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Evaluating leachate recirculation with cellulase addition to enhance waste biostabilisation and landfill gas production

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A B S T R A C T

The effect of leachate recirculation with cellulase augmentation on municipal solid waste (MSW) biostabilisation and landfill gas production was investigated using batch bioreactors to determine the optimal conditions of moisture content, temperature and nutrients. Experimentation was thereafter scaled-up in 7 L bioreactors. Three conditions were tested including (1) leachate recirculation only, (2) leachate recirculation with enzyme augmentation and (3) no leachate recirculation (control). Cumulative biogas production of the batch tests indicated that there was little difference between the leachate and control test conditions, producing on average 0.043 m^3 biogas kg^{-1} waste. However the addition of cellulase at 15×10^6 U $tonne^{-1}$ waste doubled the biogas production (0.074 m^3 biogas kg^{-1} waste). Similar trend was observed with the bioreactors. Cellulase addition also resulted in the highest COD reduction in both the waste and the leachate samples (47% and 42% COD reduction, respectively). In both cases, the quantity of biogas produced was closer to the lower value of theoretical and data-based biogas prediction indicators (0.05–0.4 m^3 biogas kg^{-1} waste). This was likely due to a high concentration of heavy metals present in the leachate, in particular Cr and Mn, which are known to be toxic to methanogens.

The cost-benefit analysis (CBA) based on the settings of the study (cellulase concentration of 15×10^6 U $tonne^{-1}$ waste) showed that leachate bioaugmentation using cellulase is economically viable, with a net benefit of approximately €12.1 million on a 5 Mt mixed waste landfill.

1. Introduction

In recent years, advances in the field of integrated waste management and better understanding of landfill processes, such as municipal solid waste (MSW) decomposition, has led to a re-evaluation of traditional landfill management practices (Hettiaratchi et al., 2015; Warith, 2002). In particular, there has been focus on the improvement of existing landfill technologies from a storage/containment based operation towards more sustainable and resource efficient activities (Townsend et al., 2015; Warith, 2002). Several methods have been studied over the past years to facilitate and enhance waste degradation within a landfill site. These include waste shredding, waste compaction, pH adjustment, nutrient balance, sludge addition and leachate recirculation (Jayasinghe et al., 2011; Cirne et al., 2007; Sponza and Agdag, 2005).

In particular, the recirculation of leachate as part of the 'bioreactor landfill' model has received much attention due to its widespread success, in both small and large scale applications (Liu et al., 2014; Nair et al., 2014; Rastogi et al., 2014; Reinhart et al., 2002; Reinhart, 1996a,b; Lagerkvist and Chen, 1993). The recirculation of leachate facilitates the rapid transformation and degradation of landfilled waste which promotes landfill space reduction and maximises biogas production. These benefits can be further used as a source of renewable energy and reduces environmental disamenity (Nair et al., 2014; Liu et al., 2014; Rastogi et al., 2014; Reinhart et al., 2002; Clarke, 2000). It further closes the resource loop allowing leachate to be used towards more economically and environmentally beneficial activities (Xu et al., 2014; Reinhart et al., 2002).

The degradation of the waste in a landfill site is facilitated by a consortium of microorganisms (Barlaz et al., 1990) and therefore any environmental modifications or bioengineered solutions need

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careful considerations. Leachate recirculation can affect the active microbial communities as the introduction of leachate can affect pH, temperature, oxidation/reduction potential as well as complex biochemical reactions necessary for microbial waste degradation (Mudhoo and Kumar, 2013; Barlaz et al., 1990). Furthermore, the recirculation of leachate can also introduce a combination of heavy metals, contaminants and xenobiotics in varying amounts which affect microbial communities (Chen et al., 2008; Bilgili et al., 2007a). This has been highlighted in a number of key studies (Zornoza et al., 2015; Mudhoo and Kumar, 2013; Frostegård et al., 1993).

The most common heavy metals found in leachate are: iron (Fe), cadmium (Cd), chromium (Cr), copper (Cu), zinc (Zn), nickel (Ni) and lead (Pb) (Mudhoo and Kumar, 2013; Bilgili et al., 2007a). Fe has been reported to have stimulatory effects on microbial communities involved in waste degradation at concentrations below 8.1 mmol L^{-1} and be inhibitory at concentrations above (Gonzalez-Silva et al., 2009). Cu, Zn, Cd and Pb have been shown to be highly toxic to microbial biochemical reactions. They increase in their inhibitory effect as follows: Pb < Zn < Cu < Cd (Mudhoo and Kumar, 2013). Therefore, while the recirculation of leachate results increases moisture content required for optimal waste degradation, its introduction also requires stringent process control to minimise its associated deleterious effect on the active microbial community.

Another important feature to take into consideration when evaluating technologies to facilitate waste degradation is the waste composition of landfill sites. Approximately 40–50% of landfill space is comprised of paper and cardboard, of which lignocellulose is a major component (Yuan et al., 2014; Kovacs et al., 2009). Lignocellulose is composed of carbohydrate polymers, cellulose (most prominent) and hemicellulose as well as aromatic polymer, lignin (Yuan et al., 2014). Within a waste mass, lignocellulosic materials are considered recalcitrant as difficult to degrade under anaerobic conditions (Pareek et al., 1998). A technique to enhance the degradation of residual waste fractions, with particular application towards difficult to degrade materials, is the addition of enzymes (Zheng et al., 2014; Jayasinghe et al., 2012, 2011; Lin et al., 2010; Romano et al., 2009). In particular, degradation of cellulose to soluble sugars and glucose is catalysed by a group of enzymes called cellulases, which include: *endo*-1,4-β-D-glucanase, *exo*-1,4-β-D-glucanase and β-glucosidase. Industrial grade cellulases have been successfully used for lignocellulose degradation in many industries (Kuhad et al., 2011).

Enzymes, however, have historically been an expensive commodity which has hindered its application in waste management practices. Recent developments in biotechnology coupled with reduced costs of manufacturing (particularly in China) have led to the use of enzyme to improve landfill gas production to be considered.

The waste used in this work comes from a site which has recorded declining biogas production over the past several years, even when taking into account the changes in waste composition prescribed by the Waste Framework Directive (2008/98/EC). The aim of the work was to investigate a cost effective and easy treatment to increase biogas output in landfill by examining the effect of leachate recirculation with and without a low-cost cellulase addition on waste stabilisation and biogas production. Additionally, a cost-benefit analysis (CBA) of leachate recirculation with enzyme addition was completed in order to inform commercial strategy. To the best knowledge of the authors, leachate recirculation with enzyme augmentation is a relatively new concept and to date there is little information available on its viability or commercial applicability at landfill site (Cirne et al., 2007; Lagerkvist and Chen, 1993).

2. Methods

2.1. Waste and leachate origin and sampling procedure

Ten municipal solid waste samples were collected from five drilled cores at depths of 10, 15, 20 and 25 m from a landfill site in the UK opened in 1992 and closed in 2012. The age of the waste material used in the work ranges approximatively between 5 and 20 years old. Details of the landfill site are presented in Table 1. The site was selected on the basis that there has been declining biogas production at the site over the past several years (from 3000 to 2200 $m^3 h^{-1}$) and the reason for this has been to date largely unaccounted for. The site therefore represented an opportunity to evaluate the influence of alternative site management strategies on biogas production. Untreated leachate used for recirculation was collected from the same landfill site in 2014 and was stored in a cold room at 4 °C until use.

2.2. Waste and leachate characterisation

2.2.1. Waste composition

Waste composition was analysed according to international standard ASTM D 5231-92 (2003) (AbdAlqader and Hamad, 2012; Gidarakos et al., 2006). The composition of plastics, paper, organic, textiles, glass and metal and was determined by manually weighing each component of the total waste fraction using a kitchen scale.

2.2.2. TS, TSS, VS, pH and sCOD

To obtain a representative waste sample for characterisation, waste samples from all depths were combined, then cone and quartered according to Rubio and Ure (1993). Solid waste and leachate was characterised in terms of total solids (TS), volatile solids (VS), soluble chemical oxygen demand (sCOD) and pH according to Standard Analytical Methods published by the American Public Health Association (APHA, 2005). sCOD was conducted using Merck COD test kits (range 100–1500 mg L^{-1} or 500–10,000 mg L^{-1}) in duplicate due to reliability of test kits while all other tests were conducted in triplicate. TS, VS, sCOD and pH were determined before and after completion of the pilot scale bioreactors experiment in order to understand the effect of leachate recirculation on the physicochemical conditions of the system. Total suspended solids (TSS) were determined by filtering a known amount of leachate through glass microfibre filter paper (70 mm diameter). The filter was then dried in an oven at 105 °C for 24 h and weighted.

2.2.3. Field capacity

Field capacity (FC) test was conducted to determine the amount of leachate that would be required to bring the waste mass to

Table 1
General information on landfill sites.

Parameter	Values
Landfill age	20 years
Waste tonnage	4.6×10^6 tonnes
Average waste density	950 kg m^{-3}
Average waste moisture content (MC)	37%
Average volatile solids (VS)	32%
Average chemical oxygen demand (COD)	545 mg L^{-1}
Methane content of landfill gas	40–49%
Landfill gas generation (average value)	
2000–2008	3000 $m^3 h^{-1}$
2008–2012	2200 $m^3 h^{-1}$
2012–2014	1650 $m^3 h^{-1}$