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Performance enhancement of batch aerobic digesters via addition of digested sludge

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Abstract

The impact of the feed sludge (FS) concentration and addition of digested sludge (DS) to an aerobic digester was evaluated with respect to its capability for removal of the total suspended solids (TSS) and volatile suspended solids (VSS). The aerobic digesters, which operated in a batch mode at constant temperature and mixing rate, were initially filled with FS to 25%, 50%, 75%, and 100% of the reactor's volume. The remaining volume of the reactor was occupied by the DS, having DS/FS ratio of 3, 1, 1/3, and 0. Analysis of the experimental data showed that in the absence of DS, TSS, and VSS destruction rates are very small; however, increasing DS/FS ratio from 1/3 to 3 results in 74–77% increase in VSS and TSS destruction, respectively. The increase of the DS/FS ratio associated with increased ratio of the measured viable biomass (Cc) to VSS concentration (Xv) suggested that DS serves as the source of viable cell mass needed for degradation of organic solids. Assuming pseudo-first-order kinetics, it was shown that while organic solid destruction rate constants (k) are inversely related to initial concentrations of sludge, their values increase with increasing DS/FS ratios.

Keywords: Aerobic digestion; Total suspended solids; Volatile suspended solids; Batch reactor; Digested sludge

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1. Introduction

Aerobic digestion has been used extensively to remove excess organic matter and to some extent, metals in waste-activated sludge produced at the municipal wastewater treatment facilities [1–3]. Aerobic digestion is mostly selected for the treatment of secondary sludge such as those generated by the activated sludge and trickling filter processes and is a preferred method for treatment of dilute waste sludge. The product of digestion is an odorless humus-like biologically stable material, which can be disposed off easily. While supernatant produced contains very little biodegradable organic matter, it was shown that for low waste concentrations, the digested sludge (DS) has good de-watering characteristics [4,5]. When compared to the anaerobic counterparts, aerobic digesters have fewer operational difficulties, and require less skilled operators. The product is suitable for land disposal since most of the sludge's basic fertilizer value is retained [4–6].

In view of waste-activated sludge being predominantly biological solids, the most important reaction controlling the digestion of organic solids would be the microbial decay. During aerobic digestion, endogenous respiration prevails over biosynthetic activity of bacteria because of the almost complete exhaustion of the food supply. Under this condition, as biodegradable portion of organic solid of sludge continuously decreases, a living cell consumes its own protoplasm and cellular matter (which is produced by lysis) in order to obtain the energy required for the metabolism [7–9]. Ultimately, this process produces a waste sludge at such a low level of energy that it can be considered biologically stable and suitable for disposal in the environment.

Since the extent of the organic solid removal and effectiveness of aerobic digestion are controlled by the kinetics of the biological processes, most of the studies have attempted to identify the most proper kinetics of biodegradation for aerobic digesters. Most of theses studies have shown that aerobic digesters may be designed considering the kinetics of organics removal to be a pseudo-first-order with respect to the concentration of volatile suspended solids (VSS) [1,2,8,10,11]. The proposed kinetic models use the measured concentration of either TSS or VSS to estimate the rate of the solid destruction at given operating conditions. It has been shown that rate and extent of biological stabilization in aerobic digesters are significantly influenced by the operating conditions such as mixing rate, aeration time, reactor temperature, mean residence time of sludge, and oxygen uptake rate [3–5,8,12].

Due to the importance of aerobic digestion process in treatment of the waste sludge produced at wastewater treatment facilities, a study was conducted to investigate the impact of the reactor environment mainly, the impact of produced DS that primarily contains low energy biomass, digested to feed sludge ratio (DS/FS) used during operation, and feed sludge concentration (FS) on the efficiency and the kinetics of digestion. It was hypothesized that due to the possible presence of viable biomass, addition of the DS to the reactor fed with FS containing organic solids can boost the process of biodegradation.

This study evaluated the impact of the FS concentration on the observed kinetics of digestion since some conflicting data about the effect of solids concentration on the efficiency of the aerobic digesters were found in the literature. For example, Ganczarczyk et al. [6] found that the rate of destruction of sludge solids by aerobic digestion increased as sludge concentration increased, which was contrary to that found by D'Antonio [8] and Droste [10]. These studies showed that the decay rate of sludge was inversely related to the thickened sludge concentration.

2. Materials and methods

2.1. Experimental setup

The bioreactor (aerobic digester) was a rectangular vessel (36, 27, and 17 cm in length, width, and depth, respectively) with a total volumetric capacity of 16.5 l. Air was supplied through a sparger located at the bottom of the reactor to ensure that the dissolved oxygen concentration was uniformly maintained in excess of 2 mg/l of the reactor content. A small motor was mounted on the top of the reactor to provide sufficient mixing and to keep solids well suspended in the reactor. The reactor was fed with sludge provided by Springbrook Water Reclamation Center (SWRC), Naperville, Illinois. The wastewater treated at SWRC consists of municipal sewage and wastewater produced at local small-scale industries. The reactor temperature was kept constant at 35°C. This temperature was experimentally determined to best inhibit foam formation. At temperatures in excess of 35°C, foam formation can significantly influence the rate of oxygen transfer and the concentration of dissolved oxygen in the aeration tank [11].

The experimental procedure included 11 h of mixing and aeration, 8 h of settling, and 1 h of withdrawal of sludge. Aeration was sufficient to keep the solids in suspension. The initial concentration of sludge ranged from 6 to 20 g/l. Parameters that were monitored simultaneously throughout each experiment were pH, total suspended solids (TSS), VSS, biodegraded VSS (DVSS), and viable biomass concentration (Cc). The employed analytical procedures were in compliance with the standard analytical methods outlined in Standard Methods for the Examination of Water and Wastewater (APHA) [13,14]. The viable biomass concentration was determined following procedures outlined in the Biological Standards Methodology [15]. Replicate samples were analyzed for quality control.

2.2. Reactor operating mode

To meet the objectives of the study, concentrations of the TSS, VSS, and cell mass (viable biomass) were monitored at certain time intervals for reactors operated in a batch mode at a constant temperature and aeration rates. A batch reactor was selected since this type of reactor is most commonly used for aerobic digestion of sludge [1,2,4,5].

To evaluate the TSS and VSS removal efficiencies, reactors were filled rapidly at each run with a constant feeding rate of 35 ml/min. The FS was added to the reactors occupying 100%, 75%, 50%, and 25% of the reactor operating volumes. The rest of the reactor volumes were filled with DS. The extent of VSS removal was also evaluated for a reactor fed with only the DS. Reactors were aerated and mixed for 11 h. Samples were collected hourly from the reactor for the analysis. The pH was also monitored simultaneously for the samples collected for the organic solids and viable biomass analysis.

2.3. TSS and VSS measurement

The total and suspended solids concentrations were determined by collecting 20 ml samples from the reactor, in 1-h intervals. The pH and the temperature of the samples were measured and recorded prior to filtering and rinsing samples on pre-weighted, 0.22 μm pore size filters. The rinsed filters were dried at 105°C and weighted to identify the concentration of TSS. This step was repeated until a constant value was observed for the sampled TSS. The volatile and fixed suspended solids concentrations (VSS and FSS, respectively) were measured by heating filters at 650°C for 15–20 min. The weight of the solids remaining on the filters was related to the fixed suspended solids. The VSS concentrations were evaluated by subtracting the FSS values from the TSS values (TSS − FSS = VSS).

2.4. Analysis of the active cell mass

2.4.1. Medium preparation

The procedure used to prepare the medium for the biomass analysis included: (1) mixing dry ingredients (15 g of Bacto agar, 5 g of Bacto peptone, which is an enzymatic digest of protein, 3 g of Bacto Beef Extra) with 1 l of de-ionized water, (2) agitating the mixture for 20–30 min, (3) autoclaving the mixture for 30 min under a pressure of 15–20 psi, and (4) filling Petri dishes to 1/3 of their depth (the Petri dishes were solidified within 24 h).

2.4.2. Bacteria count

The plate count method (solid culture medium) used for bacteria enumeration consisted of preparing 10-fold dilutions (dilution was achieved using five to seven tubes), transferring 1 ml of each dilution (starting from the highest dilution) to sterile Petri dishes, adding 20 ml of liquefied culture medium to each Petri dish and letting it to solidify, inverting and incubating dishes for 48 h, and counting the colonies. The bacterial count (number per milliliter) was finalized by multiplying the average count determined from replicate samples by the appropriate dilution factor. It was assumed that each counted colony originated from a single bacterial cell.

2.4.3. Determination of the cell mass concentration

The cell mass concentration was determined as follows. After the bacterial growth was completed, one colony was selected and was grown in a 10-ml liquid medium for 48 h (10 replicates were used). Samples were taken every 4 h and filtered on a 0.22-μm pore size filter. Filters were rinsed with 5 ml of 0.85% NaCl after filtration and dried at 55°C for 24 h. The net dry cell mass was identified by weighing the filters.

The variations of the cell mass concentration versus time and the cell mass concentration as a function of the number of the corresponding colonies (correlation curves) were constructed and used to determine the active cell mass concentration from the number of colonies identified for each sample.

Table 1
SWRC activated sludge and digester operating parameters

Activated sludge process		Digester operating parameters	
HRT[a] (h)	5.2	Digester SRT (days)	23
SRT[b] (days)	2.56	Digester solids (%)	1.05
SS[c] loading (kg/day)	11 463	Digester volatile solids (%)	71
BOD loading (kg/day)	8078	Average digester operating volume (l)	17.41E6
MLSS[d] (ppm)	1955	DO level (mg/l)	2–3
DO[e] level (mg/l)	5–6		
SS removal	98–99%		

[a] Hydraulic residence time.
[b] Solid residence time.
[c] Suspended solids.
[d] Mixed liquor suspended solids.
[e] Dissolved oxygen.

2.5. Characteristics of the DS and FS

The FS and DS were obtained from Naperville's SWRC that is an advanced wastewater treatment facility. Waste-activated sludge is gravity-thickened prior to digestion in innovative covered and insulated aerobic digesters. The FS and DS contain average solid concentrations of 1.8% and 1%, respectively. The activated sludge process provides excellent CBOD5, TSS, and NH_3–N removal (96%, 98%, and 93%, respectively). Additional data describing activated sludge process, and digester operating parameters are provided in Table 1.

3. Results and discussion

3.1. Effect of addition of DS

3.1.1. Enhancement of the organic solids (VSS and TSS) destruction efficiency

The results of organic solids analysis conducted for reactors operated at different volumetric ratios of DS to FS are presented in Table 2. As is shown, in the absence of the DS, the TSS and VSS degradation rates were very small, such that during the imposed 11 h of aeration, no significant change in their concentrations was observed. However, as it is evident from the decrease in TSS and VSS concentrations with time and corresponding increase in the degradable VSS (DVSS), addition of the DS to the reactors (with various DS/FS ratios) resulted in the quantitative and qualitative enhancement of the organic solid degradation. In fact, while organic solids degradation was negligible for reactors operated in the absence of DS during 11 h of operation, an ultimate DVSS removal was achievable within hours of operation for reactors containing 50% and 75% of DS.

The magnitude of the organic solids removal at 2-h time intervals is schematically shown in Fig. 1A. As is evident, in addition to the enhancement of the overall VSS

Table 2
Effect of addition of digested sludge on the measured concentrations of the TSS, VSS and degradable VSS (DVSS)

Aeration time (h)	TSS (g/l)	VSS (g/l)	DVSS (g/l)	Percentage of TSS degraded	Percentage of VSS degraded
Run 1: digested / feed[a] = 3					
0	7.8	6.00	0.00	0.00	0.00
2	6.1	5.10	0.90	21.53	15.00
4	4.2	3.50	2.50	46.15	41.66
6	4.0	2.04	3.96	48.71	66.00
8	4.0	2.04	3.96	48.71	66.00
11	4.0	2.04	3.96	48.71	66.00
Run 2: digested / feed = 1					
0	10	8.0	0.0	0.00	0.0
2	8.0	6.1	1.9	20.00	23.7
4	7.0	5.0	3.0	30.00	37.5
6	6.6	4.6	3.4	34.00	42.5
8	6.6	4.6	3.4	34.00	42.5
11	6.6	4.6	3.4	34.00	42.5
Run 3: digested / feed = 1/3					
0	11.7	9.24	0.00	0.00	0.00
2	11.6	9.00	0.24	0.80	2.50
4	11.4	8.89	0.35	2.50	3.78
6	11.0	8.50	0.74	5.90	8.00
8	10.6	8.00	1.24	9.40	13.41
11	10.4	7.66	1.58	11.00	17.09
Run 4: digested / feed[b] = 0 / 100					
0	15.7	13.0	NA[c]	NA	NA
2	15.9	13.3	NA	NA	NA
4	16.2	13.5	NA	NA	NA
6	16.2	13.5	NA	NA	NA
8	16.2	13.5	NA	NA	NA
11	16.0	13.4	NA	NA	NA
Control reactor: digested / feed[d] = 100 / 0					
0–11	IN[d]	IN	NA	NA	NA

[a] Feed and digested sludges provided by wastewater treatment plant.

[b] Increase in total solids concentration (15.7–16%) was related to the evaporation of the reactor content during 11 h of operation.

[c] NA: Not available due to the insignificant change in the concentration.

[d] Inconclusive data was obtained from running control reactor containing only digested sludge (observed changes in the concentration of TSS and VSS were insignificant). Note that the ratio of viable cell mass concentration to VSS concentration for DS/FS of 1/3, 1 and 3 were 0.005, 0.009, and 0.015, respectively.

removal efficiency (the VSS and TSS removal efficiencies obtained within 11 h of operation have increased from 17.1% to 66.0%, and 11.0% to 48.7 %, respectively, when DS/FS increased from 1/3 to 3), the slopes of the curves suggest faster degradation rates for reactors operated at higher DS/FS ratios. Since the control reactors operated in the absence of DS [DS/(FS + DS) = 0], and FS [DS/(FS + DS) = 1]

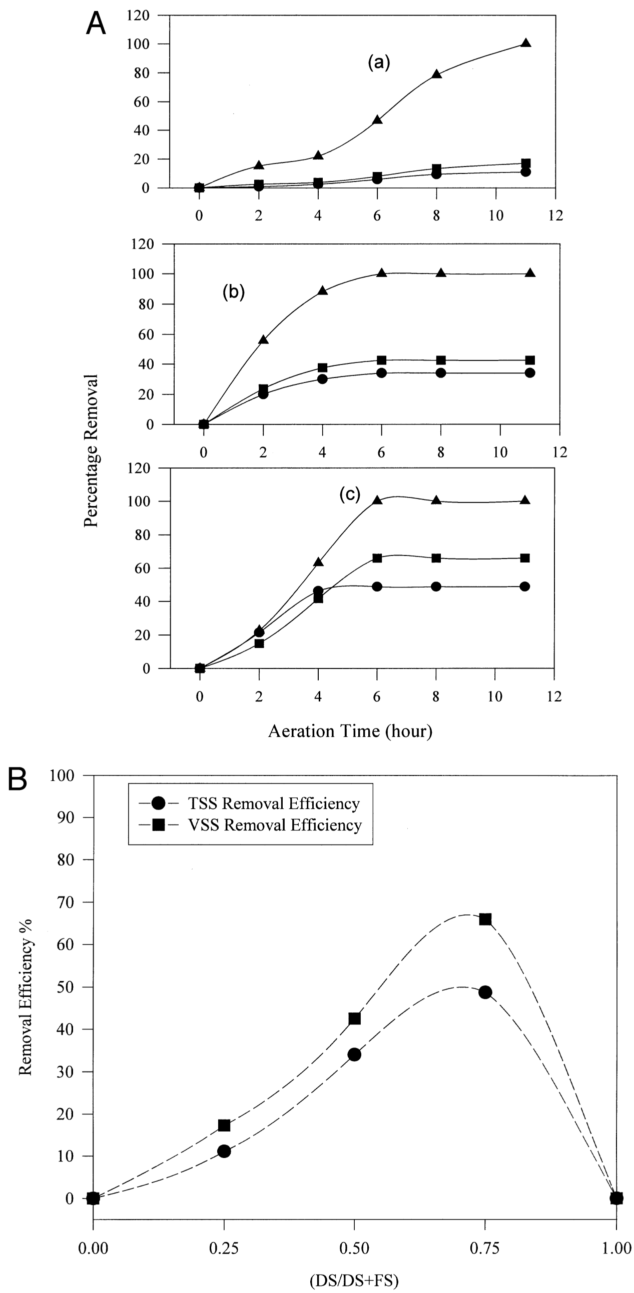

Fig. 1. (A) Variations of the measured TSS, VSS, and DVSS (as percentage) with addition of digested sludge: (a) DS/FS = 1/3, (b) DS/FS = 1, and (c) DS/FS = 3 (● TSS, ■ VSS, and ▲ DVSS). (B) Effect of addition of digested sludge on the performance of aerobic digesters.

provided inconclusive results (the VSS variations were negligible), the impact of the addition of DS was further evaluated by plotting the observed organic solids removal efficiencies versus DS/(FS + DS) ratios. As shown in Fig. 1B, the extent of the organic solids removal was significantly influenced by the added amount of DS and the imposed DS/(FS + DS) ratios. The highest organic solids removal efficiency was observed for DS/(FS + DS) ratio of about 0.69 (curves started to decline at DS/(DS + FS) ratio higher than 0.70).

These results presented the significance of addition of DS to the aerobic digesters and indicated that a desirable VSS and TSS destruction level can be achieved for aerobic digesters, if an appropriate DS-to-FS ratio is maintained. To further understand the impact of the addition of DS on the performance of the reactors, the concentration of the active cell mass (biomass) was measured from an identified number of active cells for reactors containing different volumetric ratios of the digested to feed sludge (DS/FS).

3.1.2. Enhancement of the active cell mass concentration

While the feed VSS concentration was constant, the VSS and viable cell mass concentrations in the reactors were measured periodically. As is shown graphically in Fig. 2, addition of the DS not only resulted in an increase in the measured initial concentration of the viable cell mass (Cc), and therefore estimated values of the viable cell mass to the VSS ratios (identified as Cc/Xv at $t = t_0$), it also enhanced the rate and extent of biodegradation (Fig. 1A and Table 2).

These results suggested that addition of DS promote biodegradation processes by introducing a higher number of viable cells (identified from bacteria count) to the reactor. As Fig. 2 shows, while DS has served as an inoculum for the reactors, the cell growth rate decreased drastically with increasing aeration time. These results supported the finding of Eikum et al. [5], which showed that the rate of organic solid destruction

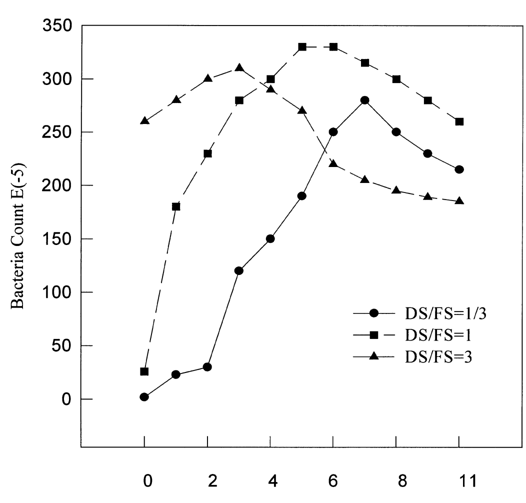

Fig. 2. Effect of the DS/FS ratio on the measured number of bacteria (viable cell concentration).

decreases with increase in the reactor detention time. This decrease was related to the idiosyncratic (specific characteristics) of the early stages of digestion, where microorganisms will rapidly use the easily available food in solution for their growth. As the process proceeds, the organisms must rely on their ability to liquefy organic material. For this, they must depend on extracellular enzymes. However, since this type of reaction is slow, the rate of VSS degradation will be slowed, overall [5].

The impact of the viable cell mass concentration on the performance of aerobic digesters has also been studied by Weddle and Jenkins [16] and Droste [7]. Weddle and Jenkins investigated the variations in sludge metabolic activity and viable microorganism percentage as a function of growth rate and showed that metabolic activity was directly proportional to the number of viable microorganisms present in the system. Droste, however, investigated the microbial activity in aerobic sludge digestion and observed that the rate of substrate removal and the decrease of endogenous mass were ultimately dependent on the active cell mass concentration within the reactor.

3.2. Impact of DS / FS and sludge concentration on degradation kinetics

Assuming a constant rate of reaction, a uniform composition of the mixture, and the microbial decay to be a pseudo-first-order reaction, the solid organic degradation rate constants were determined from the first-order reaction kinetics, i.e., $d(X)/dt = -kX$ and $\ln(X/X_0) = -kt$, while $X = X_0$ at $t = 0$. In these equations, X represents the concentration of the degradable portion of organic solids (VSS and TSS) at time t in mg/l, k is the rate constant of degradation $(1/t)$, and dX is the change observed in the biodegradable material during time interval dt. The rate constants were evaluated using TSS and VSS data collected from: (a) reactors containing different volumetric ratios of the DS/FS, and (b) reactors fed with sludge at different concentrations while the DS/FS ratios were kept constant.

3.2.1. Effect of the DS / FS ratios

Experimental data shown in Table 2 were used in a pseudo-first-order kinetic equation to calculate organic solid degradation rate constants for reactors containing different DS/FS ratios. The estimated degradation rate constants presented in Table 3 indicated that the organic solid degradation rate constants (k_{VSS}, and k_{TSS}) are signifi-

Table 3
Impact of the addition of DS on organic solids degradation rate constants (FS and DS were provided by SWRC)

(DS/FS)	Initial concentration (g/l)[a]	Rate constant k (1/day)
VSS		
3	6.00	2.9
1	8.00	1.6
1/3	9.20	0.38
TSS		
3	7.80	1.93
1	10.0	1.21
1/3	11.7	0.25

[a] Initial concentration ($t = t_o$).

Table 4
Impact of FS concentration on the organic solids degradation rate constants (k) (DS/FS = 1, Cc/Xv = 0.009)

Test number	Initial concentration (g/l)	Rate constant k (1/day)
TSS		
1	10.0	1.38
2	12.4	1.09
3	16.7	0.83
4	19.0	0.76
VSS		
1	8.0	1.40
2	10.0	1.11
3	13.6	0.83
4	15.6	0.67

cantly influenced by the addition of the DS to the reactors. The estimated k_{VSS} and k_{TSS} increased from 0.38 to 2.9 and from 0.25 to 1.9 day^{-1}, respectively, when DS/FS ratio increased by a factor of 10 (1/3–3). The VSS removal efficiency was slightly higher

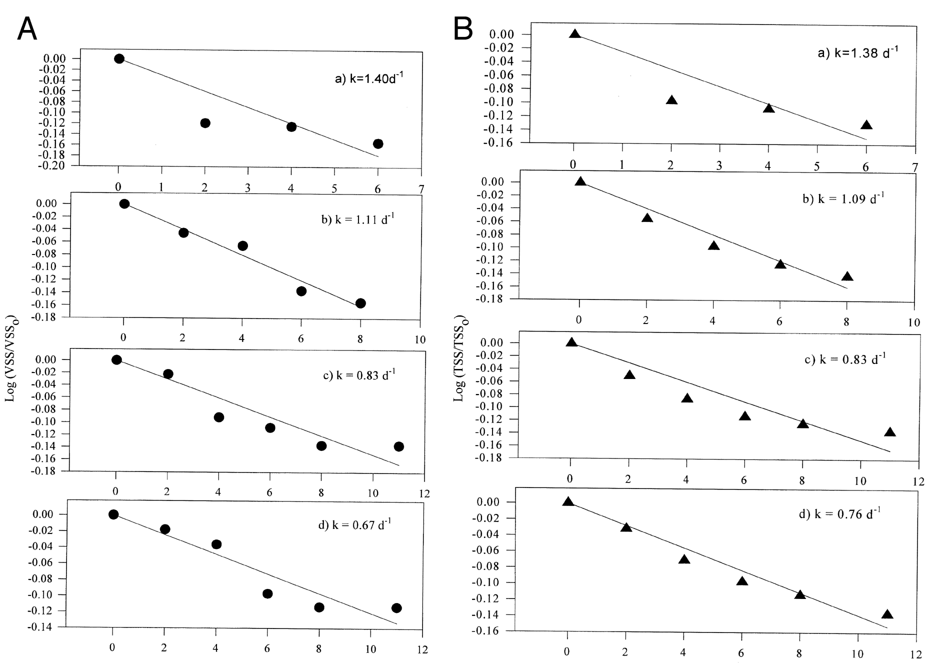

Fig. 3. (A) Effect of sludge concentration on the estimated rate of VSS biodegradation: (a) VSS = 8.0 g/l, (b) VSS = 10.0 g/l, (c) VSS = 13.6 g/l, and (d) VSS = 15.6 g/l. (B) Effect of sludge concentration on the estimated rate of TSS biodegradation: (a) TSS = 10.0 g/l, (b) TSS = 12.4 g/l, (c) TSS = 16.7 g/l, and (d) TSS = 19.0 g/l.

than that obtained for the TSS, since the latter is partially comprised of the fixed suspended solids (FSS) that resist biodegradation at the imposed operating conditions. These data supported the conclusion presented in the previous section and confirmed that addition of DS enhances biodegradation processes by increasing the concentration of the viable cell mass in the reactor.

3.2.2. Effect of sludge concentration

To evaluate the impact of the FS concentration on the degradation rate constants, additional experiments were conducted by varying initial solid concentrations in the fed sludge for DS/FS = 1. Results of the organic solid analysis presented in Table 4, and Fig. 3A and B, showed that: (a) the Cc/Xv ratios were almost constant (0.009) for all of the reactors, (b) reactors containing more concentrated sludge required a longer period of aeration to reach a desired VSS removal rate, (c) the organic solids destruction rate constants were in a good agreement with those obtained in the previous sections and those reported in other studies, and (d) the VSS and TSS decay rates are inversely related to the initial concentration of the FS. Indeed, 47–48% increase in the TSS, and VSS concentrations resulted in 45–50% decrease in the observed organic destruction rates, respectively. These results suggested that at higher organic solid concentrations, mass transfer limitations inhibit the rate of microbial degradation.

The pH of the reactors, which was simultaneously measured while sampling for the VSS and TSS analysis showed a slight increase with time during organic solids biodegradation processes, varying between 6.2 and 7.0. As suggested in previous studies [4,6], the slight increase in pH was attributed to the possible release of ammonia nitrogen during the aeration and degradation of the cell mass, because nitrification was inhibited at the reaction temperature of 35°C.

4. Conclusion

The maximum achievable degradation rate of the total and volatile suspended solids in an aerobic digester operated in a batch mode was observed to depend on the aeration time, sludge concentration, and the quantity of the added digested sludge (DS/FS ratio). Particularly, the observed aeration time required to achieve maximum VSS and TSS removal was affected by the DS/FS ratios. The estimated VSS and TSS destruction rates obtained for reactors operated at a constant DS/FS ratio were inversely affected by the FS concentration. The added DS was accounted for the observed increase in the viable cell mass concentration and organic solids degradation rates. Accordingly, the removal efficiency of the aerobic digester increased from 17% to 66% when the DS/FS ratios increased from 1/3 to 3 after 11 h of aeration. Assuming a pseudo-first-order degradation kinetics, it was shown that the organic solids destruction rate was inversely related to the initial TSS and VSS concentrations and the FS/DS ratios.

This study showed that since kinetics of batch aerobic digesters depends on the number of viable cells in the reactor and sludge concentration, the performance of the digesters with respect to their capability for removal of the VSS and TSS in the FS, can be enhanced significantly if an appropriate amount of DS is added to the reactor. The proposed procedure enhances aerobic digestion effectiveness and reduces the cost of operation since most aerobic digesters are designed on the basis of kinetic parameter, k, which suggests the aeration time and the size of reactor needed for achieving maximum organic solids removal. The significance of the addition of DS and the effect of FS on oxygen mass transfer needs to be further studied by continuos monitoring of dissolved oxygen in the reactor content.

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