Waste Management 33 (2013) 1425–1433

Contents lists available at SciVerse ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Enhancement of the anaerobic hydrolysis and fermentation of municipal solid waste in leachbed reactors by varying flow direction during water addition and leachate recycle

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ARTICLE INFO

Article history:
Received 22 August 2012
Accepted 22 February 2013
Available online 28 March 2013

Keywords:
Chemical oxygen demand
Leachate production
Leachate recycle
Leachbed reactor

ABSTRACT

Poor performance of leachbed reactors (LBRs) is attributed to channelling, compaction from waste loading, unidirectional water addition and leachate flow causing reduced hydraulic conductivity and leachate flow blockage. Performance enhancement was evaluated in three LBRs M, D and U at 22 ± 3 °C using three water addition and leachate recycle strategies; water addition was downflow in D throughout, intermittently upflow and downflow in M and U with 77% volume downflow in M, 54% volume downflow in U while the rest were upflow. Leachate recycle was downflow in D, alternately downflow and upflow in M and upflow in U. The strategy adopted in U led to more water addition (30.3%), leachate production (33%) and chemical oxygen demand (COD) solubilisation (33%; 1609 g against 1210 g) compared to D (control). The total and volatile solids (TS and VS) reductions were similar but the highest COD yield (g-COD/g-TS and g-COD/g-VS removed) was in U (1.6 and 1.9); the values were 1.33 and 1.57 for M, and 1.18 and 1.41 for D respectively. The strategy adopted in U showed superior performance with more COD and leachate production compared to reactors M and D.

1. Introduction

Anaerobic digestion (AD) of high solids waste streams such as the organic fraction of municipal solid waste (MSW), agricultural residues and animal manure presents challenges for continuous flow conventional digestion systems, either wet or dry. Wet systems with total solids TS content at 10% or less utilise large volumes of water leading to large reactors (Hall et al., 1985). This coupled with mixing requirements results in high investment cost, increased heating requirement, the need for dewatering and liquid effluent disposal problems thereby decreasing the benefits of conventional slurry AD systems (Demirer and Chen, 2008). Dry systems with TS content of 20% or more present problems of handling, mixing and pumping solid streams and the equipment required is expensive (Lissens et al., 2001). Several researchers have studied LBRs to assess their benefits for the treatment of high solids waste streams (Chugh et al., 1999; Demirer and Chen, 2008; Dogan et al., 2008; Ghanem et al., 2001; Han et al., 2002; Hegde and Pullammanappallil, 2007; Koppar and Pullammanappallil, 2008; Lai et al., 2001; Myint and Nirmalakhandan, 2009; Silvey et al., 2000; Veeken and Hamelers, 2000; Vieteiz et al., 2000)..

Leachbed reactors, variously known as percolating anaerobic or dry AD (Demirer and Chen, 2008), or batch-wise solid state digestion – BSSD (Veeken and Hamelers, 2000), are single stage reactors operated in batch mode in which leachate sprayed on top of the waste is collected at the bottom. Leachate collected from the bottom of the reactor is circulated back into the solid waste bed to increase the moisture content, promote mass transportation, redistribute the enzymes and microbes and minimise nutrient deficiency (Lu et al., 2008). Its development arose from efforts to improve the degradation rates and enhance biogas production in landfills.

Leachbed reactors can handle wastes without any pretreatment such as sieving and particle size reduction (Ten Brummeler, 2000) and together with the simple batch process results in low construction and operating costs compared to other AD technologies (Veeken and Hamelers, 2000). There is no mixing or agitation of the digester contents and with minimal water requirement, the energy input for either heating or mixing is low (Dogan et al., 2008). It has also been observed that leachbed reactors operating at mesophilic temperatures lead to the inactivation of pathogenic micro-organisms (Ten Brummeler, 2000; Turner et al., 1983) and this has been attributed to high peak concentrations of volatile fatty acids (VFAs) in leachbed reactors compared to continuous systems.

The major challenge in the utilisation of LBRs in single stage mode is the high volume of seeding material required to prevent

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http://dx.doi.org/10.1016/j.wasman.2013.02.020

irreversible acidification during the start-up process (Hegde and Pullammanappallil, 2007; Ten Brummeler and Koster, 1990). Operation of leachbed reactors in two stages overcomes this imbalance by separating the acid and the methane phase. The leachbed is operated in the acid phase with the leachate produced pumped to a methane phase digester where the COD laden leachate is converted to biogas.

Conventionally, liquid addition to LBRs is by spraying onto the top of the waste after which it traverses the waste bed and flows through a perforated floor to a reservoir at the base of the reactor. Similarly, leachate recycle entails pumping from the reservoir onto the top of the waste bed for downward flow under gravity. Water addition and leachate recycle in the downward direction is maintained throughout the digestion period. However the yield of biogas from LBRs is about 40% smaller than continuously fed one stage systems treating the same type of waste (De Baere, 2000). This has been attributed to a variety of factors including leachate channelling in which leachate flows through preferential paths within the waste fabric leading to non-uniform degradation of the waste material (Lissens et al., 2001; Nopharatana et al., 2003). There is also the problem of increasing density of the waste due to a combination of its own mass and water flow which decreases the porosity and the hydraulic conductivity (Staub et al., 2009). Density is related to void ratio, fabric and pore geometry and is therefore important to hydraulic conductivity of MSW in landfills and leachbed digesters (Chen and Chynoweth, 1995). Fowler and Robertson (1991) studied the hydraulic permeability of immobilised cell aggregates and observed that cell alignment in the direction of flow increased with time thereby reducing the void ratio which they related to decreased hydraulic conductivity. Similarly, Chen and Chynoweth (1995) measured the hydraulic conductivity of MSW and suggested that relative movement of fine particles, including cells, could play a significant role in reducing hydraulic conductivity by creating a denser matrix. From the foregoing, it is hereby inferred that intermittent change in the direction of water addition and leachate recycle would redistribute particles, enhance mixing, hydraulic conductivity and improve leachate flow.

The intention in this study was to investigate the impact of a change in the direction of water addition and leachate recycle in enhancing hydraulic conductivity in leachbed reactors. Specifically, the objective of the study was to investigate the enhancement of waste degradation in leachbed reactors by changing the direction of flow during water addition and leachate recycle. Performance would be assessed on the basis of cumulative water addition and leachate produced, total and volatile solids (TSs and VSs) reduction, and on the pH, soluble COD, VFA and ammonia nitrogen mineralised in the leachate.

2. Materials and methods

2.1. Waste feedstock and inoculum

The material consisted of municipal solid waste collected from the in-vessel composting site of TEG environmental based in Todmorden, West Yorkshire in the UK. The material was shredded within 2 days of being brought to the site using an industrial shredder. The size after shredding varied from fine particulates (⩽2 mm) to a maximum size of 10–12 mm pieces. The shredded material was collected using plastic buckets and was immediately stored in a deep freezer maintained at −20 °C until it was required for the experimental work. The digestion experiments were conducted without further shredding of the waste but visible, undigestible materials including plastics, bones, woody materials and twigs were removed by hand. The characteristics of the material including the wet mass and volume loaded into the reactors are shown in Table 1.

The inoculum used was digested sewage sludge collected from Yorkshire Water's wastewater treatment plant in Dewsbury, West Yorkshire in the UK. The inoculum was acclimatised to the waste material for about a month before digestion experiments were started.

2.2. Digester design

Three LBRs M, D and U consisting of cylindrical sections made from transparent plastic material were constructed. The digester's height and diameter were 247 mm by 286 mm respectively. Each digester has an inlet port 8 mm diameter for liquid inflow and leachate recycle. A drain port, 8 mm diameter, on the reactor wall was located 25 mm from the base allowing for 450 ml of liquor to remain in the reactor to prevent the washout of micro-organisms during effluent drainage. Gas ports were also located on top of the reactors for biogas collection via a water displacement system. Each digester had a stainless steel mesh of 10 mm by 10 mm square at a distance of 25 mm from the bottom of the reactors to support the waste material with a finer screen mesh 1.98 mm by 1.98 mm placed on top. A similar mesh screen was located on a support 50 mm from the top of the reactor to prevent fine particulates from escaping either from the top or bottom of the reactors. Spiral sprinkler irrigation systems made from a tubular polythene pipe 8 mm in diameter was used on top of the reactors to ensure uniform water addition for flow in the downflow direction. A schematic of the three reactor systems is shown in Fig. 1. The design enabled water addition to be controlled separately from the leachate recycle.

2.3. Water addition and leachate recycle strategy

Three different water addition and leachate recycle strategy were adopted. In reactor D, water addition and leachate recycle (15 min/day at 400 ml/min) was from top to bottom throughout the experiment and this served as control. In reactor M, about three-quarter (76.6%) of the volume of water added was in downflow direction while 23.4% was in the upflow direction. However leachate recycle was carried out in alternate directions at 15 min/day (7.5 min per direction at 400 ml/min). In reactor U, 54.3% of the total volume of water added was downflow while 45.7% was upflow, but leachate recycle (15 min/day at 400 ml/min) was in the upflow direction throughout. In M, initial water addition was downflow; after leachate withdrawal further water addition was downflow until day 6 when some water was added in the upflow direction. In U, initial water addition was upflow until day 6 when some water was added in the downflow direction. Details of the volume of water added and the direction of flow are shown in Table 2.

2.4. Experimental procedure

The LBRs were loaded once with the MSW and unloaded after the hydrolysis and fermentation experiment was completed. Initially 2 l of tap water mixed with 1.5 l of anaerobic seed was added in the reactors using peristaltic pumps, followed by the addition of extra 2.5 l of tap water from overhead tanks bringing the total liquid added to all the reactors to 6 l. All subsequent water additions to the reactors were from overhead tanks via gravity flow. After initial addition of water and seed mixture, the LBRs were sealed and the air spaces were filled with nitrogen gas to quickly initiate anaerobic conditions. They were operated in saturation mode with water maintained at a constant level and the waste submerged throughout. They were operated as hydrolysis/