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Research Article

Mixing effect on bio-methanation, settleability and dewaterability in the anaerobic digestion of sewage sludge fractions

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ABSTRACT

Biomethanation and dewaterability characteristics of primary sludge (PS), secondary sludge (SS) and mixed sludge (MS) fractions were assessed after anaerobic stabilization under parallel batch and continuous mixing conditions at 35°C in order to investigate the performance of the separate digestion system. Similar methane conversion/yield values were obtained in PS, SS and MS digestion with continuous mixing's positive effect only in PS digestion. Continuous mixing resulted in 50% increase in the methane yield (600(+/-100) mL/g VS_{add}.d. SS digestion produced a comparable methane yield at 650(+/-100) mL/g VS_{add}.d showing no effect due to mixing pattern. Settling and dewaterability characteristics of the stabilized PS were superior to stabilized SS samples. A reverse relationship was obtained between settling and dewaterability characteristics where intermittent mixing enhanced settling ability while continuous mixing resulted in higher dewaterability of the stabilized sludges. Polyelectrolyte (PE) addition showed a negative effect on the settleability of the sludges. Low degree mixing resulted in 50% sludge volume reduction and an SVI of 64 mL/g VS compared to 25% volume reduction and 82 mL/g SVI in the continuous mixing mode for the stabilized PS. A similar trend for the stabilized SS but weaker values with 25% volume reduction and an SVI 182 mL/g in the intermittent mixing mode compared to 15% volume reduction and 200 mL/g VS SVI indicated a much lower settleability in the continuous mixing mode and compared to stabilized PS.

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INTRODUCTION

Sewage sludge is produced as primary sludge (PS) and secondary sludge (SS) fractions in high volumes and mixed to be thickened (as mixed sludge (MS)) and then digested in completely mixed stirred anaerobic reactors applying high retention time as the most common strategy in the municipal wastewater treatment plants (WWTPs) despite they possess different biodegradability and dewaterability characteristics [1]. The biogas produced as a result of partial reduction in the volatile solid (VS) content is used in the electricity generation and contribute to the recovery of the operational costs. Many upgrading approaches deal

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with the minimization of the sludge volume, augmentation of the biological stabilization and dewaterability degree [2].

Dewaterability of sewage sludge affects the daily chemical dosage and produces a major cost in the sludge line of the municipal WWTPs. Dewaterability of sludges depends on many factors as particle size distribution, bound water, protein, fat and carbohydrate content whereas for SS, produced as the waste biological sludge, floc-structure and extra polymeric substances (EPS) play a major role in the water release in the decanters [3].

In biological treatment systems, it is important to mix the reactor to ensure efficient contact of the substrate with biomass. The mixing process is an important parameter that affects the efficiency and biochemical reaction times of the reactor. There are many advantages for anaerobic digesters in the mixing process; the homogeneity of organic/volatile matter and biomass, prevention of dead spaces, efficient contact of microorganisms with the substrate. In particular the rate of anaerobic hydrolysis increases, the methane gas produced by methanogens strips out more easily, lower retention time is needed compared to non-stirred reactors. Efficiency of the biogas production can be increased by 50% due to dilution+homogenization effect on the inhibitory products enhancing microbial reactions [4]. Contrarily, batch/intermittent mixing can improve the syntrophic relationship between methanogens and acetogens in the biomass and improve degradation in the case of fat-oil-grease (FOG) matter through lessening the degree of inhibition by long chain fatty acids [5]. As a result, methanogenic activity can proceed at a higher level in the batch than continuous mixture. Dewaterability of the final stabilized sludge is another important parameter determining the chemical cost spent in the decanters towards the final disposal of the sludge enabling reduction in the sludge volume and increase to a desired solid content. Both digestability and dewaterability of the sewage sludge fractions were seldom investigated comparatively for PS, SS and MS to optimize the sludge line in the municipal WWTPs.

In this study raw PS and SS and MS samples were subjected to anaerobic digestion and the final stabilized sludge fractions were comparatively evaluated based on dewaterability (chemical costs), conductivity (potential for land use) and volatile solid content (carbon content) as well as digestion performance in terms of methane yield. The outcome is aimed to indicate the mixing pattern's impact and different biodegradability and final biosolid quality that affect directly the operational costs and the advantage and/or disadvantage of separate sewage sludge digestion system.

METHODOLOGY

The experimental study was conducted in semi-continuous lab-scale reactors with 2000 mL total volume in parallel as continuous mixing (CM) and intermittent mixing (IM) modes for PS, SS and MS digestion at 35°C (Figure 1).

Figure 1. Lab-scale anaerobic digesters (a) IM and (b) CM modes.

PS samples were collected at the outlet of the primary settlers in the Konya municipal WWTP. SS was collected from the sludge return line in the activated sludge unit. Both PS and SS were thickened to increase the solid contents. The mixed sludge (MS) was prepared using 54:46% (v:v) of PS and SS samples, respectively. Inoculum sludge was grown in a previous study of sewage sludge digestion. The total solid (TS) and volatile solid (VS) concentrations ranged at 16380-23350 mg TS/L and 10690-15080 mg VS/L (PS) and 6430-7050 mg TS/L and 5250-5710 mg VS/L (SS). Organic loading rates (OLR) were applied as 0.53, 0.83 (PS), 0.29, 0.42 (SS) and 0.57 (MS) g VS/L.d for the digesters.

Hydraulic retention time (HRT) was kept at 20 d for all the reactors. Digesters were fed one time daily. Anaerobic digestion performance was monitored daily whereas effluent sludge settling and dewaterability were determined after the steady state was reached. Continuous mixing was provided in the PS-K, SS-K and MS-K digesters placed in the water bath by magnetic stirrers at 150 rpm placed under the water bath whereas parallel digesters, PS-A, SS-A and MS-A, kept in the incubator were subjected to intermittent mixing during the day time (Figure 1a, b). Anaerobic digestion performance was monitored by methane production via liquid displacement method and stabilized biosolid quality was determined as volatile solids (VS-2540 E), conductivity (WTW İnolob Cond 7110), Imhoff settleability and sludge volume index as mL/g VS (SVI-2710 D) and dewaterability as capillary suction time (CST) (2710 G) and time-to-filter (TTF)(2710 H) according to standard methods [6]. 304M Venture Innovations, Inc was used for CST determination. A vacuum filtration unit was used for TTF determination. Both measurements were obtained as seconds. 200 mL of sludge was used for Imhoff settling and SVI calculation. Methane yield as specific methane production was calculated as dividing the daily methane production by the VS amount of raw sludge fed in gram. A cationic polyelectrolyte (cationic acrylic acid derivative polyacrylamide) (PE) was used as aid for settling and added at 0.5, 1, 1.5, 2 and 2.5 g/200 mL sludge dosages making a concentration range as 2.5, 5, 7.5, 10 and 12.5 g/L of sludge.

RESULTS

The anaerobic digestion of PS produced the lowest methane yield at 400(+/-200) mL/g VS_{add}.d in the intermittent mixing (IM) mode (Figure 2a). Continuous mixing (CM) resulted in 50% increased methane yield (600(+/-100) mL/g VS_{add}.d). Higher degree of mixing was more efficient indicating that hydrolysis was the rate limiting stage and was enhanced for the slowly-degradable matter in the PS. SS digestion performance was low in daily methane production but produced a comparable methane yield level at 650(+/-100) mL/g VS_{add}.d due to its low VS feeding and showed no effect due to the mixing pattern indicating that biodegradability is limited and the hydrolysis stage can not be enhanced by adjusting the mixing degree (Figure 2b). Low VS concentration is considered a disadvantage for SS as low OLRs are applicable that limit the methane produced [7]. No effect of mixing degree was observed on methane yield in MS digestion at similar levels (650 (+/-50) mL/g VS_{add}.d) evidencing the dominant effect of SS in the mix (Figure 2c).

Higher methane yield values were obtained compared to previous studies of PS and SS digestion [8-10]. Winter and Pierce obtained a steady but low biogas yield at 250(+/-20) mL/g VS_{add}.d in SS digestion with a 65-70% methane content whereas higher but fluctuating value between 200-650 mL/g VS_{add}.d in the PS digestion with a 65% methane content [8]. The OLRs were higher as 1.48 and 1.67 kg VS/m^3.d for PS and SS digestion, respectively. The higher performance was correlated to lower OLR applied in this study. Methane yield decreases in cases of over exceeding on the hydrolysis rate by the OLR applied. Braguglia et al. obtained a methane yield of 170 mL/g VS_{add}.d in the SS digestion and applied pre-treatment methods to increase the yield [9]. Pinto et al. investigated an optimum proportion of PS and SS in the MS at an OLR of 1.62 kg VS/m^3.d and obtained a maximum methane yield of 372 mL/g VS_{add}.d [10]. The findings indicated that the content of the PS was the major enhancing factor on the methane yield of anaerobic sludge digestion and a variable for all municipal wastewaters.

Volatile solid (VS) concentration of the stabilized PS dropped and stabilized at 8000(+/-1000) mg/L in the end

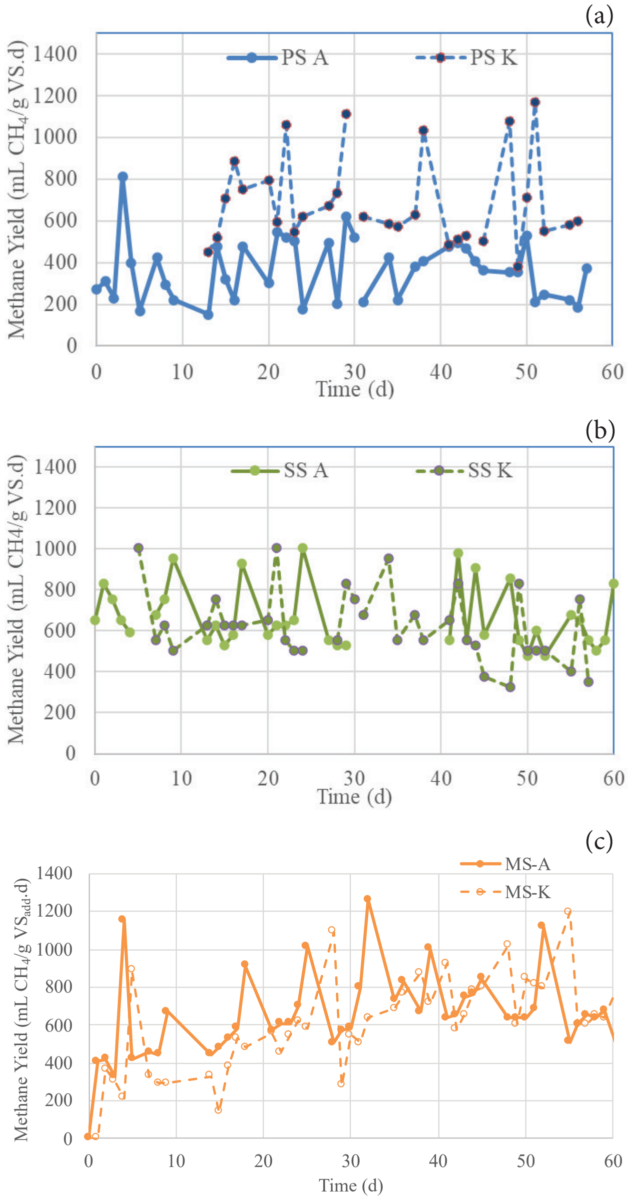

Figure 2. Methane yield values for (a) PS, (b) SS and (c) MS digesters.

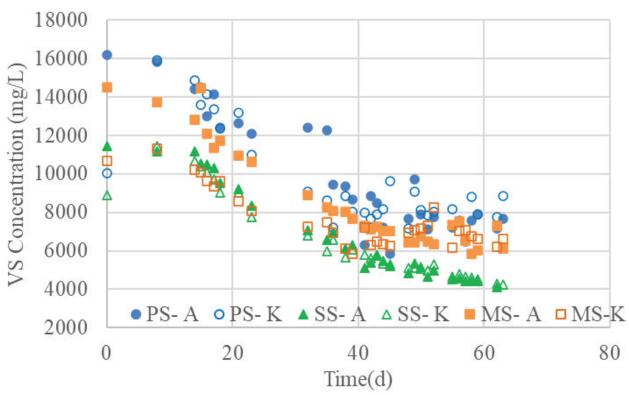

Figure 3. VS Concentration of the stabilized sludge types.

of the first 30 d-period showing no effect of mixing mode (Figure 3). Higher biomass content supported the high biodegradability of raw PS in comparison to SS digestion where VS concentration continuously dropped down to a lowest level of 4200 mg/L which supported low biodegradability and/or nutrient availability. Resistance of the SS' content to the reducing hydrolytic environment of anaerobic digestion originates from its content as bacterial cells and microbial products and has been reported in many studies [8,11]. Stabilized MS had a slightly lower VS content compared to stabilized PS. No effect of mixing degree was observed on the VS concentration for all sludge types. As a digestion performance VS removal was obtained at 39-56% (PS-A), 33-52% (PS-K), 20-27% (SS-A), 18-25% (SS-K), 27-29% (MS-A) and 23-28% (MS-K) indicated a slightly higher removal degree in the IM mode. In concordance with the methane yield data it can be concluded that biomass inhibition or loss (mostly methanogens) may have taken place in PS digestion in the low degree mixing resulting lower VS concentration (higher VS removal).

As the final biosolid quality, the conductivity of the stabilized PS showed the highest level (5.2-5.2 mS/cm) compared to stabilized SS at 4.2 and 4.4 mS/cm and MS at 4.7 and 5.0 mS/cm in the CM and IM conditions, respectively (Figure 4). The low level for SS indicated a suitability for limited agricultural use. Mixing degree affected the ion concentration of all the stabilized sludges meaning that higher microbial synthesis was promoted in the CM mode compared to low degree mixing.

Mixing degree of the stabilized sludges (in the absence of PE) was significantly effective on the settling property as low degree mixing resulted in lower Imhoff settling volume with 50% sludge volume reduction and an SVI of 64 mL/g VS compared to 25% volume reduction and 82 mL/g SVI in the CM mode for the stabilized PS (Figure 5a). A similar trend for the stabilized SS but weaker values with 25% volume reduction and an SVI 182 mL/g compared to 15% volume reduction and 200 mL/g VS indicated much lower settleability character in the CM mode and compared to stabilized PS (Figure 5b). Stabilized MS exhibited good

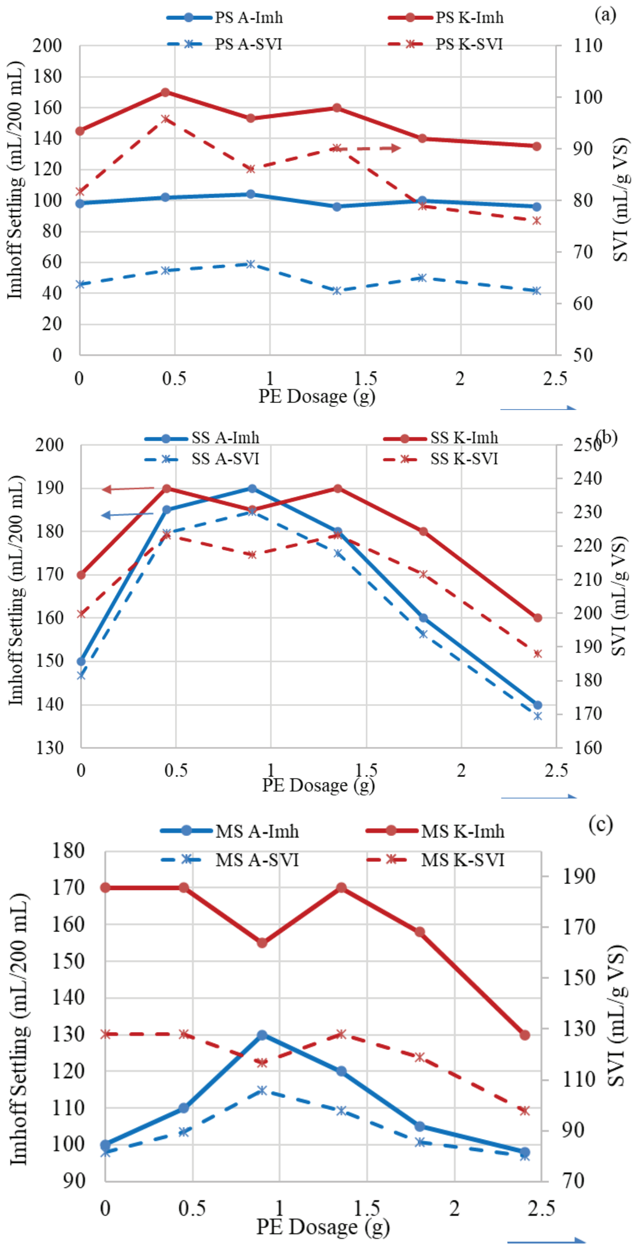

Figure 5. Imhoff settling and SVI values for stabilized (a) PS, (b) SS and (c)MS biosolids.

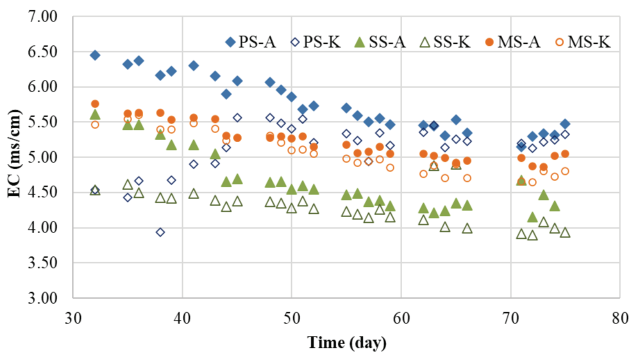

Figure 4. Electrical Conductivity (EC) of the stabilized sludges.

settleability and SVI approaching stabilized PS characteristics in the IM mode whereas bad settleability and SVI approached stabilized SS characteristics in the CM mode (Figure 5c). PE dosing exhibited no effect on the settleability and SVI for stabilized PS. A worsening effect was noticeable at all dosages with the exception of the highest dosage for stabilized SS regardless of the mixing degree. The worsening pattern was observed with the stabilized MS in the IM mode (no effect with the maximum dosage) whereas the maximum dosage enhanced settleability and SVI by 20% and 26%, respectively.

The mixing degree exhibited an opposite pattern in the dewaterability of the stabilized PS that occurred at different levels as CST:77-84 s and TTF: 560-618 s in the IM mode and much higher water release abilities with CST: 15-16 s and TTF: 195-205 s in the CM mode. Similarly for stabilized SS samples, low mixing degree produced lower dewaterability with higher CST (93-100 s) and TTF (1685-1702 s) values than CM mode with CST:71-74 s and TTF: 890-1160 s values. CM promoted dewaterability for stabilized SS and PS. Similarly, stabilized MS produced much lower CST (19 s) and TTF (281-238 s) values in the CM than CST: 74-80 s and TTF: 760-887 s in the IM mode. The results implied that compacted flocs were formed with higher settleability but poorer water release ability in the low mixing operation. High water release was an indicator of the high free water content and loose flocs that occurred in the CM operation which was shown with poorer Imhoff settling results.

Dewaterability at a higher degree for stabilized PS was shown previously in similar comparative studies with stabilized SS at higher OLRs [12,13]. Lower settling and dewaterability characteristics of the SS were correlated to a higher concentration of colloidal solids inducing a higher zeta-potential and high content as EPS matter that holds bound water [14-17]. Reverse effect of mixing degree on the settling and dewatering abilities indicated that free water content was higher in the case of IM and was separated off the flocs more efficiently by simple settling whereas lower dewaterability was caused by the high number of bacterial cells and lower amount of products [18,19]. On the other hand, CM worsened settling but enhanced water release by the lower number of cells and higher number of cell products due to harder environmental conditions where bacteria increased the EPS production. Similarly, the negative effect of PE addition was explained as the increase of bounding energy of the sludge that already contained polymeric substances and bound water resulting in floc expansion [19].

CONCLUSIONS

A parallel relation was obtained between mixing density and methanogenic activity+dewaterability with a negative impact on the settleability of the stabilized sludges in PS, SS and MS digestion. Settling and dewaterability characteristics of the stabilized PS were superior and required no PE addition compared to stabilized SS and MS samples. A reverse relationship was obtained between settling characteristics and dewaterability for all sludge types indicating denser floc formation with high settling but poor water release abilities in a low degree of mixing. No effect of solid content was calculated on the CST and TTF results in order to indicate the highest settling and water release abilities of stabilized PS despite the highest VS content requiring no need for PE addition which also did not enhance settleability at a significant level up to 12.5 g/L sludge for stabilized SS and MS.

The outcome pointed out to the benefits of the separate/parallel digestion of PS and SS when compared with MS digestion where:

- a substantial chemical and energy cost can be eliminated through mechanical settling allowing 50% volume reduction and thickening of the stabilized PS,
- a substantial savings in the chemical cost using PE in the decanters after the PS digestion,
- a substantial saving in the chemical cost with a partial intrusion of the PS into SS flow to ameliorate SS's settling ability and dewaterability significantly.

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CONFLICT OF INTEREST

The authors declare no potential conflicts of interest regarding the research, authorship and/or publication of this article.

DATA AVAILABILITY

The data used to support the findings of this study are included within the article.

AUTHOR'S CONTRIBUTIONS

All authors are contributed equally to bring out this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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