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Research article

Improvement of anaerobic digestion of sewage sludge through microwave pre-treatment

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A B S T R A C T

Sewage sludge generated in the activated sludge process is a polluting waste that must be treated adequately to avoid important environmental impacts. Traditional management methods, such as landfill disposal or incineration, are being ruled out due to the high content in heavy metal, pathogens, micropolluting compounds of the sewage sludge and the lack of use of resources. Anaerobic digestion could be an interesting treatment, but must be improved since the biomethanisation of sewage sludge entails low biodegradability and low methane production. A microwave pre-treatment at pilot scale is proposed to increase the organic matter solubilisation of sewage sludge and enhance the bio-methanisation yield. The operational variables of microwave pre-treatment (power and specific energy applied) were optimised by analysing the physicochemical characteristics of sewage sludge (both total and soluble fraction) under different pre-treatment conditions. According to the variation in the sCOD and TN concentration, the optimal operation variables of the pre-treatment were fixed at 20,000 J/g TS and 700 W. A subsequent anaerobic digestion test was carried out with raw and pre-treated sewage sludge under different conditions (20,000 J/g TS and 700 W; 20,000 J/g TS and 400 W; and 30,000 J/g TS and 400 W). Although stability was maintained throughout the process, the enhancement in the total methane yield was not high (up to 17%). Nevertheless, very promising improvements were determined for the kinetics of the process, where the r_G and the OLR increased by 43% and 39%, respectively, after carrying out a pre-treatment at 20,000 J/g TS and 700 W.

1. Introduction

Sewage sludge is generated in the activated sludge process, which is one of the most commonly used treatment technologies in municipal and industrial wastewater treatment plants (WWTPs), and whose management represents a problem of growing importance around the world (Appels et al., 2013). The management of sewage sludge is an expensive and environmentally sensitive problem given that this waste contains heavy metals, organic micropollutants and pathogens, which have led to stringent legislation for sewage sludge applications (Hendrickx, 2009).

Anaerobic digestion is one of the available technologies for the treatment of sewage sludge given that it permits recovering energy in the form of methane, reducing mass and pathogens and removing odours (Pilli et al., 2011). Nevertheless, this technology presents several disadvantages for treating sewage sludge such as low methane production and biodegradability, along with an unfavourable kinetics of the process as the hydrolysis of this waste is slow (Bolzonella et al., 2005; Ortega et al., 2008). Moreover, variations in operational variables such as organic loading rate might cause perturbations in the inoculum/substrate ratio and lead to system failure (Labatut and Gooch, 2012; Raposo et al., 2009). This problem could be associated particularly to tourist areas or management plants which have to treat occasional organic overloads and where there are important seasonal variations in the influent to be treated, thus increasing the sewage sludge flow. To deal with the problems of daily, weekly and seasonal influent load variations, it was a tradition for many years to design oversized WWTPs to guarantee good effluent quality without much process adjustment (Gernaey et al., 1998). Nevertheless, because oversizing entails important additional investment costs, this alternative should be avoided in order to ensure the economic sustainability of

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Nomenclature

Alk	alkalinity (mg $CaCO_3$/L)
C_2	acetic acid (mg C_2/L)
COD	chemical oxygen demand (g O_2/kg)
D.L.	detection limit
FS	total fixed solids (g/kg)
GAL	glucose, sodium acetate and lactic acid solution
$N-NH_4^+$	ammoniacal nitrogen (mg/kg)
OLR	organic loading rate (g VS/L·d)
r_G	methane production rate (mL_{STP}/L·d)
sCOD	soluble chemical oxygen demand (g O_2/kg; mg O_2/kg; mg O_2/L)
STP	standard temperature and pressure conditions (0 °C, 1 atm)
t_{80}	time required to reach 80% of the total methane production (d)
TN	soluble total nitrogen (mg/kg; mg/L)
TOC	total soluble organic carbon (mg/kg)
TS	total solids (g/kg)
VA	volatile acidity (mg C/L; mg C_2/kg; mg C/kg)
VS	total volatile solids (g/L; g/kg)
$Y_{CH4/S}$	methane yield coefficient (mL_{STP} CH_4/g VS)
WWTP	wastewater treatment plant

the treatment process.

As a suitable alternative for sewage sludge management, several authors have proposed the application of different pre-treatments, such as thermal, freeze/thaw, ultrasonic and/or chemical treatments in order to facilitate the hydrolysis of this waste and reduce the hydraulic retention time (Carrère et al., 2010; Carlsson et al., 2012; Martín et al., 2015). Therefore, it might be possible to treat larger amounts of sewage sludge in the same plant through the implementation of a pre-treatment step before anaerobic digestion. Moreover, this pre-treatment system could operate only when deemed necessary.

Microwave pre-treatment is one of the pre-treatment methods proposed in the literature for the solubilisation of sewage sludge and the enhancement of biogas production during biomethanisation. However, due to the diversity of the reported results, the suitability of implementing a microwave pre-treatment is not clear. Several authors have described a positive effect of microwave pre-treatment on biogas production as a consequence of the effective solubilisation of the organic matter during the process. This technique combines the effect of increasing temperature, as usually occurs with the application of other conventional thermal pre-treatments, and the disintegration of different compounds by the breakage of hydrogen bonds attributed to the rapidly changing dipole orientation in the polarised side chains of the cell membrane macromolecules (Park et al., 2004; Appels et al., 2013). Kuglarz et al. (2013), for example, reported an improvement in methane production of around 41–52% under temperatures of 60–70 °C after a microwave pre-treatment at 700 W or 900 W, with times from 58 to 493 s. Other authors have reported that the energy consumption of the pre-treatment is not compensated by the low methane enhancement (Mottet et al., 2009; Ariunbaatar et al., 2014). Nevertheless, most of these studies focus only on the variation in the soluble fraction of sewage sludge and the effect on biogas production or the energy balance between the pre-treatment requirements and the energy derived from the obtained methane. However, it is also necessary to evaluate the enhancement of the treatment capacity after applying this pre-treatment in order to increase the flexibility of the system for seasonal or occasional variations in the flow rate and characteristics of sewage sludge. Moreover, the implementation of a microwave pre-treatment could be very interesting to reduce the investment costs of enlarging plants or avoiding extra operational costs due to the oversizing of digesters.

The main purpose of this study is to optimize the microwave pre-treatment of sewage sludge at laboratory scale and evaluate its effects on a subsequent biomethanisation process, focussing on stability, methane production yield and particularly the kinetics of the process.

2. Materials and methods

2.1. Chemical analyses

The following parameters were determined in the solid fraction of sewage sludge before and after pre-treatment: total chemical oxygen demand (COD, g O_2/kg), total solids (TS, g/kg), total fixed solids (FS, g/kg), total volatile solids (VS, g/kg) and ammoniacal nitrogen ($N-NH_4^+$, mg/kg). Soluble chemical oxygen demand (sCOD, g O_2/kg), pH and conductivity (mS/cm) were also analysed to characterise the soluble fraction of the substrate. All analyses were carried out in accordance with the test methods for the examination of composting and compost developed by the US Department of Agriculture and the US Composting Council (Thompson et al., 2001). Additionally, total soluble organic carbon (TOC; mg/L) and total soluble nitrogen (TN, mg/L) were analysed using a Shimadzu TOC-VCPH combustion/non dispersive infrared analyser, which was calibrated with a standard solution of potassium phthalate prior to the TOC analyses. Separate volatile fatty acids (acetic, propionic, butyric, isobutyric, valeric, isovaleric and caproic acids) were also determined in the sewage sludge after extraction with distilled water (Thompson et al., 2001). The determination was carried out using a Hewlett- Packard HP-5890 gas chromatograph equipped with a 15 m × 0.53 mm (i.d.) Nukol-silica semicapillary column and a flame ionisation detector. The oven temperature was gradually increased from 100 to 150 °C at a rate of 4 °C/min. Helium (28.6 kPa) was used as carrier gas at a flow rate of 50 mL/min. Hydrogen (14.3 kPa) and air (28.6 kPa) were used together to ignite the flame of the FID. Additionally, the following parameters were determined in the effluents of the anaerobic reactors: pH, COD (g O_2/kg), sCOD (mg O_2/kg), TS (g/kg), FS (g/kg), VS (g/kg), TOC (mg/L), volatile acidity (VA, mg C/L), conductivity (mS/cm) and alkalinity (Alk, mg $CaCO_3$/L). All analyses were carried out in accordance with the Standard Methods of the APHA (APHA, 1989). Separate volatile fatty acids were also determined in the effluents of the digesters by the chromatographic method described previously.

2.2. Substrate

The raw material used as substrate was sewage sludge collected from the COPERO urban WWTP (Seville, Spain). A percentage as high as 85–90% of the influent of this WWTP is composed of municipal wastewater. The rest of the influent is industrial wastewater mainly derived from the agri-food industry. This WWTP generates sewage sludge at a flow rate of 500 tonnes per year, on dry basis. The sewage sludge was composed of primary and secondary sludge. The main analytical characteristics of the substrate are shown in Table 1. The sewage sludge was collected at different times from the WWTP to ensure it was fresh and to avoid uncontrolled fermentation process due to storage in the laboratory. Nevertheless, some variations in the physicochemical