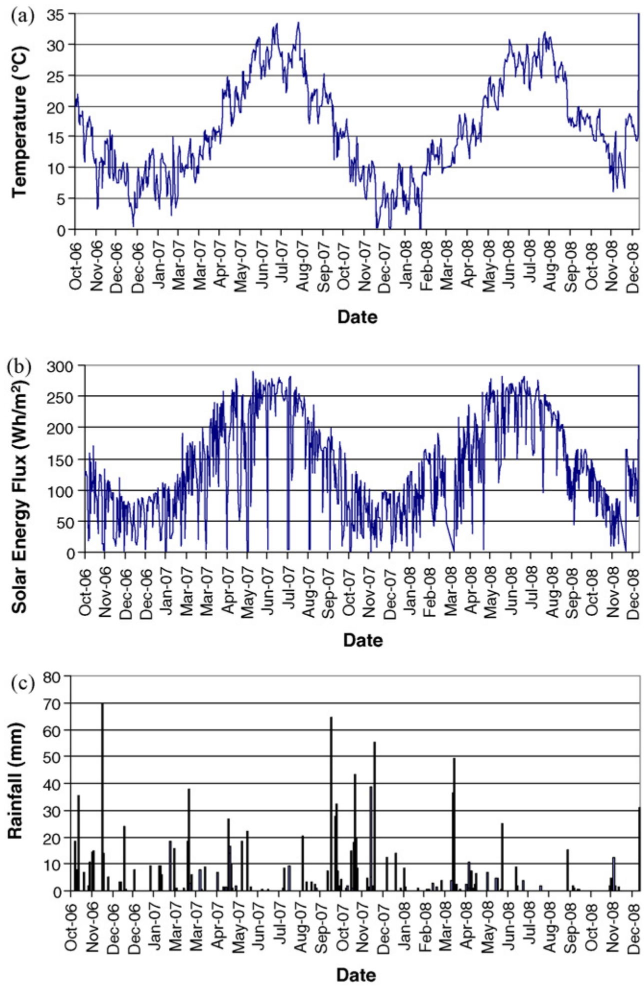

Fig. 3. Time series charts for: (a) air temperature; (b) solar heat flux; (c) rainfall depth.

Table 3
Influent SAS loadings to the two pilot-scale units (October 2006–December 2008).

Parameter	Bed-1	Bed-2
Influent SAS [m^3/m^2]	2.3	3.9
Thickness of SAS added [cm]	242	410
Thickness of dried SAS [cm]	3.5	7.5
TS [kg d.w./m^2]	7.1	11.2
VS [kg d.w./m^2]	5.1	8.6

3.3. Percolated fluid quality

Quality characteristics of the percolated fluid were determined for the first two loading cycles and are presented in Table 4. Bed-1 showed a reduction in COD of 90.0% 10 min after start of feeding and 96.1% 1 day after. Respective COD reductions in Bed-2 were 60.0% and 93.5% (Fig. 4). Apparently, COD removal is lower in Bed-2 because it receives a higher SAS load than Bed-1. TS and VS removals in Bed-1, 10 min after start of feeding, were 92.7% and 94.9%, respec-

Table 4
Mean values of quality characteristics of the percolated fluid.

Parameter	In	Bed-1			Bed-2		
		10 min	1 h	1 day	10 min	1 h	1 day
TS [g/L]	1.52	0.11	0.29	0.00	0.81	0.39	0.00
VS [g/L]	1.97	0.10	0.25	0.00	0.69	0.35	0.00
pH	7.01	6.94	6.92	7.77	6.76	6.79	7.41
COD [mg/L]	2623	262	426	103	1049	787	171
EC [μS/cm]	1293	1315	1288	1137	1297	1308	1259
NH_4–N [mg/L]	2.24	2.80	2.52	3.36	1.68	1.68	2.80
PO_4–P [mg/L]	0.16	3.52	3.55	3.42	4.51	5.04	7.47

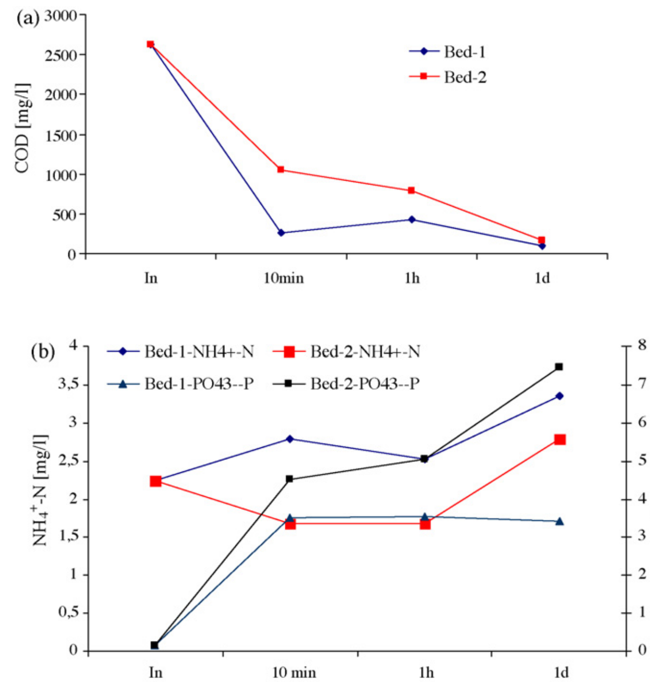

Fig. 4. (a) Mean COD reduction in the percolated fluid; (b) mean NH_4^+–N and PO_4^{3-}–P concentration increases in the percolated fluid.

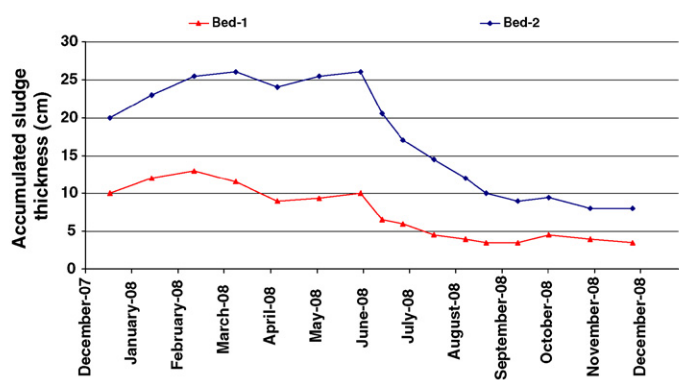

Fig. 5. Time series chart for the thickness of the residual sludge.

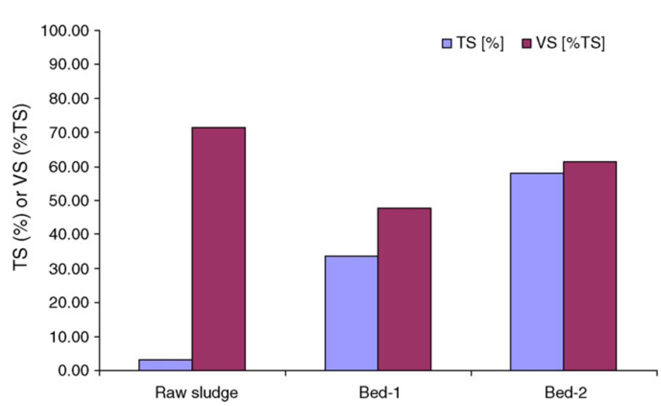

Fig. 6. Mean TS (%) and VS (%TS) in the residual sludge compared to the influent SAS after 26 months of operation.

Table 5
Pollutant concentrations in the residual sludge from October 2006 until December 2008.

Period	Sampling date	Bed-1					Bed-2				
		TS (%)	VS (%)	TP (mg/g d.w.)	TKN (mg/g d.w.)	$(NO_2^{-}–N) + (NO_3^{-}–N)$ (μg/g d.w.)	TS (%)	VS (%)	TP (mg/g d.w.)	TKN (mg/g d.w.)	$(NO_2^{-}–N) + (NO_3^{-}–N)$ (μg/g d.w.)
Cycle-1	05/12/2006	82.1	43.0	2.95	46.50	50.43	59.4	34.0	2.53	23.79	58.36
Cycle-2	21/01/2007	98.1	61.0	4.25	38.40	140.87	19.8	66.0	5.08	42.73	138.15
Cycle-3	19/02/2007	55.1	80.0	6.11	55.40	114.40	10.9	44.3	6.61	32.03	155.73
Cycle-4	19/03/2007	81.2	49.2	3.19	49.62	415.27	23.3	36.9	8.10	53.54	103.56
Cycle-5	16/04/2007	86.8	64.1	3.00	47.95	265.48	21.1	41.2	4.30	50.67	525.22
Cycle-6	14/05/2007	93.8	57.0	3.29	34.50	401.06	84.4	68.5	4.30	22.51	144.75
Cycle-7	28/05/2007	67.1	40.6	8.11	43.92	368.70	32.6	40.8	3.29	46.58	861.26
Cycle-8	11/06/2007	93.5	55.1	4.10	52.73	453.90	35.2	27.6	3.22	38.02	1023.76
Cycle-9	25/06/2007	96.5	61.4	1.03	37.50	548.94	36.3	42.7	2.55	34.50	526.53
Cycle-10	09/07/2007	78.6	37.3	2.65	43.40	495.77	47.6	34.0	1.01	22.71	144.03
Cycle-11	23/07/2007	87.6	45.9	3.19	22.80	108.09	54.0	12.3	4.12	20.55	536.24
Cycle-12	20/08/2007	90.0	40.0	2.10	18.90	95.60	60.0	10.0	3.60	13.10	500.36
Cycle-13	17/09/2007	89.6	43.8	2.50	19.70	109.40	57.8	12.4	3.50	14.50	538.70
Cycle-14	15/10/2007	50.0	56.3	3.90	25.60	256.90	40.0	48.7	3.10	25.60	589.70
Cycle-15	12/11/2007	26.9	57.8	5.40	29.40	356.90	23.6	54.3	3.20	33.50	456.90
Cycle-16	17/12/2007	9.7	66.1	6.61	35.70	652.49	8.3	69.2	3.67	43.50	176.55
Cycle-17	14/01/2008	11.9	69.1	5.42	38.70	140.96	11.1	70.1	2.86	42.40	140.96
Cycle-18	11/02/2008	16.8	63.0	12.80	40.70	515.11	13.1	67.8	9.15	43.60	515.11
Cycle-19	10/03/2008	16.6	65.5	1.14	63.90	318.94	13.8	67.1	1.39	36.70	318.94
Cycle-20	07/04/2008	14.7	67.1	2.09	43.30	744.42	11.2	67.3	4.53	46.60	744.42
Cycle-21	05/05/2008	16.3	64.7	3.42	42.20	662.81	15.5	68.1	1.64	43.90	662.81
Cycle-22	02/06/2008	33.3	62.9	5.62	20.60	211.20	11.7	68.0	7.02	51.20	211.20
Cycle-23	16/06/2008	16.3	61.8	9.52	35.00	193.14	27.3	64.4	10.72	40.70	193.14
Cycle-24	30/06/2008	18.3	61.6	9.57	34.20	178.71	31.7	68.3	7.90	31.70	178.71
Cycle-25	21/07/2008	88.6	63.6	6.12	30.10	169.22	55.4	61.9	6.32	33.70	169.22
Cycle-26	11/08/2008	85.6	58.1	6.32	31.10	125.25	59.7	60.1	6.55	30.20	125.25
Cycle-27	25/08/2008	89.3	57.7	8.93	20.40	678.61	50.7	60.3	9.23	36.30	927.12
Cycle-28	15/09/2008	51.5	58.4	9.21	39.40	3688.08	44.4	59.8	6.10	35.20	2815.77
Cycle-29	06/10/2008	39.6	54.2	10.31	40.20	1277.55	41.4	50.4	5.61	34.70	2122.54
Cycle-30	03/11/2008	55.6	60.6	11.69	43.50	2170.24	68.8	60.2	7.43	31.00	1932.15
Cycle-31	01/12/2008	33.5	47.6	10.66	14.30	2007.79	58.0	61.4	8.00	8.20	1438.63
Influent	Mean	3.1	71.6	9.29	54.85	699.20	3.1	71.6	9.29	54.85	699.20
SAS	SD	0.96	4.62	2.77	10.87	508.46	0.96	4.62	2.77	10.87	508.46
	Min	1.80	53.40	2.89	34.00	37.20	1.80	53.40	2.89	34.00	37.20
	Max	6.25	76.90	13.00	77.80	2298.45	6.25	76.90	13.00	77.80	2298.45

tively, and in Bed-2 46.7% and 65.0%. Complete TS and VS removals were observed 1 day after loading, showing an excellent retention of the influent SAS dry matter. NH_4^+–N concentration showed a slight increase 1 day after start of feeding, from 2.24 to 3.36 mg/L in Bed-1 and to 2.80 mg/L in Bed-2. PO_4^{3-}–P showed a significant increase in 1 day, from 0.16 to 3.42 mg/L in Bed-1 and to 7.47 mg/L in Bed-2 (Fig. 4). The increase of ammonia and phosphorus after 1 day indicate an increased microbiological activity.

3.4. Residual sludge quality

It was observed that, in the dewatering process in this Mediterranean climate, evapotranspiration plays a more significant role than percolation, in the case of thickened SAS. The thickness of the residual sludge reached about 3.5 cm in Bed-1 and 7.5 cm in Bed-2 (Table 3). Fig. 5 presents a time series chart for the thickness of the residual sludge. From this chart it is obvious that when the temperature, and thus evaportranspiration, are high (summer months), the thickness of the residual sludge in both units decreases. Table 5 presents TS, VS and other constituent contents observed at the end of each loading cycle, and Fig. 6 presents the increase in TS and reduction in VS after the 26 months of operation. TS values in Bed-1, loaded with the lower rate, were higher than those in Bed-2, which indicates a high degree of water removal, and demonstrates the reed-aided dewatering process. Due to the lower quantity of residual sludge, the evapotranspiration rate was higher in Bed-1 than in Bed-2. The values of the TS contents in both units show a seasonal variation due to the different meteorological conditions (temperature and rainfall values). The highest TS values (96.5%, Bed-1) on cycle-9 (Table 5) are explained from the high temperatures (up to 33.5 °C) in the summer. It should be mentioned that this maximum value of TS occurred when the loading period was more frequent (7 days feeding/7 days resting). Thus, this maximum value of TS corresponds to increased loadings of SAS. The respective VS values kept decreasing at high temperatures, and at the end of cycle-12 (August 2007) VS values reached 40.0% TS in Bed-1 and 10.0% TS in Bed-2 (from 71.6% TS in the influent SAS), showing that significant oxidation/mineralization took place. These charts (Fig. 6) in comparison with the time series charts of TS, VS, TP, TKN and nitrite and nitrate presented in Fig. 7, reinforce the argument that in periods of high temperatures and high values of solar heat flux, TS content increases while VS content and the concentrations of TKN, TP, nitrite and nitrate decrease; this indicates that the dewatering and oxidation processes are favored under these climatic conditions. On the contrary, when temperature and solar heat flux values decrease and rainfall depth values increase, dewatering and oxidation processes are inhibited, resulting in lower TS contents and higher VS content and TP, TKN, nitrite and nitrate concentrations. This phenomenon is obvious in the period from December 2007 until May 2008, when a decrease of the solar heat flux values and an increase of the rainfall depth was observed, which resulted in a decrease of TS content and an increase of VS content. The above conclusions are also reinforced by the values of correlation coefficients of TS and VS with the meteorological parameters (Table 6). Specifically, TS presents high values of correlation coefficients with humidity (−0.54), air and soil temperature (0.48 and 0.50, respectively), solar heat flux (0.41) and mean rainfall (−0.24). VS presents high values of correlation coefficients with humidity (0.41), air and soil temperature (−0.40 and −0.47, respectively) and solar heat flux (−0.28). All these meteorological parameters are highly related to evaportranspiration. TS and VS also show relatively high correlation coefficients values with the loading rate (−0.28 and −0.38).

During the period when Bed-2 was kept unloaded (from June until December 2008), the values of TS showed a constant increase and, at the end of the operation period (December 2008), they were higher than those of Bed-1 (Fig. 7). VS values were slightly higher

Table 6
Variable correlation matrix.

	TS	VS	TP	TKN	$NO_3^- + NO_2^-$	Windvane	Humidity	Air temperature	Soil temperature	Barometric pressure	Solar heat flux	Windspeed	Mean rainfall	Total rainfall	Resting days	Loading rate
TS	1.00	−0.25	−0.18	−0.31	−0.06	−0.30	−0.54	0.48	0.50	−0.06	0.41	0.03	−0.24	−0.11	0.04	−0.28
VS	−0.25	1.00	0.24	0.44	0.04	0.17	0.41	−0.40	−0.47	0.25	−0.28	−0.29	−0.01	−0.06	0.08	−0.38
TP	−0.18	0.24	1.00	0.06	0.40	−0.09	0.07	0.00	0.01	0.12	−0.08	−0.17	−0.19	−0.25	0.17	−0.42
TKN	−0.31	0.44	0.06	1.00	0.05	0.41	0.58	−0.55	−0.56	−0.25	−0.42	0.03	0.22	0.09	−0.05	−0.09
$NO_3^- + NO_2^-$	−0.06	0.04	0.40	0.05	1.00	−0.13	−0.06	0.13	0.13	0.13	−0.03	−0.19	−0.16	−0.24	0.40	−0.27
Windvane	−0.30	0.17	−0.09	0.41	−0.13	1.00	0.64	−0.78	−0.77	−0.01	−0.71	0.30	0.30	0.38	0.02	0.29
Humidity	−0.54	0.41	0.07	0.58	−0.06	0.64	1.00	−0.84	−0.85	−0.14	−0.80	−0.08	0.52	0.39	0.00	0.18
Air temperature	0.48	−0.40	0.00	−0.55	0.13	−0.78	−0.84	1.00	0.97	0.04	0.91	−0.21	−0.28	−0.32	−0.06	−0.25
Soil temperature	0.50	−0.47	0.01	−0.56	0.13	−0.77	−0.85	0.97	1.00	−0.08	0.86	−0.08	−0.28	−0.25	−0.02	−0.25
Pressure	−0.06	0.25	0.12	−0.25	0.13	−0.01	−0.14	0.04	−0.08	1.00	−0.01	−0.29	−0.24	−0.19	0.10	−0.11
Solar heat flux	0.41	−0.28	−0.08	−0.42	−0.03	−0.71	−0.80	0.91	0.86	−0.01	1.00	−0.29	−0.39	−0.46	−0.22	−0.20
Windspeed	0.03	−0.29	−0.17	0.03	−0.19	0.30	−0.08	−0.21	−0.08	−0.29	−0.29	1.00	0.16	0.43	0.10	0.18
Mean rainfall	−0.24	−0.01	−0.19	0.22	−0.16	0.30	0.52	−0.28	−0.28	−0.24	−0.39	0.16	1.00	0.70	−0.16	0.25
Total rainfall	−0.11	−0.06	−0.25	0.09	−0.24	0.38	0.39	−0.32	−0.25	−0.19	−0.46	0.43	0.70	1.00	0.00	0.24
Resting days	0.04	0.08	0.17	−0.05	0.40	0.02	0.00	−0.06	−0.02	0.10	−0.22	0.10	−0.16	0.00	1.00	−0.42
Loading rate	−0.28	−0.38	−0.42	−0.09	−0.27	0.29	0.18	−0.25	−0.25	−0.11	−0.20	0.18	0.25	0.24	−0.42	1.00

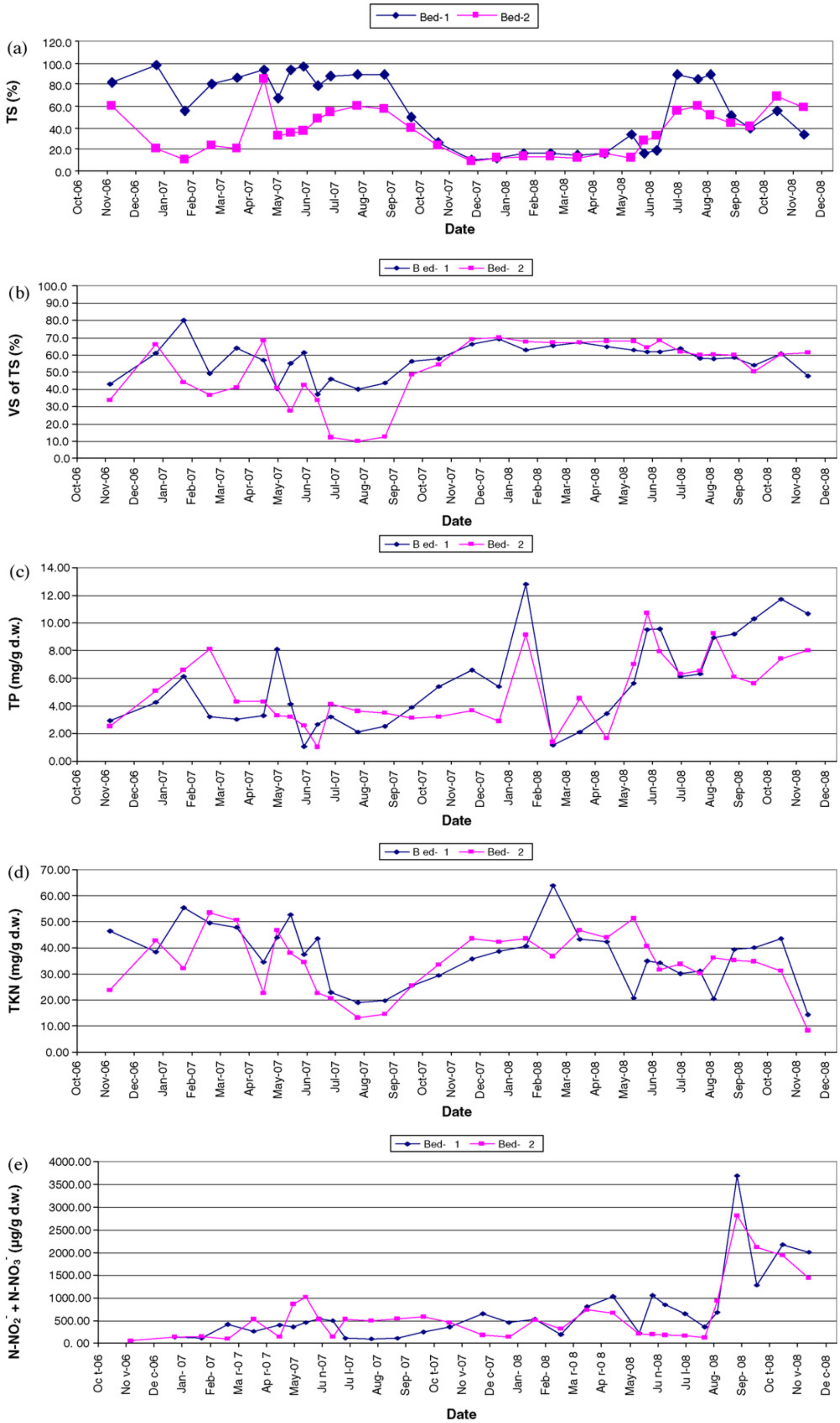

Fig. 7. Residual sludge content time series charts for: (a) TS; (b) VS; (c) TP; (d) TKN; (e) NO_2^-–N + NO_3^-–N.

than those in Bed-1. The concentrations of TP and TKN showed a constant decrease and, at the end of the operation period (December 2008), they were lower than those of Bed-1. Nitrite and nitrate concentrations showed an increase first, indicating organic nitrogen and ammonia oxidation, and a decrease afterwards.

The excellent performance of mineralization in the pilot-scale units is also indicated by the rather satisfactory decrease of TP and TKN contents in the residual sludge, as presented in Table 5, especially after the period when high temperatures occurred. Compared to the TP average value in the influent SAS (9.29 mg/g d.w.), the TP

Table 7
Analysis of accumulated residual sludge core sample from Bed-2 at the end of selected loading cycles, compared to the influent SAS.

Sample	TS [%]	VS [%TS]
Influent SAS	3.1	71.6
Bed-2, upper layer	16.1	72.8
Bed-2, lower layer	17.8	40.5

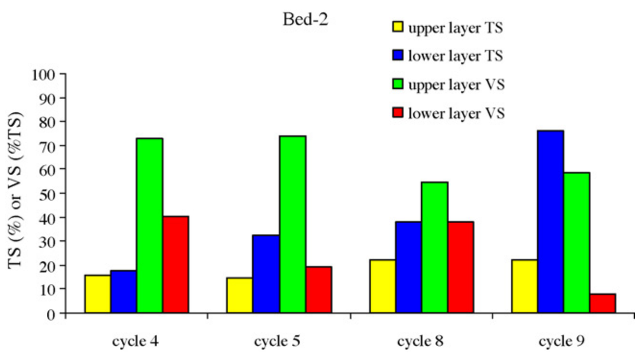

Fig. 8. Upper and lower layer comparison in the residual sludge at various loading cycles.

content decreased to 2.10 mg/g d.w. (77.3% reduction) in Bed-1 at the end of cycle-12 (August 2007) and 3.10 mg/g d.w. (66.6% reduction) in Bed-2 at the end of cycle-14 (October 2007). From Table 6, TP seems to have a high value of the correlation coefficient with the loading rate (−0.42), the number of resting days (0.17) and with total rainfall (−0.25), indicating that the removal of TP from the SAS is mostly affected by the amount of SAS added in the unit and the available time for oxidation. The same trend also appeared in TKN concentrations, where TKN content decreased from 54.9 mg/g d.w. in the influent SAS to 18.9 mg/g d.w. (65.5% reduction) in Bed-1 and 13.1 mg/g d.w. (76.1% reduction) in Bed-2 in August 2007 (cycle-12). TKN shows, similarly to TS and VS, a great correlation with meteorological parameters, which are involved in the calculation of evaportranspiaration. Specifically, TKN presents high values of correlation coefficients with humidity (0.58), air and soil temperature (−0.55 and −0.56, respectively), solar heat flux (−0.42) and mean rainfall (0.22). Although an increase of the inorganic nitrogen contents would be expected, the concentrations of NO_2^-–N and

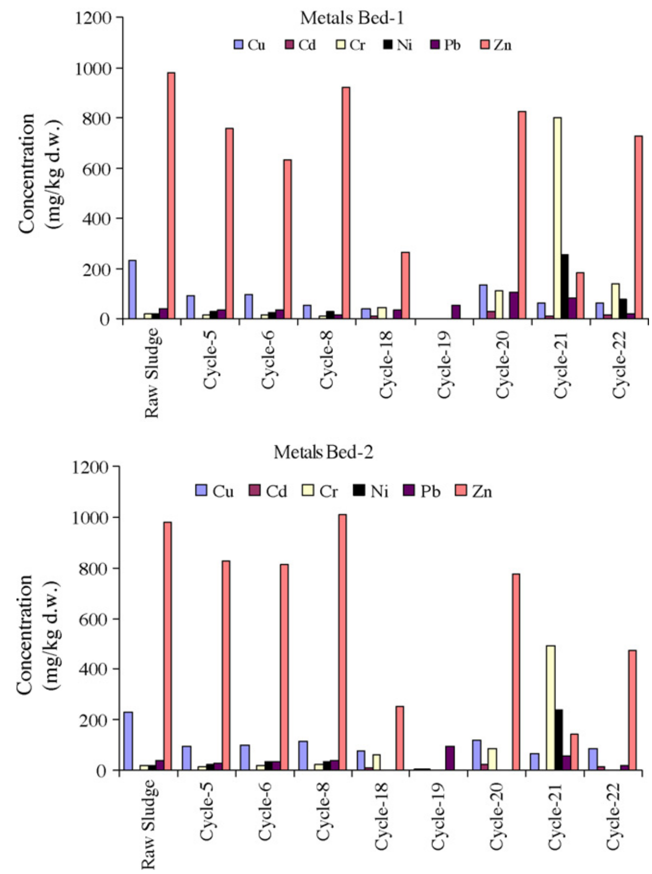

Fig. 9. Average heavy metal concentrations (mg/kg d.w.) in the residual sludge samples from Bed-1 and Bed-2 compared to the values of influent (raw) SAS.

NO_3^-–N were also decreased (86.4% and 28.7% in Bed-1 and Bed-2, respectively), indicating a significant probable nitrogen uptake by the plants. Inorganic nitrogen shows great correlation with the number of resting days (0.40), as expected, because nitrite and nitrate are the final products of the organic nitrogen oxidation, which is a slow reaction in natural systems.

Residual sludge core samples were taken from Bed-2 at the end of the loading cycles 4, 5, 8, 9, and were divided into two equal

Table 8
Heavy metal concentrations in the residual sludge (data in mg/kg d.w.).

	Cu	Cd	Cr	Ni	Pb	Zn	Fe	Mn
Bed-1								
Cycle-5	93.8	1.09	15.8	28.5	31.7	756.0	4269.0	70.6
Cycle-6	96.5	0.92	14.9	26.0	34.8	631.0	5007.0	65.7
Cycle-8	53.8	0.86	11.2	27.3	12.4	920.0	2046.0	61.2
Cycle-18	38.5	10.5	45.5	0.0	35.0	265.2	593.0	96.2
Cycle-19	0.0	1.7	0.0	0.0	50.7	0.0	564.5	54.1
Cycle-20	136.0	27.2	113.0	2.1	104.6	824.2	533.7	150.7
Cycle-21	64.3	10.0	801.6	253.1	80.4	183.8	773.5	114.5
Cycle-22	60.6	12.5	140.0	77.3	20.9	726.1	557.9	135.8
Bed-2								
Cycle-5	94.8	1.0	15.1	23.9	30.8	826.0	4190.0	57.4
Cycle-6	98.2	1.0	18.5	33.4	33.8	814.0	5101.0	74.6
Cycle-8	112.7	1.2	23.6	32.5	37.7	1008.0	4760.0	86.0
Cycle-18	76.9	10.7	62.6	0.0	0.0	252.5	447.1	105.5
Cycle-19	4.7	4.7	0.0	0.0	94.4	0.0	285.5	21.2
Cycle-20	121.1	21.8	87.4	0.0	0.0	774.1	663.1	115.1
Cycle-21	68.0	0.0	492.6	239.7	56.6	144.0	764.4	0.0
Cycle-22	84.4	14.1	0.0	0.0	20.1	474.9	920.1	96.4
Influent SAS	230.0	1.0	20.0	17.0	40.0	978.0	5225.0	183.0
86/278/EEC	1000–1750	20–40	510	300–400	750–1200	2500–4000	–	–

sub-samples (layers), to allow for an estimation of the residual sludge characteristics at different depths. Table 7 and Fig. 8 present the results in comparison with the influent SAS. The TS content in both layers increased significantly compared to the influent SAS and it is also slightly higher at the lower layer. The VS content decreased much more at the lower layer compared to the upper layer and compared to the influent SAS. This indicates a better oxidation/mineralization at the lower layer of the core sample, because this layer has been oxidized for longer time.

Metal accumulation in the residual sludge was also assessed during selected cycles. Table 8 and Fig. 9 present the average heavy metal concentrations (mg/kg d.w.) in the residual sludge samples from both beds at the end of the resting period from loading cycles 5, 6, 8, 18–22. Loading with waste SAS containing heavy metals results in accumulation of these metals in the end product (the dried residual sludge). Most metal concentrations in the residual sludge were found very low. Comparison of these concentrations to the European Union Directive 86/278/EEC limits also revealed much lower values. Furthermore, the comparison between the residual sludge and the influent SAS shows a decrease of heavy metal concentrations during the drying processes. This decrease could be attributed mainly to heavy metal uptake by the plants. Although this decrease is not very significant, one should also consider the fact that, during the drying process, SAS addition to the unit continued, leading to the increase of heavy metal concentrations in the residual sludge.

4. Conclusions

Two pilot-scale SDRBs were constructed and are in operation. Experimental results show several positive effects of SDRBs in wastewater SAS treatment, including increased TS content of the residual sludge, decomposition of organic matter and low COD of the percolated fluid. The results show clearly a higher increase in TS content in Bed-1 (lower loading rate) compared to Bed-2, and a greater decrease in the VS content in Bed-2. The residual sludge shows a rather satisfactory mineralization, as the concentrations of TP and TKN were significantly decreased compared to the influent SAS values. Metal concentrations also decreased even though SAS addition continued.

Acknowledgments

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