# An independent review of sludge treatment processes and innovations

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**Abstract:**

This paper will review the different types of sludge treatment especially from the perspective of a biosolids recycling practitioner with extensive experience in Europe and North America. The author has no commercial interest in any particular treatment technology so the review will be independent and unbiased. He has 30 years' experience of biosolids and created world-leading, quality assured, HACCP-based (Hazard Analysis Critical Control Point) biosolids recycling programmes for more than 6 million people. Sludge treatment, when it is associated with recycling, is about making biosolids that are fit for their intended markets. In this regard, the author considers that the ability to comply with legal obligations is a given, i.e. it must be considered incontrovertible; in addition it is important that biosolids are not unwelcome by those living and working near where they are applied, which most times means odour. Incineration might be appropriate in some situations. The paper will include consideration of the carbon footprints of the technologies as well as their financial comparisons. The author will consider "greenfield" and "retrofit" technologies, their "scalability" and the opportunity for sweating existing assets and increasing their treatment capacities.

**Keywords**:
biogas; biosolids recycling; carbon footprint; co-digestion; developments; dewatering; energy recovery; fertiliser recovery; HACCP; innovations; markets; sludge treatment

**Introduction**

Sludge treatment is a fundamental part of wastewater treatment but many still underestimate its importance. Wastewater yields sludge and reclaimed water. When sludge is not managed properly, the rest of the wastewater treatment is compromised. The purpose of sludge treatment is to render it fit for its intended destination. Thus, sludge treatment is like product manufacturing. When designing a manufacturing [treatment] process the intended use of the product is paramount and therefore the question of whether you are able to make a product that is fit for that intended purpose is decisive. The whole process as it affects the raw material (including sewerage) needs to be considered. Since raw material arrives at the sludge production process 24/7, it is also essential that there is standby capacity or contingency for breakdowns and maintenance.

The properties of indigenous sludge (i.e. that originating at a wastewater treatment works, WwTW) changes during a day and also seasonally; this is in addition to changes in quantity. Sludge settles in sewers during times of low flow, and is later flushed to the WwTW during high flow. Biological activity occurs in sewers, it can be aerobic or anaerobic depending on the gradient, etc. If there is a significant "resort" component to the catchment or other seasonal activity (e.g. a food processing campaign) there will be a large difference between low and high season. The alterations in sludge properties are even greater when a works is a regional sludge reception centre (i.e. one to which sludges are brought from other WwTW). This might seem fairly obvious but there are many examples of sludge treatment systems that have failed, or never been effective, because they have not been able to cope with the changes/fluctuations in the properties of the sludges that they were required to treat.

If the intended use is energy recovery, is the form of the sludge fit for that purpose? "Oil from sludge" was a high profile project that took about 18 years to develop (e.g. Bridle and Skypski-Mantele, 2003). Subiaco, Perth, Australia, (250,000 pop. equiv.) was very courageous to have built the only production plant to date. Unfortunately, the process only survived a few months. Apparently, this was because the product(s) were not fit for purpose and neither was the process (Allen Gale, priv. comm.). The process could not tolerate the variations in sludge characteristics that are inherent in real wastewater treatment, and the oil that was produced did not conform to any of the oil industry's standard specifications.

If the process, or one of its components, breaks down, is there a contingency? Superficially, raw sludge incineration or drying is attractive but if the incinerator or the dryer is not available for any reason, you are stuck with raw cake. Non-availability could be due to the dryer or incinerator, but it could also be failure of a conveyer or some other critical link in the process chain. Raw cake becomes septic and malodorous quite quickly so non-availability of one step in the treatment chain can have long-lasting repercussions. Once malodorants have been formed, some of them are intransigent to elimination by subsequent treatment steps.

In general, legislation does not regulate **odour** until it becomes a public nuisance. Legislation regulates metals and maybe organic micropollutants and/or numbers of certain microorganisms but the odour of sewage sludge (biosolids) is not a regulated parameter. Quebec Province in Canada is to date the only exception I know of (Groeneveld and Hébert, 2002). Globally, the nature of the water industry seems to be to comply with the parameters specified in legislation and, by its actions, to categorise public acceptance as less important than legal compliance. Some people talk about public acceptance but many of them do not walk the talk. The Greater Moncton Sewerage Commission in Canada (host of the IWA biosolids conference in 2007) is one of the enlightened exceptions, but it is in the minority. Representatives from national environmental regulation agencies say that the cause of more than 95% of complaints about land application of biosolids is odour. At the plenary sessions of several major international biosolids conferences, I have tested the hypothesis that odour is the root cause of most cases of public hostility to land application; nobody has disagreed. Despite this, WwTW continue to install treatment methods without satisfying themselves that the treated biosolids will have odour tolerable for land application.

Malodorants are mainly sulphur and nitrogen compounds. Sulphur compounds are easier to measure by gas chromatography (GC) than nitrogen compounds. Some publications report trends in "odour" when in fact they have only measured sulphur compounds, this is misleading. When investigating odour from dewatered cake in about 1997, the initial results of sulphur compound GC appeared to correspond to subjective (smell) odour assessment but when we extended the work to other WwTW the relationship fell apart. The importance of nitrogen compounds became evident, even if the labs had difficulty measuring them. People who only report S-compounds thinking that they account for all of odour should get out of their laboratories more often.

Arrays of electronic noses appear to be becoming robust enough for continuous monitoring though the equipment is not inexpensive (e.g. Renner, et al., 2007 and www.odotech.com). The

Nasal Ranger is an alternative to capturing air samples in Tedlar bags and taking them to olfactometry panels (e.g. Hamel and McGinley, 2004 and www.nasalranger.com).

The sense of smell remained the most enigmatic of our senses until quite recently. There are about 10,000 different odours and the basic principles of how humans recognise and remember them were not understood. It is accepted that odours are responded to differently by different people but we did not understand the basic principles of why this should be.

In 2004, the Nobel Prize in Physiology or Medicine was awarded to Richard Axel and Linda B. Buck for their work that solved the problem. In a series of pioneering studies, they clarified how our olfactory system works (The Nobel Foundation, 2004). They discovered a large gene family (comprising some 1,000 different genes, which are 3% of our genes) that gives rise to an equivalent number of olfactory receptor types, each specific for particular odorants. These genes are expressed differently in different individuals, so a smell (the product of a combination of odorants) that is pleasant to some people can be non-detectable or obnoxious to others and in a minority of cases can produce physiological reactions and symptoms of illness. Movement of air-bodies is complex because there are 3 dimensions to consider, for example at some times of day upwards dispersion is restricted by thermal inversion, which means that outdoor odour can be more intense at some times of day than at others (normally outside working hours).

Increasingly, the importance of conserving the planet's **phosphate** is being recognised. At the present rate of exploitation, the phosphate industry expects the current economic reserves to be exhausted in about 70 years (Driver et al., 1999). There could then be another 200 years of rock phosphate that is more expensive to extract and that has a larger burden of contaminants. At the present rate that we are squandering the planet's phosphate, the industry says it will be exhausted in less than 300 years. Phosphorus is essential for all life because it is part of DNA and an essential element of all living cells; there is no substitute. Phosphate rock contains cadmium in greater or lesser amount, so mining new rock brings „new' cadmium into the anthropogenic cycle. Sewage sludge contains significant amounts of phosphate. The most cost effective means of recycling phosphate and conserving it is to use biosolids on land as a phosphate fertiliser (see also Evans and Johnston, 2004). Extracting phosphate from incinerator ash costs six-times as much as from rock phosphate and has a large environmental footprint because of the energy and chemicals involved. Modern discharge consents for many of the larger WwTW have increased the amount of P in sludge because they require that effluents only contain 1 or 2 mgP/l (e.g. CEC, 1991), in some cases even less. In developed countries, the fear of adventitious contaminants should no longer be a barrier to land application of biosolids because they are excluded at source (Figure 1). If, as the phosphate industry says, the planet's reserves of P are only 100 years at the present rate of exploitation, it must be verging on criminal irresponsibility to squander biosolids-P.

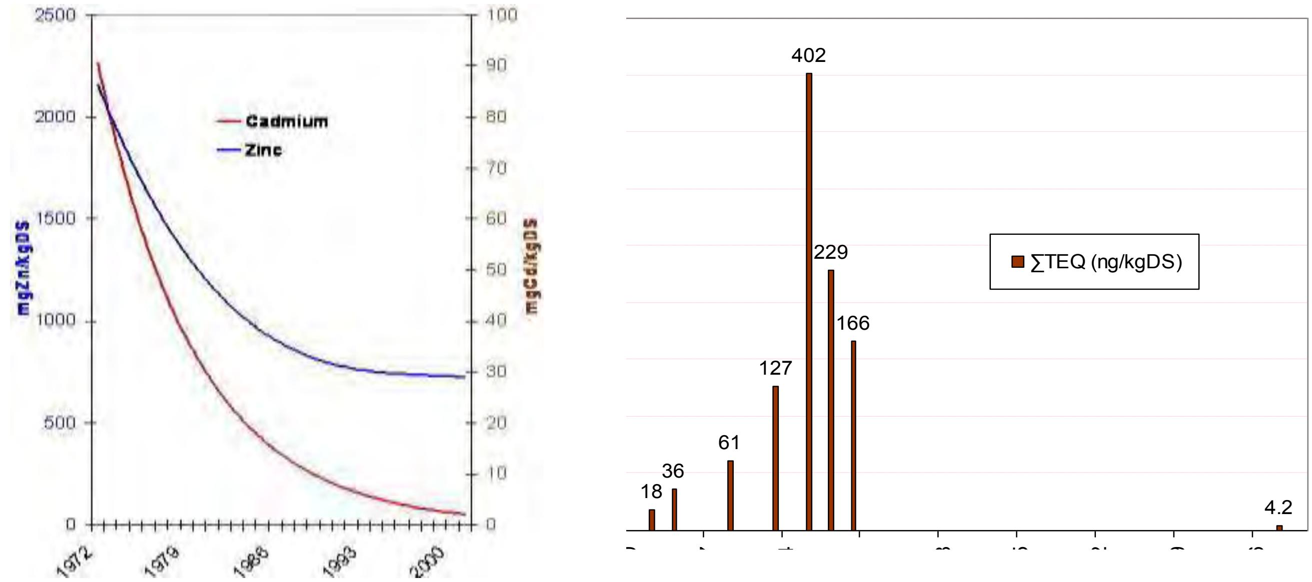


**Figure 1 Changes in concentrations of potential pollutants in digested sludge from West London: left cadmium and zinc and right dioxins and furans**

**Land application** of biosolids is an efficient means of stewarding and recycling the phosphate that we have in the anthropogenic cycle. Land application sequesters some carbon in soil, which gives the practice a credit as regards global warming potential (GWP). It is generally the most sustainable environmental option provided it is not unwelcomed by people living near the fields where it is used, i.e. it must not stink. Some people who are upset by stinking biosolids check that universal reference source, the web, and find (mis)information about chemical contaminants and disease, which they use to reinforce their demands that operations stop, but odour was the root and the hostility (outrage) was compounded by misinformation.

A fundamental of land application is that the biosolids are being used as part of crop nutrition and therefore rates should be set having regard to the agronomic value of the biosolids for the particular crop, soil and climate; in addition, the farmer should be given adequate advice about the complementary fertiliser necessary for optimum yield.

Regarding the future for land application; I think the management guru Peter Drucker summed it up nicely when he said "The best way to predict the future is to create it", in other words, run a quality assured land application programme that complies with all legal and voluntary requirements and that is not unwelcome in the community and publicise the good news of biosolids recycling (e.g. Lagerberg, et al., 2008). That will create a secure future for biosolids recycling because manifestly it is so environmentally beneficial.

I believe that branding and publicity assist the success of land application. Branding can differentiate good operations from the rest and it can boost morale. Biosolids recycling should be a good news story and is therefore something to celebrate. When biosolids recycling is public knowledge, it cannot be made into a sensational exposé. When contact phone numbers are displayed prominently, people are able to seek advice or complain easily, which is better than that they hunt around for answers getting more angry and frustrated.

The following is a brief discussion of some aspects of my experiences of sludge treatment. I do not sell sludge treatment technologies and have no financial or other potential conflicts of interest.

**Dewatering**

Dewatering is a vital step in many sludge treatment processes. Most often this is a choice between a belt filter press (BFP) or a centrifuge. Plate-and-frame [chamber] presses have been installed seldom in recent years because, although they are able to extract a little more water, the capital cost is much greater and the manning requirement is also greater. Centrifuges use more power than BFP, achieve a few percent dryer cakes, require little operator attention and are more predictable (Evans, 2006). "A few percent dryer cake" might not sound much but one tonne dry solids [1tDS] at 21%DS is 4.76 t cake; at 24%DS it is 4.17 t, a difference of 0.6 tonnes cake (water) which is a significant difference in the cost of haulage, or drying (water evaporation) etc.

Polyelectrolyte is necessary to condition the liquid sludge in order to release water. It is important to get the optimum polyelectrolyte for the particular sludge and to add the optimum amount to get the best cake but this varies with sludge quality, flow rate and solids content. Continuous automatic polyelectrolyte dose optimisation is currently more practicable for centrifuges than BFP. The surface chemistry of the sludge particles changes with time over both short and long time scales. The "Sludge Octopus" by Alfa Laval (www.alfalaval.com/octopus) is the most developed commercially available real-time dose optimisation system that I am aware of. It uses feed-forward from the properties of the feed sludge and feedback from the centrate turbidity and the resistance on the centrifuge scroll to compute the optimum polyelectrolyte dose and drive the dosing pump.

Two significant disadvantages have emerged for centrifuges, both of them resulting, I think, from the high shear forces experienced by the sludge as it enters the spinning centrifuge bowl. The first applies to sludge that has not been stabilised adequately; centrifuge cake can smell much worse than cake from a BFP. I think that shear disrupts domains of non-stabilised sludge (especially waste activated) which then biodegrade and yield malodorants. Charlotte in N. Carolina, USA had been recycling BFP cake to farmland successfully for many years, after it switched to high-solids centrifuges there were so many complaints about odour when the cake was spread that it switched back to BFP. The second disadvantage is that the number of colony forming units of *Escherichia coli* [faecal coliforms] increases after dewatering (except where the sludge is sterilised under extreme conditions, such as thermal hydrolysis, prior to digestion). The reason is not understood fully, but the result can be non-compliance with regulations. I think the shear disrupts clumps of cells, which makes more colony forming units; others think that centrifuging activates colonies that were „viable but non-culturable'. Whatever the reason, there is no real increase in disease transmission risk, these are after all only indicator organisms, but regulations are based on the numbers measured.

There is an exciting development on the horizon for dewatering. Ashbrook Simon-Hartley (www.ashbrookcorp.com) has been developing EKG (electrokinetic geosynthetic) belts for new and existing BFP. During the initial development phases, a voltage gradient of 30 volts between the belts produced cake in excess of 40% dry solids; with no voltage gradient the cake was only about 20%DS (McLoughlin, 2005). Cake from a BFP with EKG will be drier than from an existing BFP or from centrifuges and it will not suffer the problems of odour or increased *E. coli* numbers that are a feature of centrifuges. It is intended that EKG belts will be available as replacements for existing machines. Elcotech www.elcotech.ca also applies the idea of moving water through cake under an electrical potential gradient in order to achieve greater water removal with their Cinetik electro-dewatering machines. Combustion could even become truly energy yielding.

## Liquor treatment

Dewatering liquors can account for 20% of the load of N and P if they are returned to the treatment works. The load is even greater when the WwTW is used as a regional sludge treatment centre. Various high-rate biological treatment processes have been developed to strip nitrogen and convert it to nitrogen gas. However the nitrogen and phosphate can be recovered as struvite (magnesium ammonium phosphate) and ammonium sulphate both of which are valuable fertilisers (Evans, 2007). Brisbane Water Enviro Alliance (BWEA) has developed struvite crystallisation at Oxley Creek WwTW (Solley, 2006) and it has also been developed by Ostara Nutrient Recovery Technologies Inc. at Edmonton in Canada (Britton et al., 2007).

## Incineration and other thermal conversion

If landfill is discouraged, as it is in the EU, ocean dumping is banned and land application is not possible, combustion is the most [only] proven alternative. Combustion is sometimes portrayed as energy recovery but this is arguable because sludges start out with large initial water contents, which means just getting sludge to an "autothermal" condition is generally a challenge, i.e. getting it to a moisture content where combustion is sustained without requiring additional fuel is difficult. Drying dewatered sludge in an evaporative [thermal] dryer consumes energy that would otherwise be supplemental fuel in an incinerator. Energy-neutral disposal via combustion has been a reasonable target because of the limitations of mechanical dewatering. The water in sludge cake contributes to the volume of gasses that must be cleaned before emission and, since emission cleaning can account for 50% of the operating cost, it makes financial sense to minimise the amount of water. The energy yield is greater when incineration is combined with advanced anaerobic digestion. On 4$^{th}$ April 2008, Severn Trent Water in the UK announced that it would be closing its Coleshill sludge incinerator because, although it met emissions limits, the biosolids were fit for agriculture now that metals discharging industries in the area had declined.

Some power stations, cement kilns, etc. burn sludge along with the conventional fuel. However, the European Commission has said the legal classification of sludge is „waste' and if a facility burns „waste', it must comply with the Waste Incineration Directive (WID) (CEC, 2000). Cement kilns are willing to reduce their fossil fuel usage by burning other materials such as used tyres and sludge provided it is not detrimental to the quality of the cement, but coal-fired power stations have been reluctant to be brought under the WID. It would seem sensible and proportionate to have similar emission limits [proportionate to risk] for all combustion plants, irrespective of whether they are burning waste, fossil fuel or renewables, though it would be wasteful to spend significant sums on monitoring when there is no risk of exceeding safety thresholds.

Gasification is combustion in restricted oxygen such that there is conversion to volatile hydrocarbons, equivalent to pyrolysis. Gasification might be more publicly acceptable than incineration. It is a technology that works for wood and other materials but, despite well-funded projects, no one has made it commercially viable for sewage sludge. This is not to say that gasification of sludge is impossible, just that many have found it very difficult. In March 2008, MaxWest announced that Sanford, Florida will be the first municipality in North America to adopt its gasification system as an "efficient, cost-effective and environmentally friendly way to dispose of biosolids", but all of the gas that it is planned to produce will be used to heat the dryer to dry the sludge that will be fed to the gasifier – how green is that? Incineration is much easier.

Perhaps if sludge has to be incinerated the ash should be stored separately so that when the economics make it viable, phosphate can be recovered.

## Anaerobic digestion

For several years, there has been sustained interest in enhancing the performance of anaerobic digestion (AD) of sludge to increase the yield of methane-rich biogas and to attain greater and more assured reduction of the microbiological indicator organisms. AD has been widely used for sludge for more than 70 years. It is reliable, robust and tolerates variations in sludge characteristics. It is a biological process and therefore susceptible to toxic shock but such events are infrequent nowadays because of the success, established over many years, of controls on discharges from industry and the general restrictions on use of dangerous substances (Figure 1) (e.g. CEC, 1976 and amendments).

The biogas is typically two-thirds methane and the rest is mainly carbon dioxide; the actual proportion depends on the proportion of fat, carbohydrate and protein in the organic matter. For more than 70 years biogas has been used to generate electricity by burning it in adapted engines; the cooling water from the engines has been used to heat the digesters and for space heating (combined heat and power, CHP). Engines convert around 40% of the energy in the biogas into electricity, the rest is heat. The $CO_2$ from burning biogas is short-cycle and so has no global warming potential (GWP) but methane ($CH_4$) that leaks has significant GWP (21 times that of $CO_2$). If there are secondary digesters [storage tanks] they should be covered to capture the biogas and reduce GWP. Fuel cell technology is coming of age and there some operational installations on WwTW; fuel cells increase the electricity efficiency to 60%. Where there are no engines the biogas can be used in boilers to heat water. A flare is always needed for excess gas including engine shutdowns. Biogas can be used on site or piped to a more convenient location, for example siting a CHP engine in a village, hospital, industrial area, etc. It has also been used in road vehicles for many years (Figure 2).

Use in vehicles has been developed, especially in Sweden where buses, refuse trucks and taxis run on compressed methane derived from biogas. They advertise this proudly, it is renewable energy with less polluting emissions than petroleum products, so combating climate change and improving urban air quality.


**Figure 2 Using biogas as road fuel around 1943 - the idea is not new but the implementation has improved**

The optimum temperatures for AD are mesophilic (35 ºC) or thermophilic (55 ºC), abbreviated as MAD and TAnD respectively. MAD is more widespread. TAnD is quicker and causes greater reduction of enteric pathogens and the digestate might be easier to dewater. TAnD used to be thought to be less stable than MAD but apparently this was a perpetuation of faulty research results. TAnD has been implemented successfully at several works in USA.

Modern AD plants aim to maximise the feed solids of the sludge, within the limitations of the ability to mix the digester, and store the biogas away from the digesters, frequently in a double membrane fabric gas holder. They can achieve 67% volatile solids destruction (VS is measured by loss on ignition, it is equivalent to organic matter) if there is pre-treatment to maximise digestibility. Greater VS destruction means the digestate is less smelly and there is more biogas – it is a linear relationship. Digesters with a high "aspect ratio" (diameter:height) are easier to mix. In the USA, digesters typically have low aspect ratios (pancakes) but apparently, this is historic and has no objective basis. Digesters used to have floating roofs which were used as gas holders but there is appreciable loss of gas from the annular sludge surface between the wall and the roof. In a modern biogas facility with CHP raw sludge is worth £100/tDS (tonne dry solids) in the UK in income from electricity sales with "Renewable Obligations Certificates", which is a premium payment for renewable electricity.

AD is performed by two families of bacteria: acidogens and methanogens. Acidogens break down large complex organic molecules into small organic acids. Methanogens convert the organic acids into methane and carbon dioxide (Figure 3). The methanogens in MAD are predominately fragile spaghetti-shaped *Methanosaeta*, whereas in TAnD they are much more resilient coccoidal *Methanosarcina* (Chapman and Krugel, 2008). Chapman and Krugel (2008) suggest that methanogens suppress odour forming bacteria by competition and that this difference in physical resilience is a factor in the issue of odour after centrifuge dewatering.

Traditionally methanogens and acidogens have been expected to co-exist in single mixed digesters but, actually, they like different conditions. Acidogens work (optimally) at a pH of 5.0 to 5.5 and their growth rate is relatively rapid so they are happy with 1 to 3 days' retention whereas methanogens prefer pH 7.5 and grow slowly so they require more than 7 days' retention. The hydrolysis and fermentation bacteria produce a small amount of hydrogen, which acidogens use, but which inhibits methanogens. It is perhaps surprising that people did not start to look at separating the two phases until the 1970s and it has been slow to catch on. Slowly people realised that either by re-configuring their existing digesters, or by adding tanks in front of them, they could achieve a short-retention acid phase separate from the longer retention methanogenic phase. This not only gave greater solids breakdown, less digestate and more gas, but it also gave enhanced destruction of the faecal bacteria that are used as indicators of pathogen die-off.

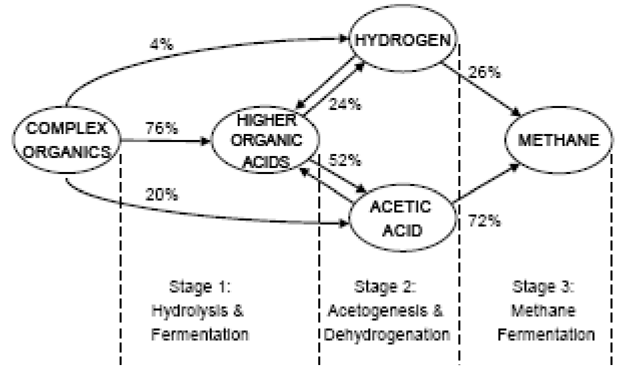


**Figure 3 Simplified anaerobic digestion pathways** (Harrison et al., 2005a)

United Utilities in the UK developed pseudo plug-flow acid phase by using six tanks in series (e.g. Mayhew, et al., 2002) and has found differing conditions through the sequence of tanks because of the differences in microbial ecosystems that develop. Plug-flow means greater reduction in faecal bacteria because there is less by-pass or short-circuiting. Thames Water (Asaadi and Marsh, 2005) has also achieved enhanced faecal bacteria reduction, biogas yield and VS destruction but using a single acid phase tank. Temperature phased AD has also been used with success. At an existing AD site, one of these enhanced-efficiency routes can be achieved by reconfiguring the pipework from digesters operating in parallel to some form of series operation.

Primary sludge digests easily but secondary sludge (particularly from activated sludge) is more difficult particularly because of extra-cellular polymer and cell walls that protect the cell contents from degradation (Figure 4). Figure 3 shows that the first stage is hydrolysis but bacterial hydrolysis alone is quite slow when working on large sludge flocs. Panter (2006) reflected that there is a 1014 size difference between a 50µm sludge floc and a 0.8nm acetic acid molecule, which is comparable to the whole of London and a house brick. When cells die they release hydrolytic enzymes that cause biochemical hydrolysis. There has been a growth in disintegration technologies to reduce the cities to bricks and release hydrolytic enzymes. Ultrasound has had variable results but there are some successful installations that have been operating for several years. The design of the ultrasound horn is a factor and it has been found serendipitously that a buffer tank after sonication has the benefit of allowing time for enzymatic hydrolysis to maximise biogas yield in AD. MicroSludge™ uses a high pressure homogeniser with alkaline hydrolysis and is under active evaluation (www.microsludge.com). Mechanical disintegration does not affect the "pathogen reactivation" phenomenon associated with centrifuge dewatering.

Prague WwTW and Technical University developed an adaptation for thickening centrifuges to increase the digestibility of [secondary] sludge. The thickened sludge is mechanically lysed by hardened knives at the outlet weir of the centrifuge (www.lysatech.com). It can be retrofitted to existing thickening centrifuges and from my own observations at Prague it is very effective. Prague WwTW has 12 digesters that have been converted from MAD in parallel to 6 series-pairs being fed lysed sludge and operating TAnD. This reduces by-pass. They are fed hourly. There is 55,000 $m^3$ digester capacity and they produce 50,000 N $m^3$ biogas/day from which water is removed by condensers (6 °C water-cooled) and activated C to remove siloxane (from 40 mgSi/N $m^3$ to 5). TAnD plus lysing centrifuge has proved stable. Compared with MAD, there is less foaming, more biogas and less $H_2S$ but more siloxane (there was only 2ppm Si in MAD biogas) and calcium carbonate in the engines, the latter is thought to be aerosolised. Lysing centrifuges reduce the viscosity enabling digesters to be fed at 10%DS. The digested sludge is dewatered in CentriPress centrifuges: the cake is 32%DS, it has low odour and was granular and not sticky.

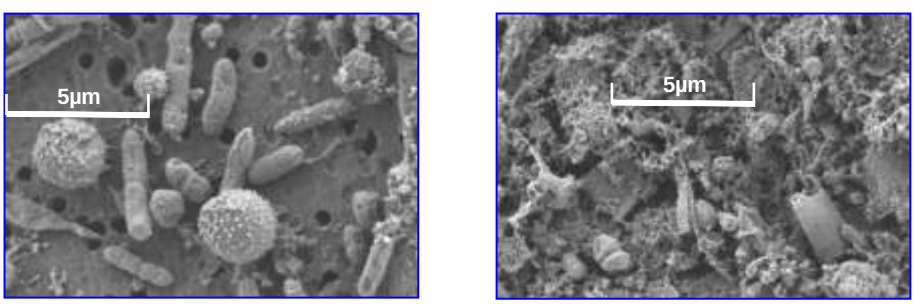


**Figure 4 Waste activated sludge: untreated (left) and after disintegration (right)** [courtesy MicroSludge™)

Cambi thermal hydrolysis was invented in 1995; 13 plants are operating worldwide, including Brisbane, with 7 more under construction/commissioning and more expected in the future (www.cambi.com). Feed sludge (dewatered to about 18%DS) is heated to 160 ºC (6.5 bar pressure) with steam. The combination of pressure-cooking for 30 minutes followed by a flash pressure drop sterilises and disintegrates the feed sludge. Thermal hydrolysis reduces the viscosity of the sludge to the extent that 13%DS hydrolysed sludge is as fluid as conventional sludge at 6%DS, which is roughly the limit for full mixing (Harrison et al. 2005b). It eliminates the "reactivation" phenomenon. Even activated sludge has a high biogas yield following Cambi. The digestate is very easy to dewater; cake in excess of 30%DS from a conventional belt press is typical resulting in considerable reductions in operating costs (Evans, 2003).

Considering 1 tDS raw sludge (80%VS), if it is treated by conventional MAD achieving 40%VS destruction and dewatered to 23%DS Class-B cake, there will be 2.957 t cake (containing 2.277 t water). When the MAD is preceded by Cambi, the VS destruction increases to 62% and the cake will be 34%DS; the weight of Class-A cake will be only 1.482 t (containing 0.978 t water).

I first heard about Cambi in 1997 and thought it sounded too good to be true, so I got a party of seven experts from different parts of Thames Water to see if it was. We could not find any flaws and so we bought a retrofit to convert an existing 2-digester MAD facility into a regional centre. The works had primary settlement with biological filters but within 20 km there were two more WwTW of similar size but using extended aeration. Extended aeration counts as raw sludge and in order for land application to continue, it needed to be treated, which was going to be difficult by "conventional" means. Retrofitting Cambi has more than trebled the capacity of the original digesters; it explodes the aerobic biomass and renders it digestible. The performance of the sludge treatment centre is exceeding expectations.

Biogas from other organic wastes has considerable potential for WwTW that already have, or are planning AD. Denmark made this part of its national energy strategy and there are more than 20 centralised biogas plants co-digesting a variety of materials and operating CHP (Evans, et al. 2002). The digestate is used on farmland to build soil organic matter and replace mineral fertiliser. Sewage sludge or manure provides the base load and food waste etc. provides additional biogas and gate-fee income. Preventing dissemination of animal disease via food waste recycling is a priority in the EU. In effect food waste must be sterilised prior to AD. Thermal hydrolysis would enable the loading of digesters to be trebled, but with the increased biogas [VS destruction] and increased dewatering the quantity of dewatered cake would be unchanged. All of the digestate would be Class-A. The Danish biogas market is quite mature and gate-fees for receiving wastes at co-digestion facilities are based on the biogas yield potential of the waste; plants might pay for "good" fatty/oily wastes because of the ease of treatment and the high gas yield. Bacteria can become acclimated to treating wastes that could otherwise cause toxic shock; as a plant manager said to me, "it is a good thing that the bacteria cannot read the text books." Source separated and supermarket food wastes invariably contain physical contaminants, the best answer that I have found is Dewaster® (Evans et al. 2007).

**Lime stabilisation**

Lime is used to treat sludge at many sites. The capital cost of the equipment is low and it is quick to install. It is very effective in destroying faecal organisms, but the product from the cheapest systems can be smelly and it is worth spending the extra money on a good quality [ploughshare] mixer to achieve lime stabilised cake with acceptable odour. The operating cost of lime stabilisation is quite high because of the cost of lime, there is also an issue that some who have selected it because of the already mentioned advantages have not thought about the lime requirement of the surrounding soils. If soils are calcareous, a bit more lime will not make any difference but if they are neutral then the addition of unnecessary lime can induce trace element imbalances. In areas of acid soils, lime stabilised biosolids are very valuable. Some alternative alkaline additives (e.g. cement kiln dust, wood ash) also contribute potassium, which makes the product a very useful agricultural input. The treatment factors are pH, temperature, ammonia and desiccation. Lime slaking is very exothermic:

$$H_2O + CaO \rightarrow Ca(OH)_2 + \text{heat}$$

The pH of the biosolids decreases slowly (months) after it has been treated because of reaction with atmospheric carbon dioxide.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O + \text{heat}$$

The RDP system (www.rdptech.com) uses lime or another alkaline additive supplemented by electrical heating to achieve the desired temperature, because slaking lime is an expensive source of heat, though it is a good means of raising pH. Done properly with due regard to "welcomed practice" lime stabilisation is very useful. The product is agricultural lime *plus* nutrients and needs to be sold with appropriate agronomic advice.

**Composting**

Composting converts the labile carbon fraction that AD converts to biogas into $CO_2$; it uses energy in the process and volatilises nitrogen as ammonia. Compost has much less fertiliser replacement value than digestate but it has other benefits. For those who want to make growing media or to sell bagged soil improver to gardeners, composting is the preferred route (Evans and Rainbow, 1998). Compost is ideal for soil blending. It is possible to develop markets for composted biosolids within municipal areas, thus diversifying from agriculture. In Helsinki, Finland the city's gardeners and landscapers buy all of the composted biosolids the 800,000 population equivalents (p.e). WwTW produces.

Sludge cake is not ideal for composting because it has more nitrogen and moisture than is ideal for composting and because it lacks structural strength; these factors combine to render it difficult to keep aerobic because it uses oxygen rapidly. Generally, carbonaceous bulking agent is essential to balance the C:N and increase the air-porosity.

The Greater Moncton Sewerage Commission (GMSC) switched from lime treatment to composting with forestry by-products (bark and shredded wood) because the product is more compatible with the needs of their markets. The land application season is quite short in New Brunswick, Canada whereas compost has a much longer season of use. Also the biosolids from their lime treatment system was quite odorous.

The Gore composting system at Moncton was the first I had seen; it is shown in Figure 5, it really was impressive.. There was no odour, because odours biofilter out before the air passes through the covers. The composting is not rushed; there are 8 weeks under the covers and then 6-10 months' maturation to give a stable, mature compost. Each windrow is moved after 4 weeks to re-mix the material and disrupt any preferential aeration pathways that have developed. The compost sample I got did not "fragrance" my hotel room, which is a good test. Moncton is quite wet (700-800mm rain per year) the covers keep the windrows dry and any exposed aeration channels drain surface water off the concrete pad. It also gets cold in winter so freezing of the covers to the composting pad could have been a problem. GMSC overcame this by circulating glycol through pipes laid in the concrete pad; this conducts sufficient heat from the windrows to keep the pad ice free. The aeration fans are controlled by temperature and oxygen sensors inserted in the windrows, the fans run for 10-15 minutes per hour. The operating costs are Can$ 40-50/t at 30%DS. Electricity costs $1500/month. The capital cost for this 90,000 p.e. (approx. 3,300 tDS/y) facility was $4-5 million.

**Drying**

Drying is a seductive process, the product is free-flowing and clean to handle. However, thermal drying is expensive; dryers are prone to "thermal events" that if not controlled can result in fire or explosion and drying can reduce agronomic value. One misconception was that because agricultural fertilisers are granular, granular biosolids would be a direct substitute; this is a fallacy because biosolids only contain one-tenth the concentration of nutrients and therefore a farmer would need a larger capacity spreader. However dried biosolids are attractive for particular circumstances such as where land application sites are far distant from the WwTW or for particular markets such hobby gardeners, golf courses and amenity uses.

The latent heat of evaporation of water is 2260 $kJ.kg^{-1}$; to raise the temperature of water from 25 °C to 100 °C requires 313.8 $kJ.kg^{-1}$, therefore the minimum heat requirement to evaporate water at 100% efficiency is 2573800 $kJ.t^{-1}$ water evaporated or 714.9 $kWh.t^{-1}$ water evaporated. At UK prices for biogas-generated electricity (since electricity generation is an alternative use for biogas) and for loading and hauling biosolids and if a **thermal dryer** is 70% efficient one could haul water to a location approximately 255 km distant from the WwTW for the amount of energy required to evaporate it. Thermal drying using fossil fuel or biogas is questionable for many locations.

**Solar drying** was practised widely until the second half of the twentieth century but footprint, labour and unreliable weather caused many to switch to alternatives. Solar drying was revived by the use of "greenhouses" and computerised turners that automate the work of disrupting the crust and maintaining an evaporative surface. Thermo-System GmbH was founded in 1997 by scientists at the University of Hohenheim (www.thermo-system.com) and now has more than 100 plants worldwide serving populations ranging from 1,000 to 650,000 p.e. including Brisbane and Melbourne. Veolia has followed with Solia™ (www.veoliawaterst.com/solia/en/) which has 7 plants in France ranging from 9,000 to 70,000 p.e. Both systems claim to be able to dry liquid or dewatered sludge and to produce Class-A biosolids with no emission of odours.

**Figure 5 Gore windrow cover deployment and retrieval machine at Moncton, NB, CA - the cover is tied down to limit windlift when the water ballast tubes have been drained.**

**Reedbeds**

Reedbed treatment of sludge started in the 1980s and has been gaining acceptance steadily. Engineered reedbeds can be a very effective form of sludge treatment. The beds are sealed; they contain drains set in a bed of aggregate on which reeds are planted. Sludge is applied in shallow layers to the beds in sequence. Odour is contained within the reed canopy, even in winter. The reeds excrete oxygen from their roots which maintains the root zone aerobic. Bacteria initially, and later earthworms, mineralise the sludge and sanitise it. I visited Helsinge WwTW, Denmark (20,000 p.e.) in December 2003 and was very impressed by the absence of odour and the clarity of the treated water. The reeds were brown and appeared dormant but there was no odour and the treated water from the drain was crystal clear. The beds can be loaded at 55 kgDS/$m^2$ per year for about 15 years before they have to be dug out, and when they are, E. coli is $log_{10}$-2 and Salmonella <2 /100gDS (i.e. Class-A). The mature material is 30%DS and 45%VS; it is odourless and soil-like. The process (described by Neilsen and Willoughby, 2006) requires negligible energy but it does require quite a large area of land. Orbicon in Denmark designed the Helsinge plant and probably has the most experience of this type of treatment at present http://www.orbicon.com/Sewage.2473.aspx. The liquid sludge applied to the reedbeds at Helsinge is from extended aeration wastewater treatment but it has been mineralised to the extent that the average VS is 52% (range 50-60%VS). The pH of the feed sludge is in the range 7-8. Energy and chemical use are very low.

**Conclusions**

This paper has reviewed the various types of sludge treatment from the perspective of a Soil Scientist, biosolids recycling practitioner with no vested interest in any particular technology. Hazard Analysis Critical Control Point is a very useful tool for designing sludge treatment processes containing as it does the engineering principle of Failure Mode and Effect Analysis. A fundamental consideration should be whether the process and product will be welcomed by neighbours and other stakeholders. The world price of mineral fertilisers has leapt recently and so have agricultural commodity prices, there seems little likelihood that these trends will be reversed. The world's population is predicted to increase from 6 billion today and top out at 9 billion in 2050, by which time there will be less farmable land because of climate change. There are already warnings that mineral fertiliser might be becoming scarce in 2009 because of global demand and supply. In the light of this situation, land application of biosolids should continue to be the future since it contains fixed nitrogen, phosphate, some potassium, magnesium, sulphur and trace elements. Attention to source control of contaminants is essential as is proper treatment, especially avoidance of odour nuisance, and an understanding of the agronomy of biosolids so that reliable advice can be given to farmers.

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