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Theoretical analysis of municipal solid waste treatment by leachate recirculation under anaerobic and aerobic conditions

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ABSTRACT

Long-term emissions of Municipal Solid Waste (MSW) landfills are a burden for future generations because of the required long-term aftercare. To shorten aftercare, treatment methods have to be developed that reduce long-term emissions. A treatment method that reduces emissions at a lysimeter scale is re-circulation of leachate. However, its effectiveness at the field scale still needs to be demonstrated. Field scale design can be improved by theoretical understanding of the processes that control the effectiveness of leachate recirculation treatment. In this study, the simplest and most fundamental sets of processes are distilled that describe the emission data measured during aerobic and anaerobic leachate recirculation in lysimeters. A toolbox is used to select essential processes with objective performance criteria produced by Bayesian statistical analysis. The controlling processes indicate that treatment efficiency is mostly affected by how homogeneously important reactants are spread through the MSW during treatment. A more homogeneous spread of i.e. oxygen or methanogens increases the total amount of carbon degraded. Biodegradable carbon removal is highest under aerobic conditions, however, the hydrolysis rate constant is lower which indicates that hydrolysis is not enhanced intrinsically in aerobic conditions. Controlling processes also indicate that nitrogen removal via sequential nitrification and denitrification is plausible under aerobic conditions as long as sufficient biodegradable carbon is present in the MSW. Major removal pathways for carbon and nitrogen are indicated which are important for monitoring treatment effectiveness at a field scale. Optimization strategies for field scale application of treatments are discussed.

1. Introduction

A major challenge for this human generation is to develop treatment methods that reduce long-term emissions from Municipal Solid Waste (MSW) landfills. Because landfills can emit gas and leachate for hundreds of years (Belevi and Baccini, 1989), they pose a risk for human health and the environment. Long-term aftercare is required which puts a burden on future generations.

Reduction of long-term emissions can be achieved by accelerating degradation within a waste-body (Scharff et al., 2011) which is normally slow due to inhibitions and transport limitations (Kjeldsen et al., 2002; Laner et al., 2011; Meima et al., 2008). Enhanced degradation leads to accelerated release of carbon and nitrogen containing compounds. In the case of methane, accelerated release is also economically attractive because this gas can be utilized as an energy source.

Treating MSW by recirculating leachate under anaerobic or aerobic conditions has shown to accelerate emissions in experiments at a lysimeter scale (Veeken et al., 2000; Kasam et al., 2013; Erses et al., 2008; Brandstätter et al., 2015a; Brandstätter et al., 2015b; Bilgili et al., 2007). By inducing (increased) water flow, leachate recirculation stimulates mixing of solutes and bacteria within the waste body which removes inhibitions and transport limitations for degradation (White et al., 2011). Dissolved compounds in the leachate are furthermore removed by bleeding of the leachate stream. Normally, the enhanced consumption of readily available electron acceptors leads to strictly anaerobic conditions.

In order to generate (partly) aerobic conditions, leachate recirculation can be combined with aeration (Ritzkowski and Stegmann, 2012). This has two main advantages: aerobic degradation is generally faster than anaerobic degradation (Heijnen and

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Kleerebezem, 1999) and ammonium can be removed by oxidation to nitrogen gas via subsequently nitrification and denitrification (Bolyard and Reinhart, 2016).

Although effective in enhancing biodegradation, full-scale application of leachate recirculation or aeration has not yet been proven to reduce long-term leached emissions (Benson et al., 2007; Hrad et al., 2013). Apparently, the understanding of processes that control the effectiveness of these treatments is insufficient and needs to be improved. We believe that a good point to start is to revisit data obtained in lysimeter experiments and to distill the simplest, most fundamental biogeochemical process networks that explain the measured emissions.

A fundamental model that is as 'simple' as possible highlights the controlling processes, reactions and factors that drive (measured) emissions. It allows to identify major and minor degradation and transport pathways and rate-limiting factors. Moreover, such a model provides insight in any specific mass balance which is not directly measured in the context of the processes, inhibitions and limitations. The challenge, however, is to identify which combination of fundamental processes are least ambiguous (or subjective) and contain minimal uncertainty. We use the toolbox developed by van Turnhout et al. (2016) to find the most simplistic and best describing fundamental model; it allows to integrate several environmental frameworks, quickly build different models and compare performances objectively with a set of qualitative and quantitative criteria.

This paper presents the least ambiguous biogeochemical process networks that are responsible for the emissions measured in lysimeter experiments performed by Brandstätter et al. (2015a, b). With these networks, the processes and factors controlling the effectiveness of the applied anaerobic and aerobic leachate recirculation treatment are discussed. Major and minor removal pathways for carbon and nitrogen compounds are presented. Implications of the findings for full-scale treatment design are given together with suggestions for improvement.

2. Material & methods

2.1. Characteristics of the lysimeter experiments

For this study we used the data measured in two lysimeter experiments of Brandstätter et al. (2015a,b). In both experiments leachate was recirculated and the temperatures in the lysimeters were kept constant (~ 309 K). To allow for drainage of leachate by gravity, a fine meshed grid of 8 cm was placed at the bottom of the reactors. Leachate removed during sampling was replaced with distilled water (Aqua dest) to maintain the degree of water saturation.

In one experiment the conditions were anaerobic and in the other (partly) aerobic due to continuous injection of air. The experiments were carried out in duplicate on MSW which was mined from a landfill where operations stopped 40 years ago. The MSW was sieved to a grain size of <20 mm. In the reactors, the MSW had initially a water content of 23% and a dry bulk density of 846 $\frac{kg}{m^3}$. An illustration of both set-ups is presented in Fig. 1 and the initial and environmental conditions are listed in Table 1.

From each experiment, the following time series are used which were measured over 2.25 years: cumulative produced biogas (CO_2 and CH_4), partial pressure of CO_2, CH_4 and O_2, pH, Biological Oxygen Demand (BOD), NH_4^+ and Cl^- concentrations. One time series of each experiment was used for calibration and the other for validation. The calibration dataset was used to find the least ambiguous process network with the toolbox developed by van Turnhout et al. (2016). Subsequently, the network was tested on the validation dataset without further parameter fitting.

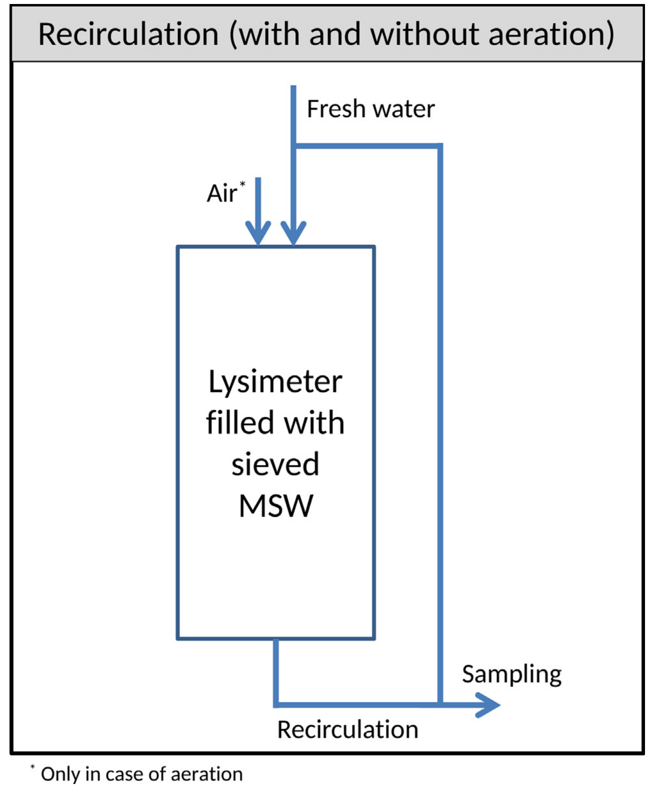

Fig. 1. Illustration of the experimental set-ups for leachate recirculation under anaerobic and aerobic conditions (Brandstätter et al., 2015a; Brandstätter et al., 2015b). The lysimeters were made of stainless steel and had a cylindrical shape with a volume of 121 L.

Although the MSW was mined from a 40 year old landfill, it contained a significant percentage of readily degradable organic content such as cellulose (Brandstätter et al., 2015a). This can be explained by the heterogeneity of landfill bodies which can cause many types of local limitations and inhibitions on the degradation of its organic content.

In order to arrive at a generic modeling framework, average compositions of the biodegradable fraction of Solid Organic Matter (SOM) of $C_6H_{10}O_5N_{0.036}$ and $C_6H_{10}O_5N_{0.032}S_{0.03}$ are used for respectively the anaerobic experiment and the aerobic experiment following generic principles of anaerobic digestion modeling ((Batstone et al., 2002; Reichel et al., 2007)). The fractions of nitrogen and sulfur are deduced from the fractions measured in the MSW at the beginning and the end of the experiment. Because sulfur was not significantly detected under anaerobic conditions, it was not considered in the model. Most likely, the released sulfur under anaerobic conditions was immediately converted into H_2S. For generic purposes, BOD is assumed to consist of Acetic Acid which accumulates strongest when methanogenesis is rate-limiting. The elemental composition of bacteria of $CH_{1.4}O_{0.4}N_{0.2}$ is taken from Henze et al. (1995).

2.2. Selecting the least ambiguous biogeochemical process network to describe measured data

Fig. 2 shows the approach to select the least ambiguous biogeochemical process network describing the measured data (van Turnhout et al., 2016). First, a model structure is build to be evaluated. Relevant kinetic, equilibrium, transfer and transport reactions within a multiphase environment are selected together with appropriate environmental inhibitions and limitations. Fundamental parameters can be obtained from an extensive