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Improvement of anaerobic digestion of sewage sludge in a wastewater treatment plant by means of mechanical and thermal pre-treatments: Performance, energy and economical assessment

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HIGHLIGHTS

- The efficiency of AD on WAS in the largest Italian WWTP has to be improved.
- Mechanical and low-temperature thermal pre-treatments were tested.
- Thermally treated samples produced from 20% to 30% more methane than untreated samples.
- Low-temperature thermal pre-treatments caused a significant decrease in WAS viscosity.
- Total revenues from electricity sale raised by 10% compared to the present scenario.

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ABSTRACT

Performances of mechanical and low-temperature (<100 °C) thermal pre-treatments were investigated to improve the present efficiency of anaerobic digestion (AD) carried out on waste activated sludge (WAS) in the largest Italian wastewater treatment plant (2,300,000 p.e.). Thermal pre-treatments returned disintegration rates of one order of magnitude higher than mechanical ones (about 25% vs. 1.5%). The methane specific production increased by 21% and 31%, with respect to untreated samples, for treatment conditions of respectively 70 and 90 °C, 3 h. Thermal pre-treatments also decreased WAS viscosity. Preliminary energy and economic assessments demonstrated that a WAS final total solid content of 5% was enough to avoid the employment of auxiliary methane for the pre-treatment at 90 °C and the subsequent AD process, provided that all the heat generated was transferred to WAS through heat exchangers. Moreover, the total revenues from sale of the electricity produced from biogas increased by 10% with respect to the present scenario.

1. Introduction

Waste activated sludge (WAS) is an important source of biological matter that is commonly produced in secondary processes of wastewater treatment plants (WWTPs). According to Wilson and Novak (2009) and Cho et al. (2014), WAS handling is one of the most difficult and expensive items for a WWTP, since it accounts for 30–40% of capital costs and 50% of operating costs of the plant.

Anaerobic digestion (AD), with its four steps of hydrolysis, acidogenesis, acetogenesis and methanogenesis, is one of the most common and widely adopted methods for WAS treatment and stabilization. In fact, in addition to reducing the overall amount of biosolids to be disposed of by about 40%, and stabilizing organic substance, AD produces biogas, the two main components of which are methane and carbon dioxide, that can be exploited for energy recovery. Other beneficial features of the AD process include inactivation and reduction of pathogens and improvement of sludge dewaterability (Appels et al., 2010).

Nevertheless, AD is not completely effective towards WAS from WWTPs because the complexity of the WAS structure limits the biological process. Low biodegradability of WAS is due to the retarded hydrolysis, because microbial cells, cell walls and membrane in the

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WAS are strong barriers that do not easily permit the penetration of hydrolytic enzymes (Cho et al., 2014; Romero et al., 2013).

In order to accelerate the step of hydrolysis, thus improving degradability of sludge with subsequent lower digester retention time and higher methane production rates, several types of pre-treatments have been tested with the purpose of:

- reducing macromolecule dimensions and avoiding presence of macro-flocks inside the sludge;
- breaking bacteria cell walls with release of intracellular organic matter.

WAS pre-treatments can be classified on the basis of the lysis system employed. Pre-treatments can be grouped into biological, thermal, mechanical, chemical as well as different combination of these (Appels et al., 2008; Barjenbruch and Kopplow, 2003; Bougrier et al., 2006; Carrère et al., 2010; Kavitha et al., 2014; Kim et al., 2003; Nagare et al., 2008; Rajesh Banu, 2014). In the wide scenario of lysis technologies, mechanical and thermal pre-treatments are the most common systems available on the market, working in full scale plants with good results in terms of COD solubilization and AD performance improvement (Bougrier et al., 2008; Choi et al., 2006; Climent et al., 2007; Dohányos et al., 1997, 2004; Ferrer et al., 2008; Grübel and Machnicka, 2009; Kampas et al., 2007; Machnicka et al., 2009; Zábranská et al., 2006). Soluble COD (SCOD), that is the amount of COD in the liquid phase (after 0.45 μm filtration), is a parameter of easy analytic determination strictly related to sludge degradability.

In the field of mechanical pre-treatments, several systems for mechanical disintegration are available, such as lysis-thickening centrifuge, stirred ball mills, high pressure homogenizers, high pressure jet and collision, rotor–stator disintegration system. The aim of the mechanic disintegration is to enhance sludge solubilization as a consequence of bacteria cell disintegration and disaggregation of biological flocs. In general, at low applied energy only floc disintegration is observed, while high energy is required to damage microbial cells (Appels et al., 2008; Carrère et al., 2010). Although not many results are available for mechanical pre-treatments in respect to the other methods, it is demonstrated that the efficiency of most of the technologies in improving AD of sewage sludge is rather low, if not coupled with other methods (Cho et al., 2014; Grübel and Machnicka, 2009; Kampas et al., 2007; Machnicka et al., 2009).

In thermal pre-treatments sludge is generally heated to temperature values in the range 150–200 °C, although lower temperatures have also been tested (Appels et al., 2008; Climent et al., 2007; Dhar et al., 2012). The most significant drawback of high temperature pre-treatments is the high energy requirement. The surplus of energy that can be recovered because of the increase in biogas production is largely balanced by the high energy requirements for rising the temperature of sludge to the temperature of the thermal process. This largely reduces the overall profitability of the process. Application of low temperature thermal pre-treatments (<100 °C) could be an alternative to overcome this drawback. However, at low temperature values, treatment time plays a more dominant role than treatment temperature (Appels et al., 2008). Lysis pre-treatments, other than having effect on COD solubilization and subsequent methane production rate, are able to affect the structure of sludge thus lowering its viscosity with the consequence of improving sludge handling and pumpability in the WWTP (Novarino et al., 2010; Ratkovich et al., 2013).

In this study, in the view of improving the efficiency of the AD process performed on the WAS produced in the largest Italian WWTP (2,300,000 p.e., population equivalent), located near Turin, in the north of Italy, the experimental activities listed in the follow were carried out:

- comparison of the performances obtained from mechanical and low-temperature thermal pre-treatments on WAS samples thickened to final total solid (TS) contents of 2%, 4% and 9% b.w. (by weight). The TS values employed in this study were in the range that may be obtained using dynamic thickeners;
- evaluation of the influence of temperature (70–80–90 °C) and treatment time (from 1 to 15 h) on the performances of low-temperature pre-treatments;
- evaluation of the increase in biogas and methane generation from AD of WAS, due to thermal pre-treatments, using batch tests at semi-pilot scale;
- evaluation of the effect of low-temperature thermal pre-treatments on the rheology of sludge samples at different TS values;
- preliminary assessment of the energy and economic feasibility of full scale low-temperature thermal pre-treatments.

2. Methods

2.1. The WWTP and the present performance of sludge AD

The largest Italian WWTP treats municipal and industrial wastewater with a capacity of about 2,300,000 p.e. (about 1.5 million of civil inhabitants, over 1000 industrial discharges and also tank truck wastewater). It consists of four parallel lines devoted to wastewater treatment and a modular sludge treatment. Each line for wastewater treatment, with an average flow rate of about 25,000 m^3/h, is made up of the following processes: grid screens, grit and grease removal, primary sedimentation, pre-denitrification, biological oxidation, secondary sedimentation, phosphorous removal and final filtration. The wastewater treatment process generates an average amount of primary and secondary sludge equal to about 300–350 m^3/h, with an average TS content of 1%, that is sent to the sludge treatment. The sludge treatment line is made up of the following unit operations: pre-thickening, mesophilic AD, post-thickening and final dewatering. The pre-thickening process reduces the amount of sludge to be treated by AD to about 110 m^3/h, with an average TS content of 2.75% for both primary and secondary sludge. The pre-thickening process is carried out by means of gravity devices with the addition of polyelectrolyte for thickening of the secondary sludge. The total sludge amount is treated in six anaerobic digesters, one of them periodically in maintenance. Each digester has a volume of 12,000 m^3 (for a total volume useful to the digestion process of 60,000 m^3), a D/H (diameter, height) ratio of 26/30, a filling coefficient of 0.8, an hydraulic retention time (HRT) of about 17 days, a fed sludge amount of 23.5 m^3/h with a TS content of 2.75%, for a mass flow rate of dry substance of 650 kg/h.

The digestion process is carried out in mesophilic conditions, at the temperature value of 38 °C. In order to heat the sludge from the average temperature of 15 °C (ambient temperature) to 38 °C and keep the process temperature constant, each digester is coupled with a double-tube heat exchanger fed by the hot water (70 °C) circuit. Four cogeneration engines (GE-Jenbacher JMS 420 GS-B.L.), that produce heat and electricity by burning the biogas generated in the AD process, supply heat to the hot water circuit. The cogeneration engines have thermal and electrical efficiency of 42%.

In the present working condition (no pre-treatments applied to WAS), each digester requires 2425 MJ/h to heat the sludge to the process temperature (38 °C) and offset the thermal losses with the outside. Each digester, fed with 50% primary sludge and 50% secondary sludge, produces about 1900 MJ/h (yearly average), considering that the average methane production of the primary sludge is of 0.385 Nm^3/kgVS and the average methane production of the secondary sludge is of 0.167 Nm^3/kgVS (data supplied from the WWTP). In the present situation the AD of the mix made of primary and secondary sludge has an economic revenue of 530 €/h