Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2021.26475

215 (2021) 319–327
March

Potential of auto-thermal mesophilic aerobic stabilization for sludge reduction and organic carbon removal

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Received 12 April 2020; Accepted 19 August 2010

ABSTRACT

The study involved an experimental study to evaluate and optimize the potential of auto-thermal aerobic stabilization; for this purpose, the impact of major operating conditions was investigated for sustaining a mesophilic environment that would provide the highest possible rate of volatile suspended solids (VSS) reduction. Experiments were conducted in four different sets in order to separately evaluate the effect of significant parameters, such as the aeration rate, the mixing rate, the initial sludge load, and the ratio of primary sludge to biological sludge (PS/BS) on process efficiency. The aeration rate was gradually reduced together with parallel increases in the mixing rate. In the final experimental set conducted with a PS/BS ratio of 50/50, a low aeration rate of 0.2 L/min, and a high mixing rate, reactor temperature was raised to an average level of 36.7°C, with 47.0°C the highest value; the mesophilic conditions sustained by the liberated energy of biochemical reactions induced a VSS reduction rate of 53%, the highest level ever achieved in aerobic stabilization studies reported in the literature. The corresponding chemical oxygen demand (COD) removal was observed as 62%, confirming the observed trend always inducing 10% higher COD removal than the achieved VSS reduction exhibited in all the experiments of the study.

Keywords: Auto-thermal aerobic stabilization; Mesophilic conditions; Sludge reduction; Organic carbon removal

1. Introduction

The activated sludge process is perhaps the most remarkable milestone in the history of environmental engineering. After its discovery at the beginning of the 20th century, it was immediately adopted, tested in major research centers, and found a positive response in practice; 17 activated sludge plants were either completed or under construction by 1922 [1]. While it promptly proved itself as an effective biological treatment system for wastewaters, it gave birth to an equally important problem: excess sludge generation. Later on, when the commonly implemented treatment scheme also included a primary sedimentation unit, the sources of sludge production diversified as primary sludge (PS) and biological sludge (BS). Both sources involve different but an equally complex array of particulate organics, so that sludge management represents today one of the most critical and costly steps in waste management [2]. Traditionally, landfilling, land application and incineration are applied for the disposal of sewage sludge. Because of the drawbacks of these methods, international and local authorities define protective measures and acceptable characteristics requiring extensive stabilization and conditioning for safe disposal of sewage sludge as waste [3,4]. Especially, EU regulations became almost prohibitive for some sludge disposal options such as landfilling: The results of a recent study suggested that restrictions imposed on sludge stabilization and conditioning were not

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Presented at the 2nd International Conference on the Environment Survival and Sustainability (ESS 2019), 7–11 October 2019, Nicosia, North Cyprus

attainable, and for this reason not justifiable on the basis of currently available technologies [5]. Although a lot of technology have been studied, biological treatment methods are still considered as most economical methods for sludge reduction in wastewater treatment. In large treatment plants, anaerobic digestion is the traditional component for sludge stabilization. The aerobic stabilization process becomes a feasible option and a counterpart for smaller size treatment systems [6]. The aerobic stabilization is a common approach, applied for decreasing the concentration of organic compounds in the management of sludge generated in treatment plants. The energy aspect of this method due to intensive aeration should always be given serious consideration to limit its application to small wastewater treatment plants. However, it is always a profitable option compared to internal stabilization in the biological reactors operated at excessively high sludge ages, where the entire mixed liquor remains aeration with no appreciable benefit [7].

Aerobic stabilization is applied either as an external process or inside the activated sludge reactor operated as an extended aeration configuration, which supposedly mineralize the sludge. The study carried by Ozdemir et al. [8] on the biomass of an extended aeration plant treating domestic sewage at a sludge age of 20 d proved that mineralization was only partial: the sludge was further subjected to external stabilization, which achieved additional volatile suspended solids (VSS) reduction of 68% after 60 d. This level of VSS reduction was explained on the basis of a relatively higher rate of hydrolysis of particulate metabolic products of 0.012 d^{-1} observed at a sludge age of 10 d selected for system operation. External aerobic stabilization of municipal sludge was reported to achieve maximum 51% VSS reduction [9], a level slightly higher than the 40%–45% range commonly associated with anaerobic digestion [10,11]. Ubay Cokgor et al. [12] obtained a slightly lower VSS reduction of 34% for the mixture of chemical and biological sludge from tannery wastewater treatment; they argued that the characteristics and the organic content of sludge significantly affected the efficiency of aerobic stabilization. Ozdemir et al. [13] studied the impact of the sludge age sustained in the treatment system on aerobic sludge stabilization; they suggested that achieved VSS reduction depended on the major particulate chemical oxygen demand (COD) fractions in sludge, which should be evaluated as an interface with corresponding wastewater characterization based on COD fractionation. Their results indicated that the level of particulate metabolic products accumulated in sludge acted as the major limiting factor for the achievable efficiency of stabilization. Ozdemir et al. [14] observed the same effect on the sludge generated in an activated sludge unit fed with acetate as the sole carbon source.

Aerobic stabilization basically duplicates the biochemical reactions taking place in the activated sludge process, where the reaction rates may be increased at elevated temperatures [15]. Aerobic sludge stabilization at elevated temperatures, although beneficial, is costly to the extent that it may become prohibitive if it relies on external energy sources. Therefore, related research efforts also considered the possibility of securing auto-thermal conditions, that is, utilizing the energy dissipated by biochemical reactions during aerobic stabilization. Energetics of microbial processes taking place in activated sludge systems is well-studied [16,17]. Energy released by catabolic reactions is biologically utilizable only if it is captured and stored in ATP (Adenosine tri-phosphate). Only a fraction of the generated energy can be utilized in this way as defined by the yield coefficient corresponding to heterotrophic activity; the remaining part is released to the environment as heat energy. The numerical evaluation of this process is provided in detail in the literature.

The extent of auto-thermal conditions primarily depends on the concentration of feed sludge as the heat release is originated from the degradation of volatile solid during the exothermic reaction [18,19]. Capture and utilization of released energy, while quite promising, require a high amount of volatile solid degradation and consequently a high reactor volume for maintaining high temperature. Liu et al. [20] could obtain an auto-thermal reactor temperature of 61.5°C in a pilot plant of 10 m^3 volume, which could only trigger a 41% VSS reduction after 15 d. As auto-thermal conditions are difficult to be maintained in small volumes, only a few lab-scale studies have so far been conducted on the subject especially on the effect of different parameters selected during operating conditions by applying external heat to the stabilization reactor: Liu et al. [19] tested the aerobic stabilization of the biological sludge at a temperature range of 35°C–65°C. After 23 d, 45% was the highest VSS reduction rate obtained at 55°C with a 34.6 g/L VSS loading. Cheng et al. [21] carried out a similar experiment with primary sludge, biological sludge, and the mixed sludge for investigating optimum operating conditions for thermophilic aerobic stabilization at 55°C; the best result was obtained for the mixed sludge with 43% VSS reduction after 15 d. Similarly, aerobic stabilization of primary sludge at 55°C produced slightly dissimilar results of 40%–45% VSS reduction, under different conditions [19,21]. Shao et al. [22] used a lower temperature of 35°C in their experiment on biological sludge and reported 39%, 50%, and 67% VSS reduction after 20, 30, and 89 d of aerobic stabilization, respectively. The optimum operating conditions determined at laboratory scale thermophilic aerobic digestion experiments by applying external heat are summarized in Table 1.

The reported results were too diverse for deriving a general basis of understanding for the impact of auto-thermal conditions. These studies, although useful, mostly represent case studies carried out under different conditions and they are not conducive to an overall evaluation basis other than simply indicating the favorable impact of heat energy on the rate of VSS removal. Further researches on the physico–chemical and biological parameters of auto-thermal aerobic stabilization are required to optimize performance and stability [24]. In this context, the objective of the study was to evaluate and optimize the potential of auto-thermal aerobic stabilization and to investigate operating conditions, such as mixing and aeration, most suitable for sustaining a mesophilic environment that would provide the highest possible rate of VSS reduction.

2. Materials and methods

2.1. Experimental plan

Aerobic stabilization experiments were conducted in four different sets in order to separately evaluate the

Table 1
Reported optimum operating conditions for thermophilic aerobic digestion

Sludge type	Total solid (%)	Air flowrate (L/min)	Temperature (°C)	Time (day)	VSS removal (%)	References
PS:BS	5.5	0.1	55	23	45	[19]
PS:BS	6	1.0	55	20	40	[23]
PS:BS	5.4	0.2	55	15	43	[21]
BS	5.2	0.2	55	15	40	[21]
BS	2.3	2.5	35	30	50	[22]

effect of significant parameters, such as the aeration rate, the mixing rate, the initial sludge load, and the ratio of primary sludge (PS) to biological sludge (BS) on process efficiency. Operation conditions of successive experiment are summarized in Table 2. The first set of experiments were carried out without external mixing; a high aeration rate of 1.0 L/m and a relatively high total solids (TS) concentration of 5.8%–6.3% in a sequence of three runs, where the PS/BS ratio was adjusted to 50%/50%, 25%/75%, and 30%/70%, respectively. In the second set, external mixing at 360 rpm was introduced and the TS concentration was slightly reduced to 5.1%–5.5%. In the third set, the PS/BS ratio was fixed at 50%/50%; two different combinations of aeration rate and mixing were tested at 0.4 L/m–400 rpm and 0.2 L/m–650 rpm, respectively, where the TS concentration was gradually reduced from 4.9% down to 3.48%. The fourth set basically investigated the impact of a higher mixing rate of 750–850 rpm together with a low aeration rate of 0.2 L/m on three previously selected PS/BS ratios.

2.2. Source of sludge samples

Samples of primary and biological sludge were obtained from the primary sedimentation and the secondary sedimentation units of Hurma municipal wastewater treatment plant in Antalya, Turkey, treating approximately 210,000 m^3/d of wastewater. The plant was designed and operated to remove nitrogen and phosphorus, together with COD, as a five-step Bardenpho process, after preliminary treatment for the elimination of course solids by screens, grit chamber, and removal of settleable total suspended solids by primary sedimentation.

2.3. Experimental setup

The BS were sieved to remove residues greater than 0.5 mm. For obtaining a solids content of at least 4%, PS and BS were centrifuged at 3,000 g for 15 min. The sludge samples were stored at 4°C until they were fed to stabilization reactors. Auto-thermal mesophilic aerobic stabilization experiments were performed in two parallel stabilization reactors having each a total working volume of 5 L. The outer layers of stabilization reactors were covered by glass wool as insulation material. Aeration was provided by pressured air supply. For applying different air flow rates, flowmeters were installed on the air inlet of reactors. A mechanical mixer was mounted on top of both reactors to provide the desired mechanical mixing rates. During the stabilization period, evaporation losses were compensated with water prior to sampling. The temperature and pH were continuously monitored.

2.4. Analytical measurements

The total COD, soluble chemical oxygen demand (sCOD), total suspended solids (TSS), and VSS were measured daily throughout the digestion periods. The concentrations of ammonium nitrogen (NH_4–N) orthophosphate (PO_4–P) were measured at the start up and the end of stabilization period in order to evaluate the release of NH_4–N and PO_4–P into supernatant. The COD samples were measured as described in the ISO6060 method [25]. TS, VSS, NH_4–N, and PO_4–P analyses were conducted by using the related procedures defined in Standard Methods [26].

3. Results and discussion

3.1. Sludge characteristics

The study essentially used a mixture of primary sludge (PS) and biological sludge (BS) generated in the treatment plant. Obviously, the characteristics of the two sludge fractions are quite different: the primary sludge basically includes the settleable portion of the influent COD and TSS content of the domestic sewage treated in the plant. From the VSS/COD balance perspective, it contains the slowly biodegradable COD, X_S, and the inert COD, X_I, fractions that can be separated through settling before biological treatment. On the other hand, the biological sludge is excess sludge generated in the course of biochemical reactions composed of active biomass with entrapped particulate organic residues. The major characteristics of two different set of sludge samples used for auto-thermal stabilization are summarized in Table 3.

The sludge samples were mixed in the proportions indicated in Table 2 for each run, after thickening to the desired TS concentrations. The VSS/TSS ratios of the two sludge samples were comparable around 0.80. However, the COD equivalent of VSS was quite higher for the primary sludge, with COD/VSS ratios of 1.92 and 1.95 g COD/g VSS for the samples used for the first set and the other sets of experiments, respectively. These values should be compared with 1.75 and 1.62 g COD/g VSS associated with biological sludge. The difference between the two ranges of ratios is clearly due to the more complex and reduced state of settled organic matter in the primary sludge compared to biomass. Studies suggested a wide bracket for this ratio between 1.33 and 1.93 g COD/g VSS depending on the oxidation state of the organic matter [27–29].

Table 2
Operation conditions selected for aerobic stabilization experiments

Run	No	PS/BS (%/%)	TS (%)	Air flow rate (L/min)	Mixing rate (rpm)
1	S1R1	50/50	6.3	1	–
	S1R2	25/75	5.7	1	–
	S1R3	30/70	5.8	1	–
2	S2R1	50/50	5.1	1	360
	S2R2	25/75	5.1	1	360
	S2R3	75/25	5.5	1	360
3	S3R1	50/50	4.9	0.4	400
	S3R2	50/50	4.17	0.4	400
	S3R3	50/50	4.06	0.2	650
	S3R4	50/50	3.48	0.2	650
4	S4R1	25/75	4.34	0.2	750
	S4R2	75/25	4.85	0.2	750
	S4R3	50/50	4.51	0.2	850

Table 3
Major characteristics of sludge samples

Sludge	TSS (g/kg)	VSS (g/kg)	VSS/TSS	COD/VSS (g/g)	COD (g/L)	Soluble COD (g/L)	NH_4–N (mg/kg)	PO_4–P (mg/kg)
Experimental set 1								
PS	69.6	54.6	0.78	1.92	104.8	6.56	120.93	4.17
BS	57.7	41.3	0.80	1.75	72.3	2.05	52.81	2.57
Experimental sets 2–4								
PS	57.8	45.5	0.79	1.95	88.7	7.50	101.1	3.49
BS	55.4	42.0	0.76	1.62	68.1	0.59	50.7	2.47

3.2. Sludge stabilization results

3.2.1. Effect of high aeration rate

A high aeration rate of 1.0 L/min was applied without additional mixing to all three runs in the first set of experiments. These experiments were also characterized by a relatively high initial VSS levels of 45.6 to 50.6 g/kg. Major features of the initial conditions are summarized in Table 4. The experiments were conducted without full insulation of the reactors, so that auto-thermal conditions were not achieved and the highest reaction temperature stayed around 20°C–21°C. After 21 d of stabilization, the observed VSS removal rate was quite high and remained in the 40%–43% range, possibly due to elevated biomass levels sustained in the system. COD removal was always higher than the VSS removal by 10%–15% in all the experimental runs, as shown in Table 5. The average pH during the experiments was around 7.3–7.5 without any significant variation.

3.2.2. Combinations of aeration and mixing

In these experiments, sludge stabilization was carried out with different combinations of aeration supplemented with mechanical mixing. The second set (set 2) of experiments involved the initial high rate of aeration at 1.0 L/min together with moderate mechanical mixing at 360 rpm. As shown in Table 4, the initial VSS input was still maintained in the high range of 5.1–5.5 g/kg, including three different ratios of primary and biological sludge. The observed VSS reduction rate was slightly reduced to 36%–41%, the maximum level corresponding to the 50/50 mixture of the two sludge samples. Auto-thermal conditions were quite limited since the reactor temperature was only raised to around 25°C, possibly due to the dissipation of the generated heat by intense aeration. Major characteristics of system performance were summarized in Table 6.

The next set of experiments (set 3) incorporated four different runs carried out with gradually decreasing aeration rates and increasing mixing; in the first two runs (S3R1 and R2), they were set as 0.4 L/min and 400 rpm and they were further changed into a new combination of 0.2 L/min and 650 rpm in the other two runs (S3R3 and R4). The reduction in the aeration rate were made in a way to ensure a dissolved oxygen concentration of more than 1.0 mg/L in the stabilization reactor. These experiments were all conducted with the same PS/BS ratio of 50/50, where the initial VSS concentration was gradually reduced from 36.1 g/kg down to 26.2 g/kg. Other characteristics of starting conditions are summarized in Table 4. This set is quite important in the sense that the establishment of auto-thermal conditions were progressively observed. In the first run (S3R1) the highest reactor temperature was 28.7°C with an average value of 26.0°C throughout the reaction period, which was further raised to 34.7°C and 32.4°C, respectively, in the last run of the series (S3R4). Parallel to the increase in the temperature, a high pH variation was observed in the last two reactors (S3R3 and S3R4). The increase of pH under thermal conditions was associated with the increase in ammonia released by biodegradation of protein-based material [30].

The corresponding VSS reduction exhibited a parallel increase from 32% to 41% as shown in Table 6. It should be noted that the kinetic energy imparted into the stabilization reactor through mechanical mixing also plays an important role in maintaining auto-thermal conditions initiated by wasted biochemical energy. The practice has indicated that up to 30% of the heat energy necessary for the system can be provided by the kinetic energy of mixing [18,31]. Therefore, sustainable auto-thermal conditions critically depend on the balance between energy supply from biochemical and mechanical sources and the energy fraction that is dissipated and lost from the system.

3.2.3. Effect of high mixing and low aeration

The final and concluding experimental set (set 4) was started with moderate initial VSS concentration in the range of 33.5–38.6 g/kg, with different combinations of the PS/BS ratio in three runs. In all the runs, the low aeration rate of 0.2 L/min was maintained but the mixing was raised to 750 rpm in the first two runs and finally to 850 rpm in the final run S4R3 where the PS/BS ratio was set as 50/50. Also, the pH was kept between 6.0 and 7.0 in this experimental set in order to prevent any effect of pH on the stabilization performance. The starting conditions are outlined in Table 4. The operation of stabilization reactor could not be sustained in the second Run (S4R2) beyond 6 d, because extensive foaming of the sludge. The reasons of foaming at thermal conditions were suggested as intense mixing, aeration or gasification, organic overloading, the filamentous bacteria, and other hydrophobic substances such as surfactants [32]. According to this information, the foaming observed in S4R2 may be caused by the combination of organic overloading which arose from implementation of primary sludge in high ratio, and intense mixing.

The performance values in Table 6 presented a clear indication that sludge stabilization could be carried out in mesophilic conditions sustained by the liberated energy of biological reactions, which raised the reactor temperature to an average level of 36.7°C, with 47.0°C the highest value, with low aeration and intense mixing. These operating conditions induced a VSS reduction rate of 53%, the highest level ever achieved in aerobic stabilization studies reported in the literature. The corresponding COD removal was observed as 62%, confirming the observed trend always inducing more than 10% higher COD removal than the achieved VSS reduction exhibited in all the experiments of the study.

3.3. Evaluation of results

The main advantage of auto-thermal stabilization compared to conventional aerobic stabilization is the achievement of higher organic matter removal efficiency in a shorter stabilization time. Obviously, it is accomplished with intensive aeration creating energy demand and it is also subject to emissions associated with sludge stabilization. However, this performance is obtained is a much

Table 4
Initial conditions in the experiments

No	PS/BS	TSS (%)	VSS (g/kg)	COD/VSS (g/g)	COD (g/L)	Soluble COD (g/L)	NH_4–N (mg/kg)	PO_4–P (mg/kg)
				Experimental set 1				
S1R1	50/50	6.3	50.6	1.84	93.10	2.91	74.40	3.38
S1R2	25/75	5.7	45.6	1.78	81.20	2.40	77.84	2.40
S1R3	30/70	5.8	46.2	1.80	83.20	2.41	89.00	1.97
				Experimental set 2				
S2R1	50/50	5.3	42.9	1.78	76.4	3.17	75.8	3.0
S2R2	25/75	5.1	41.3	1.70	70.2	1.46	63.3	2.7
S2R3	75/25	5.5	44.6	1.86	82.9	5.71	88.4	3.2
				Experimental set 3				
S3R1	50/50	4.9	36.1	1.80	65.0	2.95	197.29	1.87
S3R2	50/50	4.17	34.1	1.78	60.7	2.27	167.41	2.17
S3R3	50/50	4.06	33.3	1.78	59.3	2.97	188.90	2.27
S3R4	50/50	3.48	26.2	1.77	46.4	2.37	159.02	2.33
				Experimental set 4				
S4R1	25/75	4.34	33.5	1.87	62.6	1.67	55.09	1.81
S4R1	75/25	4.85	38.6	1.75	67.6	5.95	276.50	4.95
S4R3	50/50	4.51	37.1	1.77	65.7	4.16	166.21	3.58

Table 5
Stabilization performance observed in set 1, under high aeration

No	Initial VSS (g/kg)	Removal (%)			NH_4–N (mg/kg)	PO_4–P (mg/kg)	Temperature (°C)		Average pH
		VSS	COD	Soluble COD			Highest	Average	
S1R1	50.6	42	62	75	20.96	1.35	20.9	18.9	7.46
S1R2	45.6	43	48	79	1.48	1.69	21.2	19.9	7.33
S1R3	46.2	40	50	75	0.80	1.39	20.7	19.4	7.51

Table 6
Stabilization performance observed in experimental sets 2–4

No	Initial VSS (g/kg)	Removal (%)			Effluent COD/VS	NH_4–N (mg/kg)	PO_4–P (mg/kg)	Temperature (°C)		Average pH
		VSS	COD	Soluble COD				Highest	Average	
Experimental set 2										
S2R1	42.9	41	51	80	1.48	14.30	0.57	25.0	22.7	7.91
S2R2	41.3	36	39	78	1.63	49.40	2.11	23.6	22.8	7.20
S2R3	44.6	38	44	76	1.67	0.00	0.00	25.8	22.6	8.36
Experimental set 3										
S3R1	36.1	32	40	86	1.59	81.44	0.77	28.7	26.0	7.58
S3R2	34.1	36	41	82	1.64	69.11	0.89	32.9	28.6	7.48
S3R3	33.3	40	52	83	1.43	67.03	0.81	36.8	33.4	5.83
S3R4	26.2	41	56	84	1.32	58.01	0.85	34.7	32.4	6.76
Experimental set 4										
S4R1	33.5	40	52	86	1.49	41.25	1.36	34.8	32.9	6.34
S4R3	37.1	53	62	78	1.43	91.02	1.96	47.0	36.7	6.98

smaller footprint. Whereas in conventional aerobic stabilization, which requires more than three-fold system operation to reach the same organic matter removal efficiency, more energy consumption may be needed due to prolonged aeration with limited efficiency. While the energy budget is always a priority issue, it should be a factor of evaluation for each specific application.

The results in the study could be better understood and interpreted by clarifying the nature and the composition of sludge as a function of the wastewater and the treatment process, where it was generated. This may be properly done by establishing an interface with the characteristics of wastewater based on COD fractionation. In this context, the VSS in the primary sludge (PS) is essentially a mixture of the settleable fractions of the slowly particulate slowly biodegradable COD, X_{SS} [33] with the initial inert particulate COD, X_I; on the other hand, the biological sludge (BS) consists of excess biomass with embodies, aside from active microbial community, X_H, inert particular organics of influent origin, X_I, the remaining fraction of particulate slowly biodegradable substrate, X_S entrapped into biomass and residual particulate microbial products, X_P generated during endogenous processes. All these fractions serve as components of process modeling of activated sludge systems [34,35]. Therefore, during the initial phase, stabilization is governed by a substrate removal mechanism, where PS supplies the substrate (X_{SS}) and BS provides the active biomass (X_H). When external substrate is fully consumed, stabilization reverts back to diverse endogenous activities such as maintenance energy requirements, cell decay, death-regeneration, generation of X_P, etc. [9]. Researchers usually prefer to group all these activities, into a single process, that is, endogenous decay (k_D), which may be expressed simply in terms of VSS concentration (X_T) by the traditional rate equation (Eq. (1)) [36,37]:

$$\frac{dX_T}{dt} = k_D \times X_T \tag{1}$$

The endogenous decay coefficient k_D reflects the sequential impact and control of stabilization through both viable biomass, X_H and X_P. Thus, as all the biochemical reactions proceed, X_I and X_P should be regarded as significant parameters limiting stabilization efficiency.

Experiments with mixed sludge (PS; BS) as in this study, may provide, a good demonstration of the balance between substrate removal and endogenous processes. The hydrolysis of particulate COD is usually represented by the following surface-type reaction kinetics equation (Eq. (2)) [38]:

$$\frac{dX_{SS}}{dt} = k_{hXS} \frac{X_{SS} / X_H}{K_{XX} + X_{SS}} X_H \tag{2}$$

where k_{hXS} is the maximum hydrolysis rate of the settleable COD and K_{XX}, the half-saturation coefficient for hydrolysis.

The VSS profiles obtained during the stabilization period for two different experiments in set 1 are plotted in Fig. 1. In the run S1R1 conducted with a PS/BS ratio of 50/50, the VSS profile in Fig. 1a gives approximately a straight line, with a slightly higher slope at the beginning; the profile evaluated in terms of Eq. 1, yields a k_D value of 0.03 d^{-1} for the first 3 d and 0.025 d^{-1} for the entire profile. However, for run S1R3 conducted with a higher initial fraction of BS (30/70), the VSS profile indicates two different stabilization rates, which slow down after 6 d (Fig. 1b); the first period may be approximated by a k_D value of 0.032 d^{-1}, whereas the k_D value for the second period after 6 d, drops down to 0.02 d^{-1}. These results are in agreement with the literature: Ozdemir et al. [8] observed that the stabilization rate, k_D, remains in the range of 0.01–0.02 d^{-1} after an initial higher value; it is also stated that modeling with k_D of 0.06 d^{-1} indicated a VSS reduction much higher that the observed VSS profile during the stabilization period [14].

The positive impact of auto-thermal conditions secured in the final set of experiments may be clearly visualized in the VSS profile achieved in Run S4R3, which distinctly shows two different rates of stabilization changing after day 6 during the stabilization period as plotted in Fig. 2. The k_D value associated with the first period was calculated as 0.09 d^{-1}, the highest value so far reported for aerobic stabilization, which evidently indicates the impact of mesophilic conditions for establishing a much higher hydrolysis rate k_{hXS} for substrate utilization. In the remaining period, k_D drastically drops down to 0.013 d^{-1}, supposedly representing the balance between endogenous decay and generation of residual metabolic products X_P. In fact, Ozdemir et al. [13] also observed a slow hydrolysis of X_P in the long run and stated that it occurred with a k_{hP} value of 0.012 d^{-1} only in sludge samples generated at high sludge age levels. No similar hydrolysis was observed at low sludge ages.

An equally significant aspect set forth by the results in the study was the COD transformations taking place during aerobic stabilization: In all experiments, (i) a major portion (mostly more than 80%) of the soluble COD was readily utilized as expected, presumably leaving behind only soluble residual COD, either of influent origin or generated as soluble microbial products, (ii) the rate of COD removal was always higher than the corresponding VSS removal, by at least a 10% margin. This observation would have significant practical implications for the final disposal of stabilized sludge, which is subject to strict limitations in terms of the remaining organic carbon [5], (iii) a higher COD removal rate obviously changed the COD/VSS ratio throughout stabilization. In fact, this ratio, which was always high (1.74–1.86 g COD/g VSS) at the start of the experiments was significantly reduced (1.32–1.64 g COD/g VSS) in the stabilized sludge. From the standpoint of the biochemical reaction mechanism, this observation clearly indicates that the complex structure of the sludge, and especially the primary sludge, gets oxidized to simpler compounds along with the hydrolysis process, leading to lower COD/VSS ratios. Fig. 3 illustrates this mechanism using the COD and VSS profiles obtained in the experimental Run S4R3: It shows that the experiment was started with a COD/VSS ratio of 1.77 g COD/g VSS; this ratio gradually dropped to 1.65, 1.60, and 1.55 g COD/g VSS within the first 6 d, which corresponded to the hydrolysis and utilization of the primary sludge fraction. After this period, the COD profile continued almost parallel to the VSS profile, ending with a final COD/VSS ratio of 1.42 g COD/g VSS.

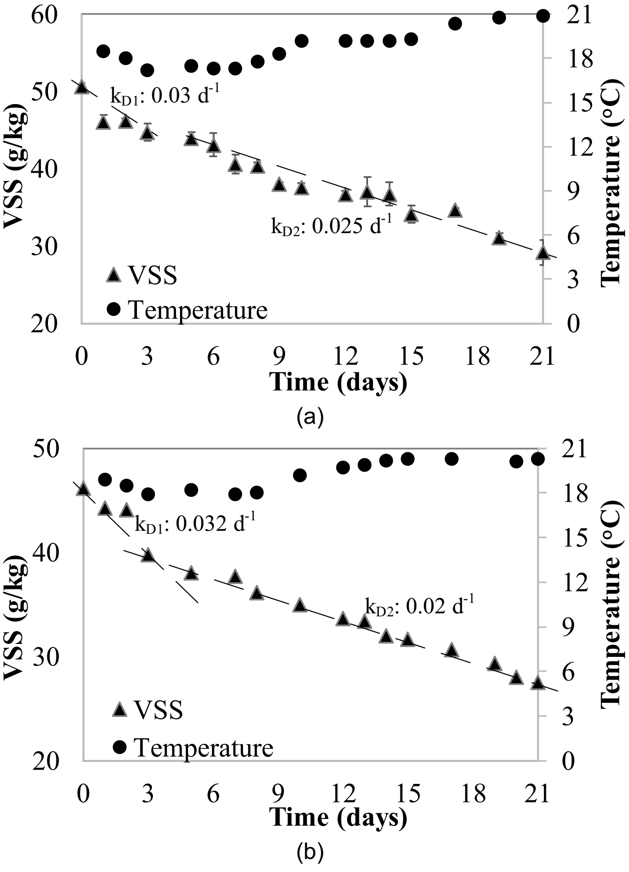

Fig. 1. VSS profiles obtained in the experiments (a) S1R1 and (b) S1R3.

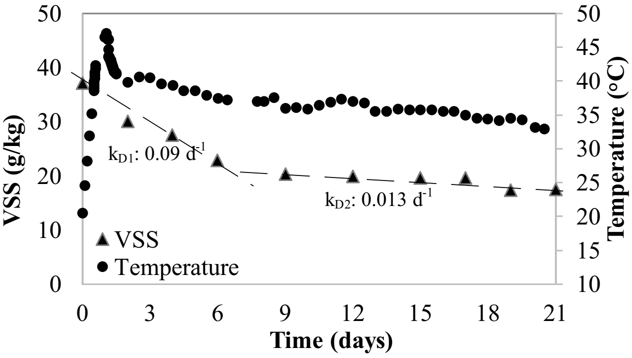

Fig. 2. Two-phase reduction of the VSS obtained under mesophilic conditions in the experiment S4R3.

4. Conclusion

The results in the study provided conclusive experimental evidence that the aerobic stabilization of the mixture of primary sludge and biological sludge proceeded in a sequence

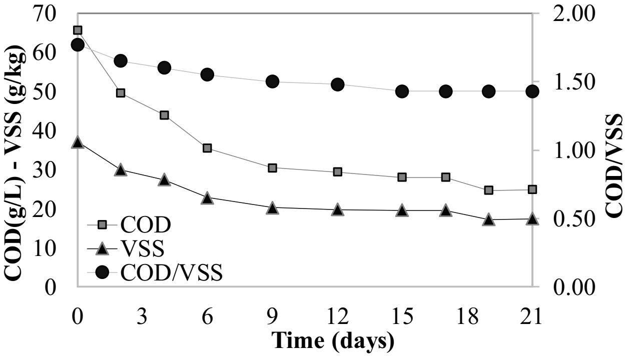

Fig. 3. COD and VSS profiles with corresponding COD/VSS ratios in the experimental run S4R3.

of two distinct phases: the utilization of the slowly biodegradable substrate in the primary sludge and the following endogenous processes based on the balance of endogenous decay and generation of residual particulate metabolic products.

The mesophilic conditions could be sustained under conditions of low aeration rate with a high mixing rate. The highest removal efficiency and temperature were obtained at the experiments performed with a primary sludge to biological sludge (PS/BS) ratio of 50/50. Increasing the PS ratio to 75% resulted in foaming problems probably because of organic overloading while the PS ratio of 25% was not enough to raise of temperature to mesophilic levels. The implementation of an aeration rate of 0.2 L/min with a high mixing rate on the sewage sludge at the PS/BS ratio of 50/50 enabled to raise of reactor temperature to 36.7°C. In the experiments, auto-thermal conditions could be sustained, which secured mesophilic operation yielding a VSS reduction as high as 53%, with a much higher COD removal to due oxidation of substrate in the primary sludge.

Capture of the excess energy from catabolic processes could be maximized by optimizing operating conditions, where energy loss through spend air flow (high aeration) could be reduced with a low aeration mode coupled with intense mixing.

Acknowledgment

This work was supported by the Scientific and Technological Research Council of Turkey (TUBITAK) [Grant number 116Y332].

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