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Research article

Evaluation of the rotary drum reactor process as pretreatment technology of municipal solid waste for thermophilic anaerobic digestion and biogas production

Petros Gikas [a, b, *], Baoning Zhu [b, c], Nicolas Ion Batistatos [a], Ruihong Zhang [b]

[a] *Design of Environmental Processes Laboratory, School of Environmental Engineering, Technical University of Crete, Chania, 73100, Greece*
[b] *Department of Biological and Agricultural Engineering, University of California, One Shields Avenue, Davis, CA, 95616, USA*
[c] *Department of Environmental Science and Technology, Beijing University of Chemical Technology, Beijing, 100029, China*

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A B S T R A C T

Municipal solid waste (MSW) contains a large fraction of biodegradable organic materials. When disposed in landfills, these materials can cause adverse environmental impact due to gaseous emissions and leachate generation. This study was performed with an aim of effectively separating the biodegradable materials from a Mechanical Biological Treatment (MBT) facility and treating them in well-controlled anaerobic digesters for biogas production. The rotary drum reactor (RDR) process (a sub-process of the MBT facilities studied in the present work) was evaluated as an MSW pretreatment technology for separating and preparing the biodegradable materials in MSW to be used as feedstock for anaerobic digestion. The RDR processes used in six commercial MSW treatment plants located in the USA were surveyed and sampled. The samples of the biodegradable materials produced by the RDR process were analyzed for chemical and physical characteristics as well as anaerobically digested in the laboratory using batch reactors under thermophilic conditions. The moisture content, TS, VS and C/N of the samples varied between 64.7 and 44.4%, 55.6 to 35.3%, 27.0 to 41.3% and 24.5 to 42.7, respectively. The biogas yield was measured to be between 533.0 and 675.6 mL g^{-1}VS after 20 days of digestion. Approximately 90% of the biogas was produced during the first 13 days. The average methane content of the biogas was between 58.0 and 59.9%. The results indicated that the biodegradable materials separated from MSW using the RDR processes could be used as an excellent feedstock for anaerobic digestion. The digester residues may be further processed for compost production or further energy recovery by using thermal conversion processes such as combustion or gasification.

1. Introduction

A large fraction of municipal solid waste (MSW) consists of biodegradable organic materials. Some of these materials have been separated from the MSW and converted into compost (Onwosi et al., 2017). The compost can be used as soil amendment for agricultural or landscape applications (Martinez-Blanco et al., 2013; De Lucia and Christiano, 2015), although the quality of compost made from MSW and/or biosolids has been recently questioned (Cesaro et al., 2015) due to relatively high concentrations of pathogens (Sharma and Reynnells, 2016), harmful elements, such as heavy metals (Kupper et al., 2014), or recalcitrant organic substances (Kapanen et al., 2013). The economical value of the compost is usually low - often less than US$10/$m^3$ (Meyer-Kohlstock et al., 2013), thus the income alone from compost sales does not normally justify the investment unless other waste reduction and treatment objectives are strongly desired, including the reduction of biodegradable organics in landfills, which has been mandated in some countries by legislation and directives (European Communities June 1999).

Under appropriate conditions, the biodegradable materials can be digested by anaerobic microorganisms to produce biogas (Gikas, 2008; Zhang et al., 2014). Biogas can be collected and used as an alternative biofuel, which is highly desirable as the replacement of fossil fuels by biofuels is often subsidized by the national authorities (European Communities May 2003). In landfills, the

* Corresponding author. Design of Environmental Processes Laboratory, School of Environmental Engineering, Technical University of Crete, Chania, 73100, Greece.
E-mail address: petros.gikas@enveng.tuc.gr (P. Gikas).

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biodegradable materials are naturally degraded by indigenous microorganisms present in the waste and biogas is produced; however the degradation process may take many years to complete (Havukainen et al., 2014; Barlaz et al., 2002). Part of the biogas can be recovered using landfill biogas recovery systems, however, a significant amount of biogas inevitably escapes from the landfill (Frank et al., 2016). Methane release to the atmosphere contributes significantly to the creation of the greenhouse effect, as 1 kg of methane has the same effect as 21 kg of carbon dioxide (Intergovernmental Panel on Climate Change, 2001). The relatively low biogas production rate in landfills makes the economical return of the landfill gas recovery project not attractive in many cases. In geographic areas where the cost of land is relatively high, the use of high-rate anaerobic digestion processes has been proved not only to cause less environmental damage, but also to be more cost effective compared to landfilling (Edelmann et al., 2000). As the anaerobic digestion technologies of solid wastes improve, it becomes clear that the biogas recovery from the MSW prior to landfilling or composting can be technically feasible and financially sustainable (De Baere, 2006). Generally, thermophilic (~55 °C) anaerobic digestion has several advantages over mesophilic (~35 °C) anaerobic digestion in terms of volatile solids reduction, biogas yield, and pathogen reduction (Labatut et al., 2014; Mao et al., 2015). It is particularly favorable for biodegradable organics separated from MSW by mechanical methods (Bernal et al., 1992).

Using *in vessel* anaerobic digestion processes, a large fraction of the biodegradable organics in MSW can be converted to biogas within a relatively short time period (10–30 days). However, the heterogenic nature and large sizes of the MSW, makes difficult the controlled digestion of the raw MSW. Ideally, the anaerobic digestion process would preferably be applied only to the fraction which is rich in biodegradable compounds, after size reduction and separation. Common approaches for separating biodegradable organic materials include direct screening or a combination of size reduction and screening. For source separated wastes such as food and green wastes, direct screening may work well for removing large contaminants (e.g., plastics, metals). However, for the wastes that contain papers, cardboard and woody residues (e.g., tree trimmings), size reduction is often necessary in order to have them to pass the screens of 25–50 mm openings which are normally used to separate the food waste from the mixed MSW. Grinding and wet pulping/separation, autoclave and steam treatment and rotating drum reactor (RDR) are three major processes used by the waste processing industry. The organic materials produced from grinding and wet pulping/separation typically have a high moisture content of over 90% while the organic materials produced from autoclave steam treatment and RDR processes have a lower moisture content of 50–70%. A promising way for separating the biodegradable materials from MSW is by utilizing the rotary drum reactor (RDR) process (Hayes, 2004; Spencer, 2006; Kalamdhad and Kazmi, 2008). The RDR process is currently employed as pre-composting process in many MSW treatment plants, however, the MSW treated by the RDR process, has a high potential for biogas production (Zhu et al., 2009, 2010). During the RDR process, the MSW is subjected to both mechanical and biological breakdown and as a result, the biodegradable materials are reduced in particle sizes and can be separated from the larger biologically inert materials through screens. Market search indicated that the RDR process requires less capital and less energy (10–13 million US$ for a 100,000ton MSW/yr; 70–110 kWh/ton MSW).

The research presented in this paper was aimed at evaluating the potential for biogas production form MSW pretreated by the RDR process. For the above purpose, on-site surveying and sampling was conducted at six RDR facilities in USA; samples (the organic fraction of MSW) were collected and biogas production potential was evaluated experimentally. The research results are useful for developing an integrated system such as illustrated in Fig. 1 (A, B and C), which shows an RDR process followed by anaerobic digestion and composting. However, for the design of an industrial scale system, further studies will be conducted using continuous mode digesters.

2. Materials and methods

2.1. Description of the rotary drum reactor (RDR) process

The RDR process is an in-vessel aerobic digestion process, which has been used as a pretreatment process for the production of compost from solid wastes, such as MSW, biosolids, or animal manure. The initial RDR process was patented during the 1980s by Dr. Eric Eweson (Eweson and Eweson, 1991); it comprises an specially designed rotary drum, followed by solid-solid separation using trommel screens. The rotary drum is used to break down the biodegradable materials in the MSW through a combination of aerobic biological reactions and mechanical forces, thus making them easily separable, via screening, from the bulky materials, such as plastics metals and glasses. The separated biodegradable materials are often further processed for compost production.

A typical RDR system is schematically illustrated in Fig. 1A. The solid wastes (typically a mixture of MSW and biosolids) is initially placed onto a tipping floor, where bulky materials, usually recyclables (such as plastics, metals etc), are removed by hand or using automated screening processes. The waste is then fed into a large rotary drum resembling a cement kiln. Loading in the rotary drum is usually assisted by a hydraulic ram. The MSW is retained inside the drum for 6 h to 3 or more days, moving slowly from the one end (entrance) to the other end (exit) of the drum. The drum has headspace between 20 and 30% and usually operates as a continuous plug-flow reactor though it has also been used as a batch reactor. The movement of the materials through the drum is controlled by the loading rate of the fresh materials, which pushes the older materials in the drum towards the exit. In some cases, the movement of the materials can be controlled by the drum rotation speed, if multiple speed rotation mechanism is available. Some drums are compartmentalized by the use of specially designed baffles. The material is discharged from the exit of the drum through hydraulically or pneumatically controlled gates. The drum normally rotates at a constant speed, 1 to 5 rpm depending on the design characteristics of the plant. Some drums are equipped with multiple speed gearboxes, employing higher rotation speeds during the loading or unloading stages. The drums in the plants studied in this research had lengths of 9.1–73.1 m and the diameters of 3.0–4.9 m.

In most RDR facilities, air is blown into the drums from the unloading side to ensure aerobic conditions during processing. The optimum moisture content inside the drum is reported to be around 55%. As MSW in the countries of North America and Europe typically contains 35–40% moisture, water or other wet materials, such as biosolids of 75–95% moisture content, are added into the drum together with the MSW. The heat produced from the microbial degradation of MSW inside the drum allows the temperature to rise and be maintained at a relatively high level (50–69 °C).

After leaving the rotary drum, the treated MSW is screened (primary screening) through a trommel screen with openings of 2.5–4.5 cm. The materials retained over the screen (mainly plastics, fabrics, glass and metals) are collected for recycling or for disposal in a landfill. The materials that pass through the screens are mainly biodegradable materials; they are collected and sent to the composting operation (dashed arrow in Fig. 1). In most composting plants, the organics are composted in piles over aerated floors for 4

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