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In The Classroom

A Calorimetric Description of the Digestion of Organic Matter in Landfills

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Global heat balances with biomass production for aerobic and anaerobic biodigestion of organic matter are proposed. These balances nicely illustrate the thermodynamic differences between these two kinds of biodigestion, and illustrate, in a simple way, a landfill's potential for recycling energy originally contained in waste.

Establishment of a calorimetric balance for waste biodigestion clearly shows landfills' potential for energy recovery.

Introduction

Biological degradation of organic material is an important topic in studies of energy and the environment. It is difficult, however, to find calorimetric balances involving biomass yields in physical chemistry texts [1, 2] in order to illustrate the

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essential thermodynamic features of this process. Here, we will analyze the biodegradation of organic material in a landfill with the aim of providing a pedagogical illustration of calorimetric balance with biomass production. First, we will describe the main stages of organic-matter degradation in a landfill, establishing pertinent energetic balances in order to illustrate the potential of a landfill site as an energy-recovery system, with particular emphasis on the recycling of carbon compounds as methane. Second, we will improve the heat-balance analysis with the inclusion of the biomass production term. Introduction of biomass to these balances will make evident the differences between the two existing biodigestion modes (aerobic and anaerobic) and will illustrate a landfill's potential for energy recovery.

Natural Reactions

When waste is buried in a landfill, microbes degrade the organic portion of the waste. Degradation starts with *aerobiosis* [3] and later, as oxygen is exhausted, *anaerobiosis* [3] follows; carbon dioxide and methane are the principal products [4]. In a broad sense, and as proposed elsewhere [5, 6], taking the composition of glucose as representative of the organic matter contained in waste, transformation by aerobic bacteria can be expressed as:

$$C_6H_{12}O_6\,(s) + 6\,O_2\,(g) \rightarrow 6\,CO_2\,(g) + 6\,H_2O\,(l) \qquad \Delta_r H^\circ = -2816\ \text{kJ/mol} \qquad (1)$$

The above value of $\Delta_r H^\circ$ is obtained from standard formation enthalpies of reactants and products at 298 K and 1 bar [7]. Thus, this first transformation of organic matter through oxidation is characterized by the release, after some days of waste-burying, of carbon dioxide as well as by a significant temperature elevation. The landfill gas produced during this stage is a mixture of CO_2, H_2O, N_2, and O_2. Nitrogen and oxygen come from trapped air during waste-burying; their concentrations thus decrease over time. The diminution of the oxygen concentration in the gaseous phase occurs during the oxidation of organic matter. The same occurs with the nitrogen concentration; this gas is carried out of the site by the convection generated by the carbon dioxide produced in situ; this process lowers the concentration of all gases except CO_2, and anaerobic conditions thus develop. Observations made at various landfill sites have shown that the end of aerobic respiration (due to the lack of oxygen) occurs a few weeks after waste deposition, while gas production goes on for 20 or 30 years after landfill completion [8]. Indeed, current exploitation conditions (regular waste cover

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and intense compaction) limit air circulation inside the landfill, thus imposing anaerobic reactions as the main degradation mechanism.

On global terms, and supposing again that organic matter composition is well represented by that of glucose, the anaerobic organic matter degradation could be written as:

$$C_6H_{12}O_6\,(s) \rightarrow 3\,CH_4\,(g) + 3\,CO_2\,(g) \qquad \Delta_r H^\circ = -145\text{ kJ/mol} \qquad (2)$$

This transformation is weakly exothermic if compared with the total oxidation (reaction 1) and is characterized by the production of a combustible gas mixture composed mainly of methane and carbon dioxide. By comparing the enthalpies of reactions 1 and 2 it can be observed that 95% of the energy stored in the original organic matter is conserved through the methane produced. Thus the landfill gas should be considered an important energy source.

Biomass Yield

Consider now the biomass production during the degradation process. Microbes dissimilate carbon substrates to provide intermediates for biomass synthesis and energy for both their synthetic and their so-called “maintenance” functions [9]. On global terms, natural microbial processes include three main products: 1) biomass, 2) compounds arising from energy metabolism, and 3) heat. Aerobic and anaerobic digestion differ conspicuously in their biomass yields and heat evolution for a given amount of substrate (compare reactions 1 and 2). These differences are well illustrated with reference to the digestion of a carbohydrate, for example, glucose [3]. Table 1 shows that aerobic digestion is characterized by greater biomass production, and that, per mole of glucose degraded, approximately 93 g of dry biomass is obtained in aerobiosis and 23 g of dry biomass in anaerobiosis.

It is well known that digestion of organic matter in anaerobic reactors is developed with the aid of combined actions from a wide variety of bacteria [10]. Very few data exist about the numbers and the physiologic activities of the organisms involved during waste decomposition of a landfill. Nevertheless, as has been justified by Roels [11], it would be acceptable to use $CH_{1.7}O_{0.5}N_{0.2}$ as the average chemical composition of the biomass produced in these sites. Furthermore, using the following average reported

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TABLE 1. Glucose biodegradation, aerobic and anaerobic modes.

Bacterium	Dry Biomass yield (g/mole of degraded substratum)
Escherichia coli:	
Aerobic	95.0
Anaerobic	25.8
Saccharomyces cerevisiae:	
Aerobic	90.0
Anaerobic	21.0

enthalpic values [12] of 466.90 kJ per mole of O_2 consumed in aerobiosis and 35.44 kJ per mole of CO_2 produced in anaerobiosis and assuming $NH_3(g)$ as the nitrogen source, the following balances can be established:

—aerobic digestion of glucose,

$$C_6H_{12}O_6(s) + 2.11\,O_2(g) + 0.76\,NH_3(g) \rightarrow$$

$$2.21\,CO_2(g) + 3.91H_2O(l) + 3.79\,CH_{1.7}O_{0.5}N_{0.2}(s) \qquad \Delta_r H^\circ = -985\text{ kJ/mol} \qquad (3)$$

—anaerobic digestion of glucose,

$$C_6H_{12}O_6(s) + 0.18\,NH_3(g) \rightarrow$$

$$2.53\,CH_4(g) + 2.54\;CO_2(g) + 0.42\,H_2O(l) + 0.93\,CH_{1.7}O_{0.5}N_{0.2}(s)$$

$$\Delta_r H^\circ = -90\text{ kJ/mol} \qquad (4)$$

When complete aerobic digestion by microbes takes place, the carbon substrate is converted to CO_2, H_2O, and biomass. Roughly, 65 % of the heat of combustion of the organic matter is retained within the biomass and 35 % is evolved (compare reactions 1 and 3). Aerobic processes are net energy users because oxygen must be supplied for waste conversion; at present there is still no known way to recycle the energy contained

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in the biomass. Aerobic digestion, thus, is not of interest for energy recovery. Aerobic digestion is, however, the biological process most commonly used to convert the organic portion of solid waste into the stable humuslike material known as *compost* [13].

On the other hand, the standard heat of combustion per mole of methane is about –890 kJ [1]. So, generation of 2.53 moles of methane per mole of glucose degraded in anaerobiosis (reaction 4), represents a recovery of 80% of the energy contained in waste. Unquestionably, anaerobic digestion in landfills is a potentially interesting process for the recovery of an important amount of the energy contained in solid waste.

It is also worth noting that waste, in contrast to other raw materials, is not expected to be exhausted; it will always be available, in greater and greater quantities, as the human population increases.

Summary

Establishment of a calorimetric balance for waste biodigestion clearly shows landfills' potential for energy recovery. Complete anaerobic digestion of waste to obtain CH_4, CO_2, H_2O, and biomass provides a means of collecting a large part of the carbon as CH_4, a gas that still preserves about 80% of the fuel value of the carbon waste present in landfill. In this way, we have provided a pedagogical calorimetric example including biomass yield.

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