Optimizing Bioreactor Landfills: Biogas Production and Nitrogen Biotransformation

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Pollution and Environmental Microbiology, Spring 2007

Introduction

As the American public becomes more aware of the current energy crisis, the search for sufficient quantities of renewable energy to offset current fossil fuel utilization and keep pace with increasing energy demand is ever growing. Sustainable renewable energy cannot be obtained from a single source; a combination of sources such as wind, solar, hydroelectric, geothermal and biomass will be needed.

Municipal solid waste (MSW) naturally decomposes to produce carbon dioxide (CO2) and methane (CH4), a fuel gas, and bioreactor landfill technology (Figure 1) can be employed to enhance waste degradation and biogas recovery. Thus, MSW should be viewed as a fuel, and solid waste management systems should be optimized to maximize biogas generation (through the stimulation of methanogens) and collection, while minimizing energy demands. A dynamic energy balance for Burlington County's (New Jersey, USA) bioreactor landfill was developed to quantify the potential energy recovery from landfill biogas versus the energy consumed during regular landfill management (Equation 1).

Some of the energy consumed comes from the need to treat heavily ammonia-loaded leachate and ship it to a wastewater treatment facility for disposal. Classical methods for treating ammonia-rich leachate include stimulating nitrification followed by denitrification in various types of reactors, chemical precipitation, nanofiltration, and air stripping [3]. These methods are very costly and must be done ex-situ.

A newly discovered anaerobic ammonium oxidation (ANAMMOX) pathway (Equation 2) has been described in wastewater treatment plants as well as marine sediments [4-7] and research is currently underway for finding anammox capable species in a bioreactor landfill system [2]. Unlike methanogenesis where there are several archeal species capable of producing methane, there are only 4 known deeply branching *Planctomycetales* capable of catalyzing anammox [4-7]. In a bioreactor landfill system, it is likely to be easier to stimulate methanogenesis than anammox, however ammonia treatment is a large cost for the landfills and should be dealt with in the most efficient manner; currently, this involves stimulating anammox as well as methanogens within the same system.

Nitrogen Transformation

$$NH_4 + 1.26NO_2^- + 0.085CO_2 + 0.02H^+ \rightarrow N_2 + 0.017H^+ + 0.24NO_3^- + 1.95H_2O$$

Equation 2 - Anammox uses ammonium as the electron donor and nitrite as the electron acceptor in a ratio of approximately 1:1. Change in Gibbs free energy is -357 kJ/rk.

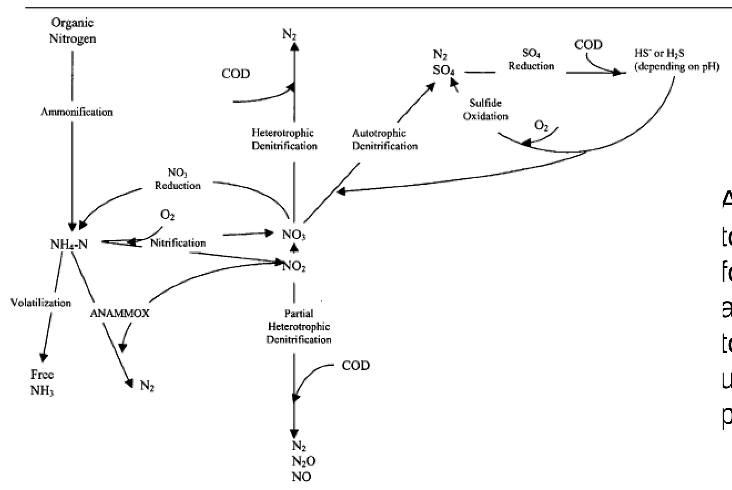

Figure 3 - Potential pathways of nitrogen transformation and/or removal in bioreactor landfills [3].

Table 1

Parameters of aerobic and anaerobic ammonia oxidation.

Parameter	Nitrification $NH_4^+ + O_2 \rightarrow NO_2^-$	Anammox $NH_4^+ + NO_2^- \rightarrow N_2$	Unit
Free energy	–275	–357	kJ/mol
Biomass yield	0.08	0.07	mol/mol C
Aerobic rate	200–600	0	nmol/min/mg protein
Anaerobic rate	2	60	nmol/min/mg protein
Growth rate	0.04	0.003	/h
Doubling time	0.73	10.6	days
K_s NH_4^+	5–2600	5	μM
K_s NO_2^-	N/A	<5	μM
K_s O_2	10–50	N/A	μM

N/A, not applicable; K_s, affinity constant.

Table 1 - aerobic vs. anaerobic ammonia oxidation [8]

As opposed to chemical treatment methods which are expensive to employ, environmentally harmful, and result in additional costs for shipping the leachate to an off-site treatment facility, anammox is "green technology" at a minimal price. When trying to engineer an ammonia treatment strategy, it is important to utilize "tools" are already in place (i.e. the current microbial population) that just need to be stimulated or enhanced.

Normal biotransformation of ammonia in a landfill system usually depends on nitrification followed by denitrification (figure 3). Nitrification is an aerobic process that requires the bubbling of oxygen into the system, which can be very costly for treatment facilities working under anaerobic conditions. Denitrification is anaerobic but requires an energy source such as methanol. This too can be costly for facilities. Anammox resolves both problems that standard biotransformation processes raise in a landfill system. It has been shown that anaerobic ammonia oxidation is actually more energetically favorable than aerobic ammonia oxidation (nitrification) so less energy input is required (Table 1) [8]. In addition, instead of needing an additional step of denitrification that requires the treatment facility purchase an energy source, anammox does not need energy input because the reaction is so energetically favorable under anaerobic conditions.

Microbial Community

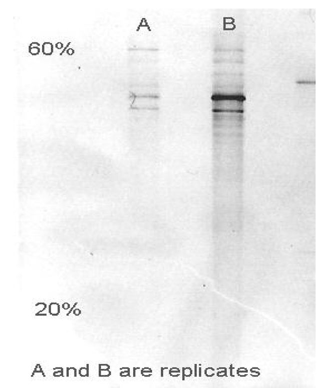

Figure 4 - Landfill leachate from Burlington County Resource Recovery Center. Universal PCR followed by DGGE (20%U/F -60%U/F).

As seen by denaturing gradient gel electrophoresis (DGGE), the microbial community within landfill leachate is very complex (Fig.4). Among the diversity, we have distinguished several species of methanogens as well as nitrifiers and denitrifiers. Anammox species are patchy and much harder to find within a given leachate collection site. We are still confident that conditions within the bioreactor landfill system are favorable for anammox species, and further investigation is being done.

It is interesting to note that while methanogens seem to be more widely distributed than anammox species, the process of methanogenesis is much more energetically unfavorable compared to nitrogen utilization by anammox species.

Optimization

Carbon Source + hydrogen source → methane + hydrogen

Ex. CO2 + 4H2 → CH4 + 2H2O

Equation 3 - Basic methanogenesis equation (change in Gibbs free energy is -131 kJ/rk)

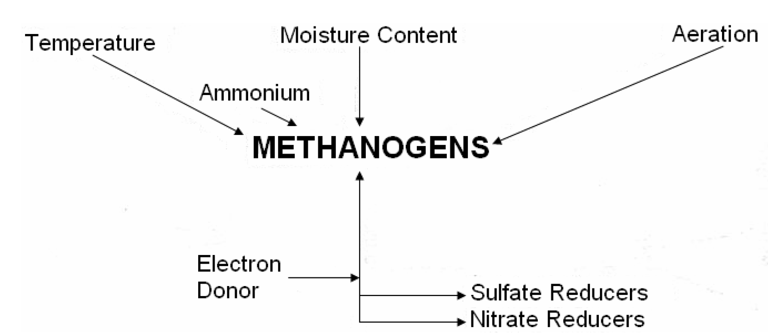

Figure 5- Competition of electron donor between methanogens and nitrogen biotransformation

At bioreactor landfills where energy from biogas is being generated, maximum methane production may be desirable, however, if the goal is also to minimize the waste management's carbon footprint or other environmental impacts, there can be numerous tradeoffs.

When attempting to minimize the carbon footprint of the waste management system, the system energy balance needs to be maximized. A tradeoff of this may be utilizing the bioreactor to lower nitrogen species in-situ by stimulating anammox. Since there is competition between the various microbial communities for available electron donor (hydrogen), anammox processes may limit methanogenesis. More study is needed to delineate such links, and to asses the extent and value of using the bioreactor to pre-treat leachate.

Energy Balance for the Bioreactor Landfill

The Bioreactor Landfill

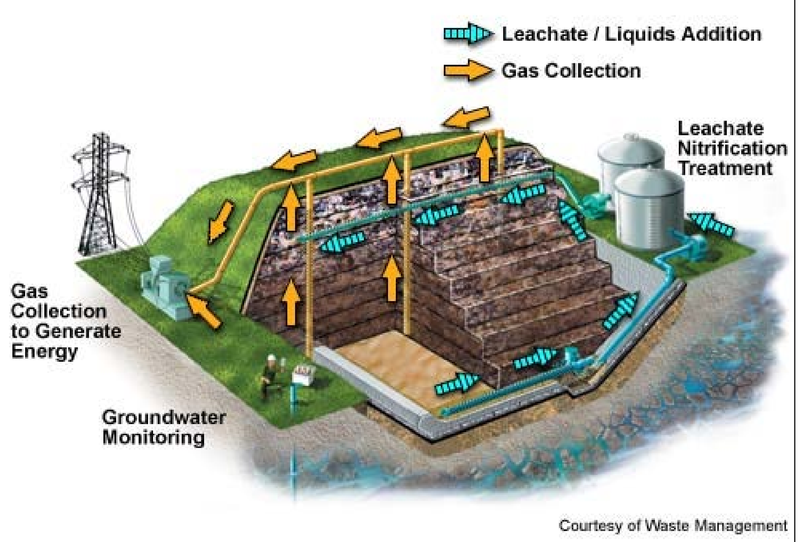

Figure 1 – Depiction of a generic bioreactor landfill

The Dynamic Energy Balance

$$\frac{dE_{net}}{dt} = E_{biogas} - E_{transport(in)} - E_{transport(out)} - E_{operation}$$

Equation 1 – The Dynamic Energy Balance

- dE_{net}/dt = Net system energy for a specified time interval
- E_{biogas} = Potential recoverable energy from landfill biogas
- *Etransport(in)* = Energy necessary to transport MSW and landfill cover from a point of origin to the landfill
- $E_{transport(out)}$ = Energy necessary to transport leachate and stormwater from the bioreactor landfill to wastewater treatment facilities
- $E_{operation}$ = Energy utilized to construct and maintain the bioreactor landfill and supporting infrastructure

The boundaries of the energy balance are broadly defined to include MSW, cover material and leachate transport as well as landfill operations. Actual data was utilized in all possible circumstances. Assumptions with respect to vehicle fuel economy were made based on sample average

The Results

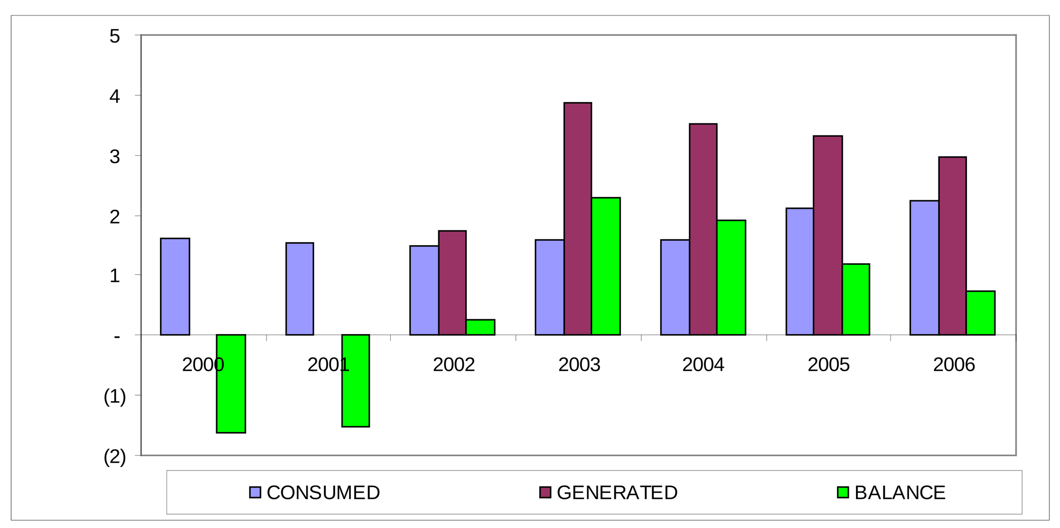

Figure 2 – Comparison of energy consumed and generated by the specified waste management system

The calculated values for energy consumed during normal waste management practices, energy associated with generated landfill biogas, and the difference between them is depicted in Figure 2. All energy quantities are normalized to the energy density of diesel fuel for simple reference (BTU/gallon of diesel).

Conclusions

- **The amount of biogas energy being generated by the Burlington County bioreactor landfill is significant and should be recovered**
- **Biogas energy generation at bioreactor landfills is large enough to offset all operating and maintenance energy expenditures**
- **Energy balances such as these are useful for assessing operating efficiency, identifying areas to be optimized, and validating management practices at bioreactor landfills**
- **The energy consumed is currently derived from fossil fuels, and the balance provides the total amount of fossil fuel energy being offset by the waste management system**
- **Methanogen stimulation in an anaerobic system, such as a bioreactor landfill, would increase the biogas produced**
- **Anammox is more cost and energy efficient than the biological and chemical processes that are currently used to treat landfill leachate with high ammonia loads**
- **Methanogens are widely distributed throughout a maturing landfill and can be stimulated relatively easily; whereas Anammox capable species are niche specific and are very sensitive to environmental conditions**
- **While methanogens are widely distributed compared to Anammox capable species, the Anammox process is approx. 3 times more energetically favorable than a basic methanogenesis process.**
- **The microbial community within a bioreactor landfill is very diverse and stimulation of a specific functional species must be well engineered with biogas production in mind**

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Acknowledgements

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