A PRIMER ON ENGINEERED METHANE RECOVERY FROM SOLID WASTES

Mark Milke
Department of Civil Engineering
University of Canterbury
Christchurch NEW ZEALAND

1. Introduction

There are a number of new systems for recovering energy in the form of methane from solid wastes. The process relies on microbes in an oxygen-free environment to decompose food waste, garden waste, and some paper waste into methane gas, carbon dioxide gas, and a solid product. Typically, the solid product is microbially degraded with oxygen to form a marketable compost. In contrast to the carbon dioxide gas produced in composting, engineered methane recovery converts some of the organic matter into methane gas. The additional cost for the engineering needed to produce methane is set off against the additional benefits of use of the methane gas. Landfills can also recover methane from solid wastes, but the landfill must meet other objectives (eg, potable groundwater, few odours) that might reduce the potential for optimising methane production there. In that sense engineered methane recovery relies on large sealed vessels for treatment of solid wastes.

The variety of the systems and the lack of local experience with the systems can make it difficult for waste managers to evaluate proposals from suppliers of these systems. There is a threat that waste managers may become mired in the details, claims and counter-claims associated with these new technologies. This paper hopes to provide background information on the methane production process so waste managers can more critically evaluate proposals. The paper will also give a few of my subjective opinions on the viability of engineered methane recovery-- the key benefits and problems, the relative advantages of design strategies, and the place of the technology within an integrated waste management system.

2. The Biological Process

Once organic material is formed it becomes liable to microbes' ability to decompose or break apart the organic matter. The way the decomposition occurs varies depending upon the environment-- different microbes specialising in decomposition in specific situations. For organic solid wastes such as garden waste, food and food-processing waste, and paper waste, it is useful to consider two types of decomposition environments: aerobic ones and anaerobic ones. What distinguishes these two is the presence of oxygen: an aerobic environment has oxygen (typically, from the atmosphere), while an anaerobic one does not. Aerobic decomposition is what happens in composting and in the rubbish bin in your kitchen, and the main product of the biodegradation is carbon dioxide gas. Anaerobic decomposition is what happens in landfills, in engineered gas recovery systems, and in your tied-off rubbish bag if you forget it in your garage until your nose finds it. The main products of anaerobic biodegradation are carbon dioxide gas and methane gas.

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To convert organic matter into methane we can think of there being a three step process:

1. break complex organic polymers into large, but manageable organic molecules
2. ferment the large organic molecules into small, simple water-soluble organics,
3. produce methane from the small simple organics

The first two steps are termed fermentation and are conducted by fermentative bacteria, the last step is termed methanogenesis and is conducted by methanogenic bacteria. We say that organic solid waste ferments, just as we say that vintners ferment alcohol from fruit using yeast. With solid waste all sorts of bacteria get involved and so the result of fermentation is usually organic acids-- principally, acetic acid (ie, vinegar). The production of organic acids during fermentation makes the waste more acidic if these acids are not quickly converted into other compounds-- if enough oxygen is available, they can be quickly converted to carbon dioxide, if not enough oxygen is available, the fermentation products can accumulate prior to step three above. As a result, in anaerobic environments fermentation often results in odours and can produce hydrogen gas.

The last step usually occurs due to bacteria consuming acetic acid-- they split the acetic acid molecule, add water, and turn half into methane and half into carbon dioxide. Some bacteria are able to combine the products of fermentation with hydrogen gas to form methane. The three steps work as if they were on a production line-- the facultative bacteria turn complex organics (eg, cellulose) into acetic acid and the methanogens turn the acetic acid into methane. If one link in the chain were to falter because of unfavourable conditions, the production of methane would cease.

Bacteria see organic waste as food-- energy and nutrition that they can consume in order to survive and reproduce. The energy in the food is converted into new biomass, waste chemical products, and waste heat. In an aerobic process, a lot of biomass is produced, a lot of waste heat is generated, and not much energy is left in the byproducts, mainly carbon dioxide. The aerobic bacteria that are successful in composting are those that eat fast, sloppily, and reproduce quickly. Fastidious aerobic eaters are quickly outcompeted. In anaerobic systems, where there's no oxygen, the bacteria are unable to eat fast because without oxygen they don't have the option of producing low-energy byproducts. Instead, they must form high-energy byproducts, namely, methane gas. Bacteria that produce methane would lose in any open competition with other bacteria since they are so inefficient as to leave so much energy in their waste products, but because there are certain environments where there is no other choice, methane-producing communities come into place. The aerobic communities have a large margin for error in their sloppy eating practices, since they can become more efficient as the environment becomes more hostile, but the anaerobic communities have less of a margin for error, and as the environment becomes more hostile, they can not tighten their belts much further, and often stop biological processes. Within the anaerobic chain, the facultatives have a reasonably large margin of error, while the methanogens have a very small margin of error. As a result, when bad environmental conditions hit an anaerobic community, the methanogens are the ones most likely to cease functioning.

When methane production stops in a batch anaerobic digestion process it's as if the last person on the production line decides to take a break-- the work starts piling up for that person. In the digestion process, the organic acids accumulate when methane production can't consume the acids at the rate they are produced, and the process "sours". The term "souring" is taken from the sewage sludge digestion literature, and a similar process can occur in anaerobic sludge digesters. A lot of research has studied ways to limit "souring" in anaerobic sludge digesters. The threat of "souring" seems, to me, to be greater in solid waste digestion, yet little research has been conducted on the topic. During the initial phases of degradation, when the facultative bacteria are churning out simple organics, this is when the threat of "souring" seems to be greatest since it demands an even higher rate of acetic acid consumption/methane production to keep a backlog from developing. During the later phases of degradation, the facultatives have harder work, and slow down, and the methane producers are more likely to cope with a backlog if a temporary environmental disturbance occurs.

3. Factors Affecting Methane Production

Composition of Organic Wastes

The way we see organic wastes-- as garden waste, food waste, paper waste-- is not how bacteria see organic waste. They see it in terms of the biochemical compounds as seen at the microscopic level; they see these wastes as composed of sugar/starch, cellulose, hemi-cellulose, lignin, protein, and fat. To understand how waste composition can affect methane generation, you need to consider waste composition from the bacteria's viewpoint, and so a few words on each biochemical compound might help:

Sugar/Starch: These do not need to be broken apart prior to fermentation, and provide a lot of energy to bacteria, as a result, they are the most rapidly decomposed in an anaerobic environment. The rapid rate of fermentation of these materials can lead to souring. These can be found in food wastes, to a small extent in garden wastes, and not in normal paper waste.

Cellulose: This a long string of sugar molecules tightly tied together-- wood fibres, paper, celery, cotton, and grass all have very high cellulose contents. Special bacteria are able to untie the sugar molecules; once the molecules have been untied they are quickly degraded as sugars. Cellulose is the principal component of paper and garden waste and is common in food waste. Most methane produced from municipal solid waste comes from cellulose.

Hemi-Cellulose: This is a variant on cellulose. It is slightly easier to degrade. It is preferentially lost during wood pulping to make paper and is so more common in garden and food waste than in paper waste.

Lignin: This is a complex web of organic molecules that cannot be microbially degraded in anaerobic environments. It is difficult to degrade in aerobic environments, but fungi can do the job in compost operations. Tree bark is a good example of lignin. All woody material contains lignin, and, during paper manufacture, wood pulping chemicals dissolve the lignin into water to leave the cellulose fibres used in paper. As a result, paper has little lignin (newspaper has more than other papers). Woodier plant tissue contains more lignin, so food waste and grass have little lignin, while wood and tree branches have more. In garden wastes, the lignin often sheathes cellulose at around a 1:1 ratio; this makes it difficult to degrade part of the cellulose in unmodified garden waste.

Proteins: These are readily degradable and have useful energy for bacteria. More importantly, they have nitrogen, an important nutrient for bacteria. Proteins are readily degraded. Proteins are most likely to be found in food wastes, but are generally not common.

Fats: These are rare in municipal solid waste, but may occur in special food processing wastes. Fats have a high energy content and can produce methane gas with little carbon dioxide gas. Their anaerobic digestion often produces hydrogen gas as well.

It should be emphasised that not all garden, food and paper waste is organic. The common method of measuring the organic content of waste is as a mass percentage found by burning the material-- the non-organic material is ash, the organic material is termed volatile (ie, burnable) solids. Food, garden and paper wastes have about 5 % ash-- wood as low as 1 %, while magazines as high as 25 % (Tchobanoglous, et al., 1993).

In addition, not all organic matter is biodegradable. As mentioned above, lignin is not biodegradable in anaerobic environments, and lignin can also encase cellulose, making it non-biodegradable. The end result is that only about 80 % of the volatile solids in food waste, garden waste and office paper can be converted into methane without processing. This reduces to 50 % for cardboard and 25 % for newspaper due to higher lignin contents (Tchobanoglous, et al., 1993).

Moisture

Bacteria need water to survive and reproduce. More importantly, they need water so food can flow to them and so their wastes can flow away from them-- they use water for transport, not just to quench their thirst. The more water, the more stimulated the bacteria are. A problem can arise, though, since the fermentative bacteria can be stimulated more by water addition than the methanogenic bacteria and "souring" can occur. Attempts to maximise methane production through moisture control are not likely to succeed without also having control over waste size and feedstock composition.

Nutrients

Anaerobic bacteria need nitrogen, phosphorus, etc., to develop. Garden wastes and mixed food wastes are likely to contain adequate enough amounts of these nutrients, but paper waste or individual food wastes (eg, potatoes) might not. The lack of nutrients tends to slow down the rate of methane generation. Poor homogeneity or poor transport can give nutrient-poor pockets and inhibited gas production even though the average nutrient content is at an acceptable level. A lack of nutrients can slow down the process, so you should infer that more nutrients tend to accelerate the methane production rate. As with moisture, this could cause a problem via "souring" since the fermentation bacteria can be stimulated by the high nutrient levels more than the methanogens.

Certain elements can be nutrients at low concentrations and stimulate bacteria, but can inhibit gas production at high concentrations. This is a particular concern for methanogens. This issue has been studied for sewage sludge digestion, but not adequately for solid waste digestion. Ammonia can inhibit methane production at high concentrations and certain wastes with high nitrogen content can lead to concern with ammonia toxicity. Two wastes of particular concern are poultry manure and protein-rich food wastes. Ions can limit gas production at high concentrations if buffers are added or leachate recycle is used.

Toxins

Specific chemicals can have a toxic effect on methane production even at low concentrations. The methane-producers are the most vulnerable to toxic shock, and if a batch of organic waste contains a relatively high concentration of a toxin, "souring" is likely to occur. Due to the heterogeneity of waste, small sections of a solid waste digester may experience toxic effects, even though the average concentration is low. The effect of toxins means that small amounts of hazardous wastes have a high potential to inhibit methane production rates.

pH/Alkalinity

Fermentation produces organic acids. These release H^+ ions, leading to decreases in pH. There is argument about whether low pH is a cause of "souring" or simply a symptom of it, but clearly digestion under decreasing pH means an increasing probability of souring. Since H^+ accumulation during the initial phases of batch digestion is a major concern, there is a lot of interest in constituents that can sop up the H^+ ions. One option is the use of a buffer. Material with high buffering capacity or alkalinity can sop up the H^+ ions, and limit decreases in pH. Woody tissue waste can be a substantial source of alkalinity, as can certain food wastes. On the other hand, waste materials that consume alkalinity (ie, acidic wastes) create more "souring" in micro-environments.

Sulphate

Sulphate in batch anaerobic digesters inhibits methane generation rates. Special bacteria can take sulphate and turn it into hydrogen sulphide gas, and they consume acetic acid as food. Since batch anaerobic digestion produces around 90 % of its methane from acetic acid, dramatic decreases in methane generation can occur in the presence of sulphate. Sulphate can come from a number of special wastes. Many paper products have appreciable sulphur (Gurijala and Suflita, 1993). A particular concern is demolition debris where gypsum (calcium sulphate) contains great quantities of sulphate.

Decomposition Temperature

The internal temperature of a digester can affect gas generation rates. Just as in composting, there can be mesophilic and thermophilic anaerobic digestion, and thermophilic is the hotter, and more rapid degradation of the two.

Initial Temperature

The initial temperature can have an indirect effect on batch anaerobic digestion. The results of Cecchi et al. (1992) show a much more rapid methane generation rate for waste collected on hotter days than on cooler days. What happens is that on hotter days, the first phase of aerobic composting has been accelerated. This produces more feedstocks than usual for methane-producing communities, and I would guess it removes the rapidly-degradable feedstocks and turns them into carbon dioxide instead of fermenting them in the digester. This means that the partially composted solid waste, when it goes into the digester, will ferment at a slower rate, creating less of a logjam of organics, and thereby allowing the methanogens an easier time to work through the processed organics and build up their populations to a steady value.

Particle Size

Smaller solid particles provide a greater surface area and the rate of microbial attack seems to be proportional to the available surface area. So smaller particles allow for faster degradation rates-- in particular, they allow bacteria to get at the cellulose that is intertwined with lignin. The upshot is that smaller particles can accelerate decomposition, but they increase the chance of souring.

Mixing

Mixing liquids can dilute the inhibitors that are causing "souring", and provide the nutrients needed to avoid the condition. It is believed that water moves down by gravity, and moves up by gas production, although I know of no thorough studies of mixing by liquid or gas. Mixing of the solids is also beneficial. Solids that are more homogeneous are less likely to sour. Attempts to mix waste to make it more homogeneous are likely to result in benefits in higher, more rapid and more stable methane generation rates.

Inoculum

Some people have advocated adding anaerobic bacteria to solid waste to speed up the onset of methane production. Often sewage sludge has been added. Sewage sludge additions have caused more problems than they've solved-- they stimulate the fermenters more than the methanogens and increase the chance of souring. Others have shown benefits by adding old, methane producing refuse to new batch reactors. The benefits seem to be due to the water absorbing capability of the old refuse, and the alkalinity of the old refuse, rather than its bacterial community. The required microbes are ubiquitous, and providing an inoculum to a batch digester is unlikely to provide many benefits.

4. System Types

Engineered systems for producing methane from solid wastes come in various types. There's little point in listing all the possible systems since new ones will appear soon to add to the confusion. Still, some mention of the key differences in system types might help others to understand the options.

Batch versus Continuous

A methane production system is a batch system when making methane is like making a batch of scones-- all the waste (batter) goes into the vessel (oven) at one time, and it is all taken out at a later time once the process (cooking) has completed. A continuous system is one that has periodic feeding of prepared waste in the vessel and periodic removal of the endproducts (gas and solid) from the vessel. Examples of continuous production systems are people (food as raw input, work and waste as outputs, with a more or less stable system within the body) or, more analogously, making yogurt from a culture. For methane production, a continuous system would use a large vessel where processed waste would be added, residue and gas removed, and the status of the inside of the vessel would remain more or less stable.

A batch system requires multiple vessels (or a large, staged machine like a rotating milking machine) since the waste will take time to be fully processed and more waste will need processing before the first batch is finished. Each batch system needs to be prepared and controlled appropriately to assure proper operating conditions. A continuous system can use one large vessel and will be easier to control.

A large research effort in the 70's and 80's, sparked by the fuel crises, examined continuous systems and the pilot-scale plants that resulted in the US were failures (Perron, 1980; Walter, 1980). The problems were due to the poor mixing that could be achieved in one large vessel (Systems Tech. Corp, 1981), and the high cost of pre-processing of waste. The new burst of interest in methane production focuses on batch systems.

Dry versus Wet

Process designs vary in the amount of water they add to solid wastes. At one extreme, wastes are ground to a small size and water added to make a slurry that might have only 8 % solids, and 92 % water. This design allows for better mixing and so a process that is easier to control and one that will produce methane more rapidly. The problems with the slurry approach are the high operating and maintenance costs associated with preparing the solid waste, and the dual problem of removing the water once the process is complete and then treating the resulting wastewater.

At the other end of the spectrum, there are relatively dry processes that add a small amount of water so waste degrades at about 50 % solids and 50 % water. Relatively small amounts of waste water are generated and can be readily dealt with in the process. The dry method relies less on mixing to accelerate decomposition, and so tends to require more space than the wet method.

Leach Beds

A relatively new approach is the use of leaching beds for solid wastes (Morks, et al., 1993). A leaching bed works like a coffee percolator-- water is poured over the solids, and oddly-smelling materials are leached out into a pot. In leach beds, the leachate is held in a separate vessel and some of the liquid is recirculated by respraying over the solid wastes allowing for more liquid to be generated. The resulting liquid is rich in microbes, nutrients, and dissolved organic compounds ready for bacterial transformation into methane. Some methane generation occurs in the leach bed itself, but the majority occurs in the liquid vessel containing the rich, leachate broth. This method allows for a batch treatment of the solids and a semi-continuous treatment of the liquid-- with further development it may allow for systems with the benefits of both the wet and dry systems now available. This method still requires some form of wastewater treatment. This method is still in the laboratory (as far as I know) and undergoing a number of design improvements, but it may become practical in the near future.

In summary, although the continuous system design seems impractical, that still leaves a huge number of potential systems for a waste manager to consider, and is not clear that one system is always better than another. The following sections consider the principal concerns that a waste manager should have in choosing between options, and in deciding whether any system is appropriate.

5. Key Concerns in System Selection

Since there are no engineered methane recovery systems for solid wastes that I know of, many waste managers are likely to be easily confused when contacted by vendors of these systems. It might be worthwhile to give one viewpoint on the key factors a waste manager should consider.

Economy of Scale

The benefits of the system (methane recovery, landfill disposal avoidance) are likely to be constant on a per kilogram basis, while the costs of the system (capital, operating costs) are likely to decrease on a per kilogram basis as the system size increases. As a result, an economy of scale will apply: the more waste that goes into the system, the more likely it is to be economical.

Waste Segregation

It would be dumb to build an expensive vessel to produce methane from organic wastes and then fill the vessel with waste that is 10 % glass, 10 % plastic, 5 % metal, and 10 % dirt: not only do these materials decrease the volume for the biodegradable materials, but they also cause greater wear and so higher maintenance costs on the plant equipment. As a result, you will want to increase the methane that can be produced per cubic meter of vessel volume by increasing the biodegradable matter going into it.

Waste segregation is needed to increase the garden, food and paper waste going in. This can be done by trying to process the waste to remove other waste types using, for example, magnets, screens, grinders, and bursts of air. These mechanical means cost a lot of money. Another way is to have the waste generators segregate wastes prior to disposal. As a result, source separation will need to be a key part of any program to recover methane in an engineered system.

Variable Waste Composition

Variable waste composition makes engineered methane recovery expensive. Methane recovery is a microbiologically-delicate process, and control of the process will be critical to avoid souring and increase methane production. Variations in the waste composition will make this difficult. To an extent, more thorough monitoring can compensate, but this costs money, making the option less viable. Variable waste in the form of toxic contaminants must also be a concern.

Organic wastes can vary greatly from day to day and season to season. If a major commercial generator decides to dispose of 20 years of paper waste during one week, the rules-of-thumb control at the local methane recovery plant may find it difficult to cope. It also might be difficult to cope with large, sporadic intakes of kiwi fruit spoils, or grapefruit rinds, for example. Even seasonal variations in garden waste could become important: nutrient-rich grasses and leaves in spring/summer would degrade differently from lignin-rich woody and leafy material in the autumn/winter.

The upshot of variable waste composition means that small systems are disadvantaged, and that there may need to be strict limits and control on the amounts and types of waste accepted at a facility. Systems that rely on relatively constant intakes of a relatively constant waste type are advantaged, and so it should be of benefit to develop methane recovery schemes around agricultural/food processing wastes.

Methane Use

As with landfill methane recovery systems, the viability of engineered methane recovery systems will greatly depend upon the value of the methane produced. If the methane can be used near the point of generation and with little treatment, the value of the methane will be much greater and the project more viable. As the conditions are less filled, the project becomes difficult to justify. It is not so simple as generating methane and selling it on an open market at a predictable price. Great effort must be expended in finding a customer, evaluating the customer's needs, and trying to match the methane produced by the engineered system to meet the needs of the customer. Burning the methane to generate heat that will be used by a nearby factory for process heat is an excellent end use. Purifying the methane so it can be bottled for commercial sale would be an awful end use for the product.

Post-Processing Needs

The solid residue from methane recovery must be dealt with; how it is dealt with will affect the overall desirability of the methane recovery project. If the residue is to be processed and marketed as compost, concern must be payed to the metal, pesticide and toxin concentrations in the compost-- to assure that these concerns are addressed, there may need to be limits placed on the sources of waste allowed into the facility, thereby affecting the overall economics of the project. Particular concern will need to be payed to the paper wastes used: more paper waste will allow for more methane production, but may limit the sale of the compost.

6. Integration into Solid Waste Management Systems

Choosing the best engineered methane recovery (EMR) system must be done as part of an integrated analysis of the total solid waste management system. Evaluation of the proper place of EMR must be done on a case-by-case basis considering relevant social and economic factors; still, it will be useful to explore a few key issues in such an evaluation.

Waste Reduction and EMR

Efforts at waste minimisation and recycling must be analysed jointly with studies of energy recovery. If an economic analysis of EMR shows viability and a large plant is built, and then a year later, the city changes policy and tries to minimise organic waste production, the EMR plant would likely be uneconomical. I prefer integrated analysis of waste minimisation rather than a hierarchical analysis, but in either case, you need to set in place a long-term strategy first, and then see if EMR fits into that strategy.

Composting and EMR

Both composting and EMR produce compost since the residue from EMR is usually composted. In some sense EMR is just another form of composting, and some people term the process anaerobic composting. But there are important differences between the two forms of composting. In the anaerobic process the lignin is not degraded, and so to improve EMR lignin wastes are often excluded. The result could be a plant that anaerobically decomposes low lignin organic waste, and aerobically decomposes high lignin waste and the product of the anaerobic decomposition. In this sense, the two methods of waste treatment are complimentary.

But to an extent the two methods are in conflict. A waste manager must choose between a dual aerobic/anaerobic treatment system, and a completely aerobic treatment system. The choice is likely to depend upon the types of waste that are available to be treated, the price of land, and the size of the facility, in addition to the factors in section 5 above. Wastes that more quickly and generously produce methane favour EMR. Expensive land favours EMR since the spread-out aerobic composting is replaced by a more vertical anaerobic process. Aerobic composting can also go vertical, but the additional expense means that methane production is likely to become favourable. As the size of the facility increases, EMR is favoured since the economies of scale are greater for EMR than for composting.

Landfill and EMR

If the residue from an EMR is to be disposed of in a landfill and not marketed as compost, it is debateable whether EMR is a better option than direct landfill. Disposal of the organic matter directly into a landfill can result in methane generation and recovery. Although methane production in landfills is slower and less controlled, it is also much less expensive.

If the residue goes into a landfill, the benefit of decreased landfill space practically disappears. Although there is a decrease in the mass of solid waste in an engineered system, a similar loss in mass would occur in a landfill, leading to a similar decrease in landfill space in the landfill- - this decrease in landfill space is commonly termed settlement, and deeper landfills rely on degradation of the refuse below to increase the space available for the upper layers of refuse. To an extent the slower processes in landfills means not all of this new landfill space is available during the life of a landfill, but to a great extent it is and must be considered in a comparative analysis of landfills and engineered methane recovery systems.

Incineration and EMR

A waste treatment system mentioned in the literature separates carbon-based waste into a dry fraction and a damp fraction (Vallini, et al., 1992). The separation can be done at source, or less efficiently, at a treatment facility. The damp fraction contains garden waste, food waste and soiled paper waste, and is sent to an EMR facility. The dry fraction contains dry paper and plastic waste and is sent to an incinerator. There is substantial experience at burning paper and plastic waste (ie, refuse-derived fuel, or "rdf"). The incinerator ash and non-carbon-based wastes would go to a landfill. This scheme is under serious consideration in Europe and North America and seems to maximise the recovery value of carbon-based municipal wastes.

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