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RESEARCH ARTICLE

Increasing the performance of anaerobic digestion: Pilot scale experimental study for thermal hydrolysis of mixed sludge

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Abstract The performance of a pilot plant operation combining thermal hydrolysis (170°C, 30 min) and anaerobic digestion (AD) was studied, determining the main properties for samples of fresh mixed sludge, hydrolyzed sludge, and digested sludge, in order to quantify the thermal pretreatment performance (disintegration, solubilisation, and dewaterability) and its impact on the anaerobic digestion performance (biodegradability, volatile solids reduction, and digester rheology) and end product characteristics (dewaterability, sanitation, organic and nitrogen content). The disintegration achieved during the thermal treatment enhances the sludge centrifugation, allowing a 70% higher total solids concentration in the feed to anaerobic digestion. The digestion of this sludge generates 40% more biogas in half the time, due to the higher solids removal compared to a conventional digester. The waste generated can be dewatered by centrifugation to 7% dry solids without polymer addition, and is pathogen free.

Keywords anaerobic digestion (AD), biogas, performance, sludge, thermal hydrolysis

1 Introduction

Owing to environmental, economic, social, and legal factors, the treatment and disposal of excess sludge represents a bottleneck for wastewater treatment plants. In large wastewater treatment plants, primary and secondary sludge are stabilized by applying anaerobic digestion, resulting in elimination of volatile solids and production of biogas. However, hydrolysis is the rate limiting step of the biologic degradation of sludge [1,2], and therefore the process is slow, big digesters are used (> 20 d residence time), and large quantities of biosolids are produced (2–50% degradation of organic matter).

By improving the hydrolysis step solid substrates are more accessible to anaerobic bacteria, accelerating the digestion, increasing the volume of biogas produced, and decreasing the amount of solids to be disposed. The main physical pre-treatments founded at research or commercial level are: mechanical (ultrasounds), thermal, chemical, or biologic technologies [3–8].

Among the different alternatives, thermal pre-treatment has proven to be of great interest. The advantage of the combined thermal pre-treatment plus the anaerobic digestion (AD) process is that the energy input needed for the hydrolysis process is thermal energy, and could be satisfied from the energy production of the process itself, resulting in an energetically self-sufficient process. A combination of thermal hydrolysis and anaerobic digestion has been widely investigated in literature from a laboratory-scale point of view [2,5,9,10]. Most of the work has focused on the influence of thermal hydrolysis in disintegration and biogas production enhancement during the subsequent anaerobic digestion, and some of them also include dewatering aspects, but very few articles refer to other properties of great importance from a full scale point of view.

The objective of this research is to cover the range of studies on the impact of thermal pretreatment not only on sludge disintegration, solubilisation and anaerobic biodegradation, but also on sludge dewaterability, settleability, viscosity, and sanitation. A pilot plant consisting of a thermal hydrolysis followed by anaerobic digestion was operated continuously. The operation conditions in the thermal hydrolysis unit were fixed in 170°C and 30 min according to Ref. [9].

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2 Materials and methods

2.1 Sludge samples

The study was performed using mixed sludge from the municipal wastewater treatment plant of Vic (Spain). Several samples were collected and characterized before and after the thermal treatment. Table 1 presents the average values for the untreated sludge.

2.2 Pilot plant

A pilot plant combining thermal hydrolysis and anaerobic digestion was operated for two years at the Municipal Wastewater Treatment Plant of Vic (Spain).

Mixed sludge was directly fed to the thermal hydrolysis pilot plant shown in Fig. 1, consisting of a feeding tank, a progressive cavity pump ($P_{\max}$ = 12 bar), a steam boiler, and a 20-L total volume hydrolysis reactor (V_{useful} = 10 L) connected to a flash tank (V = 100 L) with outlet pipes for steam and hydrolyzed sludge.

Sludge (10 L) is pumped into the reactor, and the pressure-temperature control is activated, allowing the entrance of steam from the boiler to maintain a 170°C temperature. The plant is operated in a batch mode, and is controlled with a data acquisition and control system that controls the reactor pressure and the residence time. At the end of the 30 min reaction time, the decompression valve is automatically opened and the hydrolyzed sludge flows to the flash tank.

Hydrolysed sludge from the hydrolysis unit is cooled to ambient temperature and continuously fed to a mesophilic anaerobic reactor (200 L) provided with sludge and biogas recirculations to assure mixing and avoid sludge setting inside the digesters. The mesophilic reactor is inoculated with anaerobic digested sludge and directly fed with thermically hydrolyzed mixed sludge using a hydraulic residence time of 20 d, without any acclimation period. Biogas production is automatically recorded, and the digester performance and effluent characteristics are recorded from laboratory analysis (COD, volatile fatty acids (VFA), pathogens, dewaterability and viscosity). The hydraulic residence time was decreased step by step until it reached a stable value of 12 d.

2.3 Analytical methods

All the analyses were done using the procedures given in “Standard Methods for Examination of Water and Wastewater” [11].

Solubilisation studies Sludge solubilization and particle size reduction were measured. The former is quantified by means of the increase of the soluble organic content (SCOD) and, for the latter, diffraction laser equipment (Horiba LA-900, Horiba, Japan) was used.

Biodegradability studies Anaerobic biodegradability increase is calculated by comparing the specific methane production of the raw sludge and the treated sludge. An automatic equipment and the experimental conditions described in Ref. [12] were used, and all the tests were

Table 1 Average characteristics of the untreated fresh mixed sludge (FMS) and for the hydrolysed sludge (HS)

sludge	total COD/($g\cdot L^{-1}$)	soluble COD/($g\cdot L^{-1}$)	total solids (TS)/($g\cdot L^{-1}$)	volatile solids (VS)/($g\cdot L^{-1}$)
fresh mixed sludge (FMS)	36450	2860	34.9	18.5
hydrolysed sludge (HS)	25657	7325	23.5	15.3

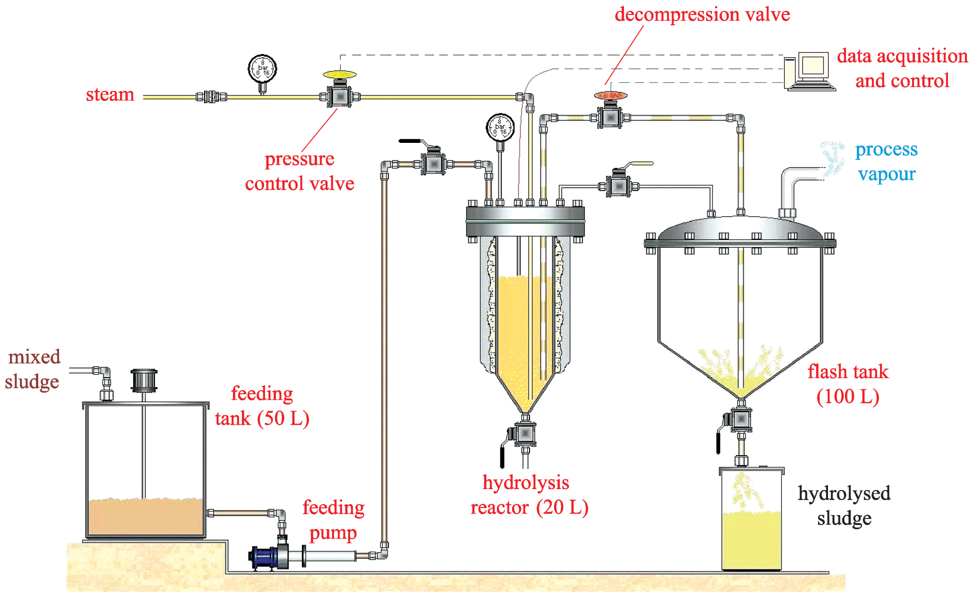

Fig. 1 Thermal hydrolysis pilot plant

made in triplicate.

Dewaterability determination The effect of thermal hydrolysis (TH) on the dewaterability of the sludge was assessed in centrifuge and filtration tests. For the former, a Kubota 5100 laboratory centrifuge was used. Samples of sludge were centrifuged at 270 g for 1 min, measuring the volume and solids content of the resulting cake and supernatant fluid. Both the percentage of water removed by centrifugation and the solids recovery fraction were calculated. Filtration tests were performed in a filtering equipment (Millipore), maintaining a pressure of 2 bar and measuring the volume filtered with respect to time. The filtration constant was calculated using Coulson's mathematical study from the slope, plotting filtrate volume (V^2) versus filtration time (t).

Viscosity measure Rheology tests were performed using a rotational viscosimeter (Brookfield LVDV-1 +, Brookfield, USA). The rheometer worked in a controlled shear rate mode. The temperature was kept constant at 25°C.

Pathogens quantification Total and faecal coliforms were determined in order to quantify the hygienisation of the final biowaste.

3 Results and discussion

3.1 Thermal hydrolysis performance—Quantification of the performance of the thermal hydrolysis unit

3.1.1 Degree of degradation: solubilisation and cell lysis

Table 1 presents the characteristics for the untreated and treated sludge. From the TCOD and solids values it can be seen that sludge is diluted by the steam condensation. Comparing the SCOD fraction before and after the thermal treatment (Fig. 2), it can be stated that soluble COD in the supernatant increased from 7.8% to 29%, meaning that hydrolyzed sludge is 4 times more soluble than non-hydrolyzed sludge.

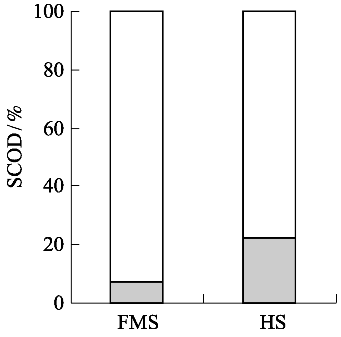

Fig. 2 SCOD fraction for fresh-mixed and hydrolyzed sludge

This solubilisation is due to the disintegration of floc structures and cell lysis. As Fig. 3 shows, particle size becomes 70% smaller after hydrolysis, but a floculation phenomenon also occurs, and bigger flocs appear.

3.1.2 Dewaterability: Filterability and centrifugability

Figure 4 shows that filterability of the sludge is radically better after the thermal treatment. Not only is more water removed by filtration, the rate of water recovery is also faster.

The centrifugability study (Fig. 5) showed that when

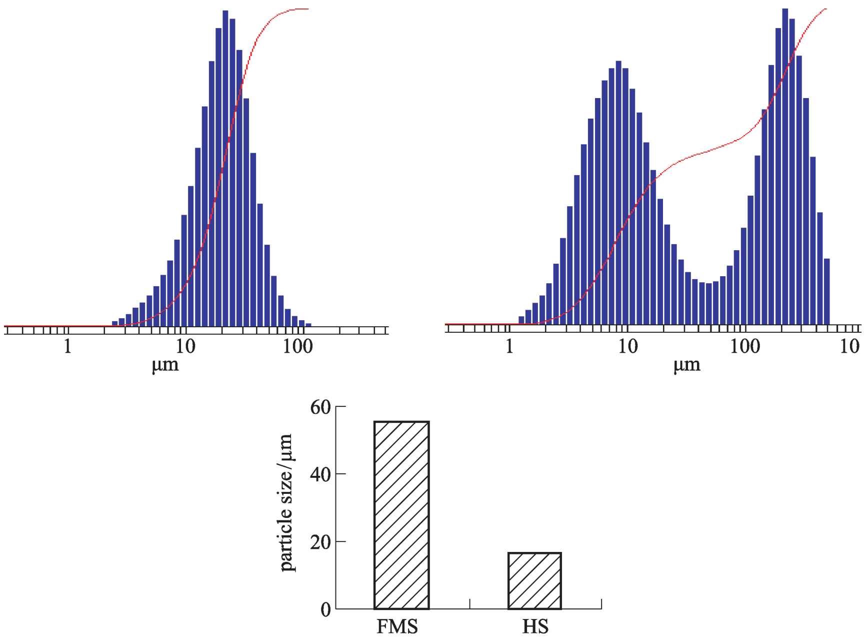

Fig. 3 Particle size distribution and average values for FMS and HS

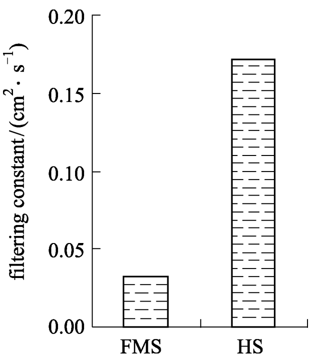

Fig. 4 Filtering constant values for FMS and HS

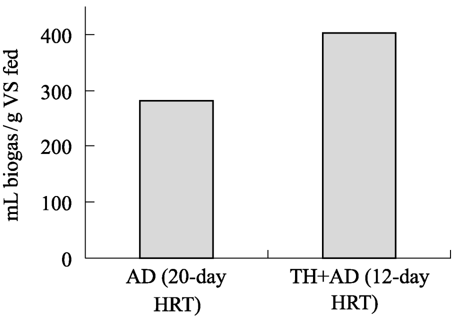

Fig. 6 Biogas productivity in the AD of FMS and HS

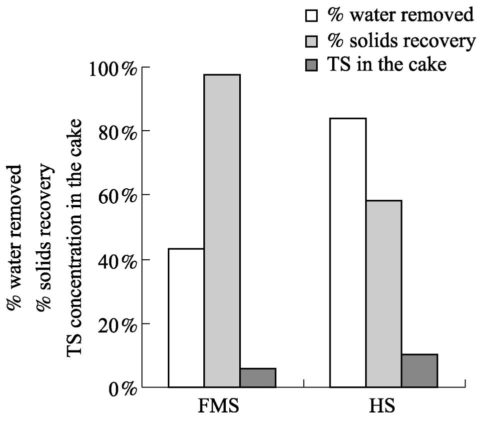

Fig. 5 Water removal and solids recovery by centrifugation for FMS and HS

applying the same force (268 G), the quantity of water removed in the centrifugation of the sludge is nearly double (84%) with respect to the centrifugation tests of FMS (43%). However, for the HS samples the percentage of solids recovered in the sludge cake was smaller (58% for HS and 97% for FMS). This can be explained due to the reduction in the particle size after the thermal treatment, and is consistent with the disintegration results: smaller particles are more difficult to recover by centrifugation.

From a global point of view, it can be said that the thermal treatment enhances the sludge centrifugability, as the total solids concentration in the sludge cake is 72% higher after the treatment, for the same centrifugation force applied.

3.2 Anaerobic digestion performance—Quantification of the performance of the anaerobic digestion of the sludge from the thermal hydrolysis unit

3.2.1 Biodegradability: Biogas productivity

The increase in biogas productivity is calculated comparing the main average operation data for the anaerobic digester fed with HS to the reference values obtained in the full scale mesophilic digester fed with the same MS. Figure 6 shows that the TH process increases the sludge anaerobic digestibility, giving a 40% higher yield of biogas with respect to the control in nearly half the time (12 d instead of 20 d residence time).

Moreover, TH not only increases biogas production, but also increases the rate of degradation, especially during the first days of digestion, due to the increase in the easily degradable organic matter. Biodegradability tests (Fig. 7) show that the biogas production of the bottle fed with hydrolysed sludge at 170°C for 30 min is faster and higher: The tests fed with hydrolysed sludge produced in the first 3 d the same quantity of biogas than the tests fed with untreated sludge over a time period of 6 d.

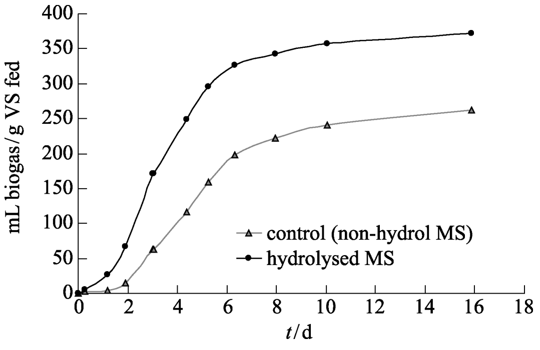

Fig. 7 Biogas production curves in biodegradability tests for FMS (control) and HS

The consequence of this improvement is that shorter retention times can be used in anaerobic digestion. Operating at short residence time, it is possible to increase the methane production by 40%, decreasing the final amount of sludge to be disposed.

3.2.2 Rheology: apparent viscosity (mixing efficiency)

The experimental curves (Figs. 8 and 9) suggest that digested sludge behaves as a non-Newtonian fluid in both cases. Viscosity strongly decreases with the shearing rate.

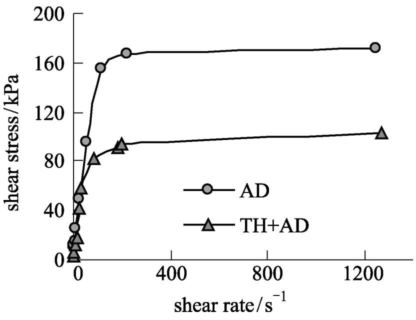

Fig. 8 Rheograms for anaerobic digesters fed with FMS (AD) and HS (TH + AD)

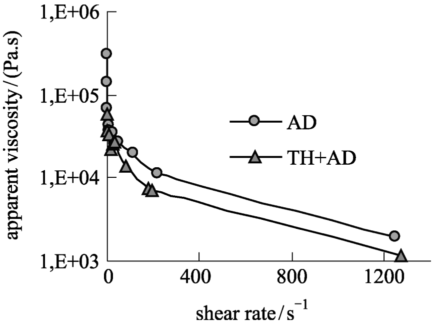

Fig. 9 Apparent viscosity curves for anaerobic digesters fed with FMS (AD) and HS (TH + AD)

Comparing the behavior of the digester fed with hydrolyzed sludge to the conventional one, it can be seen that apparent viscosity is radically smaller (70% less viscous for null shear rate) when the sludge is hydrolysed (Fig. 9). This observation probably results from the fact that the floc structure is broken during the thermal treatment, reducing the interfloc resistance.

3.3 End product characteristics—Quantification of the final effluent (biomass) quality

3.3.1 Reduction in sludge mass: Volatile Solids reduction

As Fig. 10 shows, the increase in the sludge biodegradability after the TH drives to a higher VS removal in the AD process: 36% VS removal in conventional AD and 50% VS removal in the digester fed with hydrolysed sludge. Therefore, comparing the effluent flow of the anaerobic digestion process, there is a 40% decrease in the final amount of sludge to be disposed when introducing a hydrolysis pre-treatment step prior to the anaerobic digestion. The dewaterability study presented in the following paragraph shows that the sludge cake is even smaller due to an enhancement of the dewatering characteristics of the hydrolysed sludge.

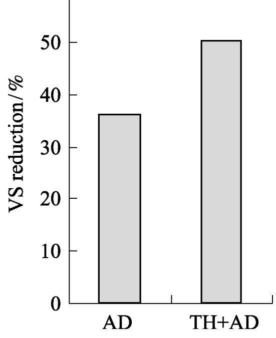

Fig. 10 VS reduction for digested sludge from AD and TH + AD

3.3.2 Dewaterability: Filterability and centrifugability

Filterability of the final biowaste from anaerobic digestion is 4.5 times better in the process with the thermal hydrolysis unit (see Fig. 11).

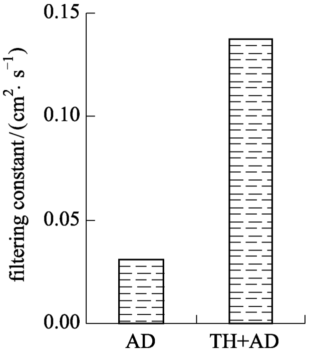

Fig. 11 Filtering constant values for digested sludge from AD and TH + AD

The centrifugation studies (Fig. 12) showed that the introduction of a TH pretreatment not only allowed removal of 40% more biosolids in the anaerobic process, but also drove to a better dewatered digested sludge: a sludge cake with almost 7% dry solids could be achieved by centrifugation without the addition of polymer conditioners, and the solids recovery rate is above 95%.

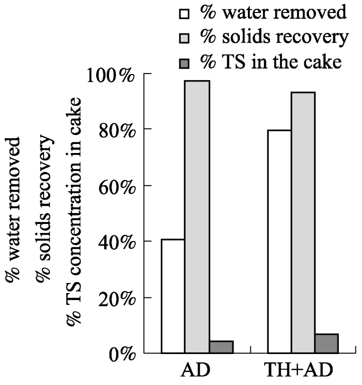

Fig. 12 Water removal and solids recovery by centrifugation for digested sludge from AD and TH + AD

Therefore, the amount of cake produced is less (up to 70% less compared to the conventional process) and the biowaste quality better (regarding stability and hygienisation). As a consequence, the overall operating cost could be reduced, thanks to both polyelectrolyte and transport savings.

3.3.3 Hygienisation: Pathogens removal

The total and faecal coliform study showed that the thermal hydrolysis kills all the pathogens present in the sludge (8.4E + 07 UFC/100 mL total coliform in FMS), and therefore hydrolysed sludge is pathogen free (0 UFC/100 mL in HS). Furthermore, no coliforms were detected in the digested sludge from the digester fed with HS.

3.3.4 Organic and nitrogen content

The analysis done to the liquid effluent from the centrifugation of the digested sludge showed higher pollution in the process with TH before AD, compared to the conventional process.

The COD was measured at all times to 1.5–1.7 g COD/g VS. The SCOD increased from 2.6% to 13.2% SCOD/VS (Fig. 13) and the nitrogen content also increased from 10.7 to 19.8% N/VS (Fig. 14). This growth produces an increase in the ammonia return load. While 55%–60% of VS is degraded, over 60% of the nitrogen from the sludge is now returned to the plant as ammonia.

4 Conclusions

Due to the thermal treatment, sludge flocs are disintegrated and sludge soluble COD increases by 40%. Boundary water is released, and dewaterability becomes better for the hydrolysed sludge (HS) compared to the fresh mixed sludge (FMS). 72% higher total solids concentration can be achieved (11% in HS vs. 6% in FMS). Sludge disintegration also drives to a smaller apparent viscosity.

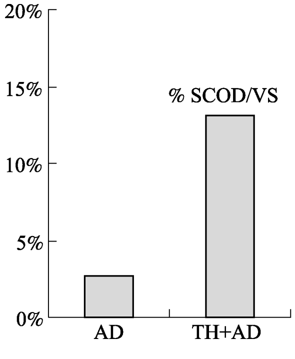

Fig. 13 SCOD/VS ratios for digested sludge from AD and TH + AD

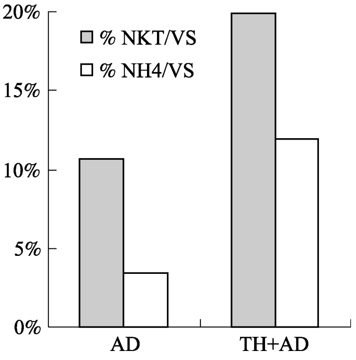

Fig. 14 NKT/VS and NH_4/VS ratios for digested sludge from AD and TH + AD

The AD of the hydrolysed sludge generates 40% more biogas in half the time, and removes 30% more biosolids compared to a conventional digester.

The pathogen-free digested sludge from a TH plus AD process can be dewatered to 7% DS without polymer addition, and the solids recovery rate is above 95%.

However, organic carbon and nitrogen content in the biowaste increase, and over 60% of the nitrogen in the sludge returns to the plant as ammonia.

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