Mass transfer limitations in solid-state digestion

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Abstract
The biodegradation of waste placed in layers was studied in 500-ml lysimeters, without leachate recycle. All four became methanogenic within 100 days but the steady-state biogas output only reached 0.09 l kg\textsuperscript{-1} d\textsuperscript{-1}, whereas an earlier study on a mixed feedstock had yielded 1.8 l kg\textsuperscript{-1} d\textsuperscript{-1}. A novel physical model of solid-state digestion is deduced, implying a crucial role for mass transfer processes, with successful operation only within a limited range of diffusion rates.

Introduction
Nutrient density differs widely from point to point in solid-state digestion (SSD), whether in a landfill or in an anaerobic composter or digester. Distinct rich and lean zones can be identified. The part played by mass transfer processes between these zones has received growing attention in recent years.

The rich zones, typically around food or garden wastes, are high in readily biodegradable materials. Acidogenesis in these zones can readily create inhibitory concentrations of volatile fatty acids, which inhibit further breakdown. The acidification can be very rapid, as food wastes are rich in small molecules that can be directly utilized by the acidogens without extracellular hydrolysis.

The lean zones, however, are composed mainly of relatively inert materials, such as paper and construction wastes. In these, acidogenesis is slow, so acid levels may be much lower. Methanogenesis can proceed in such cases if the population of active methanogens is adequate. However, the rate may be limited by the availability of substrate. Where there is little or no local hydrolysis, a mass transfer process may thus be rate-limiting: inward transport of the substrate acids from the rich zones.

Relief of this limitation is one of the arguments in favour of the flushing bioreactor (Knox 1996). In its most developed form, this requires operation with a high water content in the waste bed. Continuous collection and recycle of the copious outflow of leachate then ensures uniform flow throughout the bed. Current regulations in some countries tend to oppose this, by effectively placing limits on the moisture content. Nevertheless, a recent report from the Institute of Wastes Management has even suggested using a flooded bed, possibly in upflow mode (Anon 1999).

Any flow would accelerate mass transfer substantially, by adding convective transport mechanisms to molecular diffusion. In this situation, conditions are envisaged as approaching uniformity, with methanogenesis distributed throughout the waste. Large-scale applications of this concept in commercial landfills remain rare but it has been applied in some engineered digesters. Usually equipped with temperature control, an additional advantage, these achieve rapid stabilization of the waste.

An alternative to this ‘wet’ approach has been to operate on a ‘moist’ basis, with little free water. Like the flushing bioreactor, this principle can be applied either in a more-or-less engineered landfill or in a digester or anaerobic composter.

In landfills, the feedstock may be simply ‘as delivered’ waste, without pretreatment. An inoculum of digested sewage sludge (DSS) may be added but is not essential if the waste includes soil and other good
natural sources of methanogens. The bed is highly heterogeneous and breakdown is uneven. Some zones may stabilize in as little as a year or two, some take decades, while others never progress beyond a metastable acidified condition, which may last as long as anaerobic conditions are preserved.

In engineered digesters, the feedstock is usually a mixture of fresh waste with previously digested waste, typically at a ratio of 1:1, as seed or inoculum. Stabilization is much quicker and less variable, commonly taking just a few weeks. The initial mixing distributes the microbial population but the large size of many components of the waste militates against any approach to homogeneity. Mixing may continue during incubation too, in which case breakdown is even faster. Nevertheless, some heterogeneity remains.

Three solid phases can be distinguished in such systems. As before, the rich phase comprises the readily degradable fraction of the fresh waste, in which the methanogen population is low and inactive, due to high acidity. Similarly, the lean phase comprises the less degradable fraction, in which the methanogen population is low but active. The seed adds a third phase, comprising degraded material with a high population of active methanogens.

Kalyuzhnyi et al. (1999) have proposed a useful ‘two-particle’ process model for these digesters. This distinguishes between the ‘seed’ particles, originating from the digested waste inoculum, and the nutrient-rich ‘waste’ particles. The lean phase is not considered. However, this might be justified, since with such high seed:waste ratios, it might contribute little to the process. The model thus assumes methanogenesis to occur only in the seed particles, the acidity being too high in the waste particles. The authors conclude that mass transfer rates are commonly limiting in such forms of SSD, a conclusion that probably applies equally well within many landfills.

The segregated 64 l experimental models reported by Martin et al. (1997a) were based a similar concept of inhibited rich and active lean zones. In the rich zones, acid levels were assumed high throughout (though not necessarily uniform), so also high at the interface between the rich and lean phases. Methanogenesis was expected to proceed deep within the lean zones, utilizing acids diffusing from the rich zones. This envisaged the inner layers of the lean zones as providing ‘safe havens’ for methanogenesis, protected from the high acidity at the interface by mass transfer resistances in the outer layers. However, these lysimeters, charged with a feedstock of foodstuff and shredded paper, with a DSS inoculum but without recycle, failed to proceed to the methanogenic stage. Contact between the phases may have been inadequate.

In similar tests at 10 l scale, Martin et al. (1997b) used a similar feedstock but on a mixed basis. One lysimeter (of a pair) produced biogas at a steady rate of 1.8 l kg\(^{-1}\) d\(^{-1}\) for some 20 weeks. Stabilization, including breakdown of the (office stock) paper, was 94% complete in 400 days and complete in 700. The final gas yield was 288 l kg\(^{-1}\) of simulated waste. These results, from a simple batch digester, are comparable with the best of the wide range observed in landfills operated without leachate recycle. Vietez et al. (1999) seem to have obtained no higher rates from a much more complex two-stage system incorporating leachate recycle. Their process may, however, be more suitable for scale-up.

The duplicate lysimeter was slower but later sustained a comparable rate of 1.3 l kg\(^{-1}\) d\(^{-1}\) and reached stabilization after about 900 days (unpublished data). The poorly replicated time scales of these two lysimeters left some uncertainty regarding the suitability of the method for routine use. However, the second was proceeding in step with the first until an equipment failure, which may have been the sole cause of the differences between them. These results consequently suggested that lysimeters could yield useful data without the complication of recycle, a valuable simplification at bench scale. It was concluded that the method of preparing the feedstock might have allowed enough heterogeneity to create an adequate distribution of the hypothetical safe havens. There was no size reduction before mixing, so the charge was far from homogeneous.

The present work was therefore undertaken to determine whether heterogeneity was indeed an essential feature of the method.

**Materials and methods**

Four 500-ml lysimeters (Set B) were charged with 56 g of simulated waste, comprising 56% shredded paper and 44% food. The food was layered onto the uncompacted paper then the DSS was distributed over the whole by pipette. The paper was omitted from another four lysimeters (Set D). Further detail of the method is given by Martin et al. (1999).