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Effect of ultrasonication on anaerobic degradability of solid waste digestate

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ABSTRACT

This paper evaluates the effect of ultrasonication on anaerobic biodegradability of lignocellulosic residues. While ultrasonication has been commonly applied as a pre-treatment of the feed substrate, in the present study a non-conventional process configuration based on recirculation of sonicated digestate to the biological reactor was evaluated at the lab-scale. Sonication tests were carried out at different applied energies ranging between 500 and 50,000 kJ/kg TS. Batch anaerobic digestion tests were performed on samples prepared by mixing sonicated and untreated substrate at two different ratios (25:75 and 75:25 w/w). The results showed that when applied as a post-treatment of digestate, ultrasonication can positively affect the yield of anaerobic digestion, mainly due to the dissolution effect of complex organic molecules that have not been hydrolyzed by biological degradation. A good correlation was found between the CH_4 production yield and the amount of soluble organic matter at the start of digestion tests. The maximum gain in biogas production was 30% compared to that attained with the unsonicated substrate, which was tentatively related to the type and concentration of the metabolic products.

1. Introduction

The renewed interest in anaerobic digestion (AD) of biodegradable organic wastes stems from its ability to attain waste stabilization, at the same time exploiting the energy content of the waste. Moreover, the AD digestate, composed of partially stabilized organic matter, anaerobic biomass, inorganic matter and nutrients, may be suitable for utilization as an organic fertilizer or soil conditioner (Mata-Alvarez et al., 2014). Thus, AD contributes to concomitantly meet the targets of materials and energy recovery from wastes, along with the reduction of biodegradable waste landfilling. A variety of organic residues has been considered for biogas production, including pig, poultry and cow manure, cheese whey, maize silage, straw, residues from food preparation, olive mill residues, food and kitchen waste, as well as sludge from wastewater treatment plants. Although some of these wastes have been used, either individually or in co-digestion, for full-scale biogas production and although AD is a well-established technology, the identification of appropriate strategies aimed at further improving the overall process performance and stability is still a matter of concern. In particular, the maximization of both waste stabilization and conversion into biogas, as well as the improvement in digestate quality, appear as key targets to increase the competitiveness of the process. To this regard, one of the simplest strategies to improve the overall process yield is considered to be co-digestion of different residues. The advantages of co-digestion can be ascribed, for example, to the control of the organic load, the reduction of seasonal variability of individual waste streams, the supply of nutrients and active biomass, as well as the dilution of contaminants and inhibiting compounds. However, co-digestion may not be suitable for substrates containing high amounts of cellulose, hemicellulose and lignin (Zheng et al., 2014), which are all highly resistant to microbial degradation due to their structural and chemical properties. For such materials, dedicated more severe treatments are required to enhance the availability of substrate constituents to the biomass (Shah et al., 2015). Specifically, in order to convert lignocellulosic substrate into biogas, carbohydrates should be made available through the hydrolysis of the original complex molecules. However, the activity of hydrolytic microorganisms is limited by several factors, including operating parameters (e.g. pH and temperature) and substrate characteristics (e.g. lignin and hemicelluloses content; cellulose crystallinity and degree of polymerization; specific surface area and particle size distribution; cell wall thickness) (Hendriks and Zeeman, 2009). In order to enhance the hydrolysis of recalcitrant lignocellulosic substrates, pre/post-processing is required (Behera et al., 2014), which relies on various mechanisms (Carlsson et al.,

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2012): physico-mechanical (milling, grinding, ultrasonication), physico-chemical (steam explosion, wet oxidation, etc.), chemical (alkaline or acidic treatment, chemical oxidation and organic solvents treatment) or biological. So far, according to a review by Mata-Alvarez et al. (2014), research activities have been mainly focused on mechanical pre-treatments, followed by thermal and chemical pre-treatments. Among the investigated mechanical methods, ultrasonication (US) has been extensively applied for wastewater sludge processing as a means to produce particulate matter disintegration (Weemaes and Verstraete, 2005), enhance biodegradability (Khanal et al., 2007), minimize sludge production (Onyeche et al., 2002), reduce retention time (Tiehm et al., 1997) and increase the CH_4 yield (Barber, 2005). However, more recently, some authors have applied US to other substrates, such as manure (Castrillón et al., 2011; Elbeshbishy et al., 2011), food waste (Elbeshbishy and Nakhla, 2011; Jiang et al., 2014), agricultural wastes (Fernández-Cegrí et al., 2012), distillery residues (Sangave and Pandit, 2006) and by-products from bio-ethanol production (Cesaro et al., 2014).

The application of US to a liquid produces molecules oscillation around the average equilibrium position, resulting in a variation of their average relative distance. The increase in the relative distance among the molecules may turn into liquid breakdown and voids (cavitation bubbles) generation. If US intensities above 10 W/cm^2 are applied, transient cavitation bubbles are formed, reaching a radius size which is twice the initial value and collapsing violently upon compression (Santos and Lodeiro, 2009). Two phenomena result from cavitation bubbles collapse, namely the formation of high mechanical stresses causing both particulate matter disintegration and cells lysis, and the production of highly reactive radicals (such as hydroxyl radicals and hydrogen peroxide) potentially able to oxidize complex molecules (Badday et al., 2012; Luo et al., 2014).

Cavitation is known to be affected by a number of factors, including operating conditions (e.g., treatment duration and temperature, US frequency, power input), physico-chemical properties of the substrate (e.g., solids and lignin content, viscosity) as well as system design (e.g., reactor configuration, diameter and position of the transducer) (Gogate et al., 2011). The abovementioned factors may be interdependent, so that their mutual interactions become relevant, which also complicates the prediction of their overall effect on process kinetics and yield. Consequently, the comparison of results of different studies often shows inconsistencies due to the different experimental conditions adopted (e.g., substrate properties, power input and transducer design).

Despite so far US has been widely investigated as a method for substrate pre-treatment (Khanal et al., 2007; Pilli et al., 2011; Tyagi et al., 2014), a limited number of studies has been carried out to evaluate the ability of US to increase the biodegradability/bioavailability of recalcitrant organic compounds remaining in the digestate downstream of AD. Such a process scheme represents an innovative interesting option that, applying US to the sole hardly degradable fraction remaining after the digestion process, allows to exploit the residual energetic potential of the digestate and to increase the biological stability of the final residues, making US post-treatment of digestate technically and economically more attractive compared to its application ahead of AD. Literature studies on this topic for the digestate from the organic fraction of municipal solid waste are currently limited to a single publication (Cesaro et al., 2014), therefore there are numerous aspects involved that still deserve further investigation. Even the mechanisms of substrate dissolution upon sonication may differ depending on whether the treatment is applied as a pre-processing or as a post-processing step, since – as already mentioned above – the nature of the species involved changes even drastically as a result of AD.

In order to make a step forward to understanding the effect of US as a post-treatment on the biodegradability of food waste, in the present study a non-conventional process configuration based on sonicated digestate recirculation to the biological reactor was evaluated at the lab scale. The main aim of the present work was to evaluate the effect of sonication on both digestate properties and AD process performance, in terms of residual CH_4 production yield and kinetics.

2. Materials and methods

2.1. Substrate composition

The experimental campaign was carried out on a digestate sample (referred to as the substrate), collected at the outlet of a full-scale AD plant located in Central Italy, treating a mixture of organic wastes of a food industry, with high lignocellulose and fibers contents, and activated sludge from a wastewater treatment plant. Substrate samples were stored under controlled conditions at 4 °C and characterized for pH, Total Solids (TS), Volatile Solids (VS), Chemical Oxygen Demand (COD), $N\text{-}NH_3$ and metals content, which were determined according to APHA et al. (2005). The Total Organic Carbon (TOC) concentration was measured using a Shimadzu TOC analyzer equipped with a dedicated module for the analysis of solid samples. Dissolved organic carbon (DOC) and soluble COD (sCOD) were analyzed in the liquid phase after sample centrifugation at 5000 rpm for 15 min and subsequent filtration through a glass microfiber filter (1.2 μm pore size). Carbohydrates were analyzed using the colorimetric phenol–sulfuric acid method using glucose as the standard (Dubois et al., 1956). The metal content was determined using an atomic absorption spectrometer (Perkin Elmer Model 3030B) after sample digestion according to APHA et al. (2005).

The same analytical procedures were also adopted for the characterization of the mixtures subjected to the AD process (see Section 2.2.2).

The substrate properties are summarized in Table 1, where the average values and related standard deviations of three replicate measures are reported.

2.2. Experimental set-up

2.2.1. US treatment

A lab-scale ultrasound generator (model VCX 750, Sonics, USA) was used for the US treatment of the substrate. The US frequency and maximum power input were 20 kHz and 750 W, respectively.

Table 1
Substrate properties.

Parameter	Unit of measure	Average	Std. deviation
pH	–	7.6	0.1
TS	g/l	23.7	1.5
VS	g/l	16.3	1.0
TOC	g/l	8.2	0.4
DOC	g/l	0.5	0.04
COD	g/l	24.6	1.2
sCOD	g/l	1.5	0.3
Carbohydrates	g/l	3.2	0.4
Soluble carbohydrates	mg/l	63.6	15
$N\text{-}NH_3$	mg/l	610.4	35.7
Fe	mg/l	195	6.74
Mn	mg/l	3.5	0.09
Mo	mg/l	4.3	0.20
Co	mg/l	0.2	0.05
Ni	mg/l	0.6	0.02
Acetate	mg/l	124.0	12
Propionate	mg/l	60.6	22

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