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High temperature pyrolysis of sewage sludge as a sustainable process for energy recovery

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ABSTRACT

This study explored the potential of high temperature pyrolysis for energy recovery from domestic sewage. It mainly defines optimum operating conditions to maximize syngas generation. A pyrolysis unit was operated in batch mode, at temperatures of 450, 600 and 850 °C, rotation speeds of 10, 40 and 60 Hz. The sludge had 6% moisture content; it contained 65% organic matter and involved a low calorific value of 13.535 kJ/kg dry matter. Pyrolysis at 850 °C and high rotation speed of 60 Hz yielded the highest conversion of sludge to syngas, with an average of 59% of the organic matter as syngas, 29% as tar and 12% as biochar. Pyrolysis enabled 74% of the energy recovery as syngas and tar. Continuous full-scale pyrolysis systems would further increase the syngas by recovering condensable gaseous products and/or recycling tar back into the pyrolysis unit. A unified approach for energy recovery management should equally consider what fraction of the energy contained in the wastewater was consumed and wasted before generating the sludge. Therefore, the adopted management scheme should also cover all design and operation parameters of the treatment plant, because this is how the energy is best conserved even before the sludge is generated.

1. Introduction

In recent years, there has been a major shift in research efforts towards sustainable sludge management. The driving force of this shift was the ever-increasing cost of sludge disposal, accounting for a major fraction of the total cost of wastewater treatment (Wei et al., 2003). Therefore, the traditional approach primarily focused on minimizing sludge generation: a number of physical and chemical methods have been suggested to reduce the sludge generation potential of conventional treatment processes (Odegaard, 2004). Earlier studies attempted reducing sludge production by operating biological treatment plants at high sludge retention times as *extended aeration* systems; this mode decreased the amount of sludge but required excessive aeration (Orhon, 2015). Recently, new activated sludge modifications, such as the *OSA process*, have been developed to provide substantial reductions in sludge production (Novak et al., 2007; Chon et al., 2011; Yagci et al., 2015). Sludge management was also affected by the growing concern for low technology disposal and reuse practice. While landfilling is still implemented for the major portion of municipal sludge in EU countries, related regulations aim to minimize landfilling (EC, 1999); they now include constraints that may totally prohibit landfill applications rather than trying to reduce its adverse effects on the environment (Sözen et al., 2015). Similarly, reuse in agriculture is also advocated as a beneficial option for municipal sludge and practiced to a limited extent (Lederer and Rechberger, 2010). However, this is now estimated to be a much more sensitive disposal route as compared to landfilling, due to potential health risks (Horn et al., 2003; Hospido et al., 2010).

Increasing concerns and stringent limitations on traditional sludge disposal practice diverted the major interest towards the energy content of waste material, regarding sludge as an energy resource. The possibility of recovering this energy also affected the conventional biological treatment, which tends to minimize generated excess sludge at the expense of additional energy for stabilization. The energy recovery concept modified the biological treatment practice towards high rate systems enabling to harvest the maximum possible level of sludge for energy recovery. Studies have shown that a membrane bioreactor system operated at extremely low sludge ages would provide optimum energy conservation

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Nomenclature

A_2O	anaerobic-anoxic-oxic process	OMF	organic matter fraction
ASM	activated sludge model	OSA	oxic-settling-anaerobic
ASTM	American Society for Testing and Materials	RPM	revolutions per minute
COD	chemical oxygen demand	SFMBR	super-fast membrane bioreactors
CV	calorific value	VSS	volatile suspended solids
DM	dry matter	WWTP	wastewater treatment plant
HHV	higher heating value		
LHV	lower heating value		

in the sludge also including particulate COD entrapped onto biomass, while removing soluble COD and securing an effluent quality suitable for reuse (Başaran et al., 2012; Sözen et al., 2016). Studies estimated the energy equivalent of the organic matter (COD) in wastewater in the narrow range of 13.807–14.895 kJ/kg COD (Heidrich et al., 2011; McCarty et al., 2011). Depending on the type of selected biological treatment scheme, a fraction of this energy is transferred to generated sludge. The novel energy recovery concept should be designed to increase this fraction and to maximize energy recovery by novel processes (Garrido et al., 2013).

Anaerobic digestion is the traditional biochemical extension of conventional wastewater treatment for energy recovery, where biogas is obtained at the expense of partial biodegradation of the organic matter in sludge. Biogas recovery was first practiced in 1985, 20 years earlier than the discovery of activated sludge process, using the primitive version of anaerobic digestion (Bushwell, 1957). While biogas generation is useful, the process is quite ineffective: It only breaks down 35–50% of the COD/VSS in sludge and converts it into methane; it leaves behind a highly diluted, half stabilized sludge, which needs to be processed before final disposal (Svardal and Kroiss, 2011; Bolzonella et al., 2012). Aside from anaerobic digestion, energy recovery can also be accomplished by means of thermochemical processes, which include a range of technologies including gasification, pyrolysis, reforming and hydrothermal conversion, aiming to obtain similar end products, but often involve a series of chemical transformations (Luque et al., 2012).

Pyrolysis is one of the innovative technologies that has been extensively investigated and implemented in the past decades to recover energy from a wide range waste material ranging from feedstock; organic residues to plastics and many others (Fytili and Zabaniotou, 2008; Basu, 2010; Antoniou and Zabaniotou, 2013; Miandad et al., 2016a, 2016b, 2017a, 2017b). Briefly, the pyrolysis process involves heating and holding biomass for a specified time in the absence of oxygen, to disintegrate into various energy–rich products; the principle products are commonly defined as *syngas* (CO, H_2, CO_2, CH_4)*; tar, also known as bio-oil* (organic compounds with low volatility mixed with water) and *biochar,* the solid by-product. Depending on the selected pyrolysis temperature, the nature and composition of products may be changed. Most of the early studies were focused on *flash pyrolysis* at medium temperature to maximize bio-oil production (Scott et al., 1985; Piskorz et al., 1986; Yaman, 2004; Dominguez et al., 2005; Fonts et al., 2009; Zaimes et al., 2015). Aside the temperature, there are many parameters such as particle size, heating rate, residence time, and rotation speed in case of using a rotating reactor, which would affect the yield of the ultimate products along the process (Basu, 2010).

This study was basically conducted to evaluate and propose high temperature pyrolysis as a promising energy recovery alternative to the traditional anaerobic digestion of sludge. Essentially, this technology is not so widely applied at industrial level, especially not for sludge generated by sewage treatment. As summarized in Karaca et al. (2015), similar studies (Dominguez, 2006; Dominguez et al., 2008; Fonts et al., 2009; Zhang et al., 2011; Pedroza et al., 2014; Ospanov et al., 2015) were conducted to explore the energy recovery potential of pyrolysis from sewage sludge. As it will be analyzed in the following sections of the paper, these studies, although useful, were conducted as random research efforts, lacking the basic information for a unified evaluation. In this context, this work was basically focused on recognizing all the necessary parameters for defining a unified basis of high temperature pyrolysis of sewage sludge mainly aiming at syngas generation, emphasizing the influence of temperature and rotation speed on the composition of syngas. The results were compared with the expected outputs of anaerobic digestion based on comparison of the respective energy generation levels.

2. Materials and methods

2.1. Experimental rationale

The experimental study was designed to determine the energy recovery potential of high temperature pyrolysis from sewage sludge; it essentially aimed to uncover conditions that would maximize syngas generation, a product quite suitable to be used as a potential renewable energy supply that would replace natural gas after appropriate treatment. A laboratory scale pyrolysis system designed for batch mode operation was used for this purpose. The energy recovery achieved in the pyrolysis unit was evaluated in terms of solid (*biochar*), liquid (*tar*) and gas (*syngas*) components obtained at the end of batch operation; the variation in the relative magnitude of these components was observed as a function of selected operation conditions. In this study, pyrolysis temperature and rotation speed were chosen as the major parameters to determine the diversity of the products. The applied ranges for these two parameters were selected based on practical experience reported in the literature (Dümpelmann et al., 1991). The rotation speed was chosen to have a homogenous mixture in the system. The system should be well mixed in order to see how the sample thermally cracked within different temperatures. The system temperature was sequentially set at 450 °C, 600 °C, and 850 °C to represent the conditions for the low, medium and high temperature pyrolysis (Inguanzo et al., 2002; Dominguez 2006; Ospanov et al., 2015;). A similar approach was also accepted for the rotation speed, where 600 rpm, 2400 rpm and 3600 rpm were applied (Wagenaar et al., 1993; Pedroza et al., 2014; Liu et al., 2018). Rotation speed defines the number of turns of the pyrolysis reactor by time as revolutions per minute (1 rpm = 0.016 Hz) so the selected rotation speeds were identified as 10 Hz, 40 Hz and 60 Hz through the paper.

2.2. Experimental set-up

Dried sludge was subjected to pyrolysis in an electrically heated rotary kiln pyrolysis system. The rotary kiln pyrolysis set-up was