Energy and nutrient recovery from sewage sludge via pyrolysis

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Abstract Energy recovery and nutrient reuse from sewage sludge has traditionally been achieved via anaerobic digestion/power generation with land application of the biosolids. By contrast, thermal processes such as pyrolysis have typically been used only for energy recovery. One such technology has demonstrated at commercial scale that all of the energy in sludge can be beneficially recovered and reused. No attempt was however made to recover and reuse sludge nutrients. There are many potential benefits of using pyrolysis for both energy and nutrient recovery. Firstly, unlike digestion, the principal energy product is oil, which can readily be stored and used when required, ensuring that energy recovery is maximised. Secondly is that the sludge nutrients are recovered in the pyrolysis char. Laboratory soil incubation studies using char from the Subiaco demonstration plant were conducted over an eight-week period to confirm nutrient availability. Results from this study showed that the phosphorus in the char is plant available although the nitrogen was insoluble. Based on these results it appears that there is potential to use pyrolysis as an effective means to recover and reuse both the energy and the very valuable phosphorus present in sewage sludges.

Keywords Biosolids; energy recovery; nutrient recovery; pyrolysis; sewage sludge

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Introduction

The ENERSLUDGE™ technology has been developed and commercialised over the past 15 years, with extensive pilot plant demonstration programs conducted in both Australia and Canada (Bridle and Campbell, 1986; Bridle *et al*., 1989; Gough *et al*., 1991). The technology involves pyrolysis of dry sludge pellets at about 450°C and a pressure of 1–5 kPag in the absence of oxygen. Under these conditions the process converts the dry sludge into oil, char, non-condensed gas (NCG) and reaction water (RW). A contract to build the first commercial demonstration plant was awarded in late 1996 and called for the design, construction, commissioning and operation of a 25 dry t/d sludge pyrolysis plant, at the Subiaco WWTP in Perth, Western Australia. The plant comprises sludge dewatering and drying facilities, the pyrolysis (conversion) plant, energy recovery facilities (the Hot Gas Generator) and gas cleaning equipment. A back-up lime stabilisation facility was also provided for periods when the dryer is down for maintenance. A process flow diagram of the conversion plant is shown in Figure 1.

After dewatering and drying to 95% TS, the pellets are then fed to the conversion plant. The pellets are first heated to 450°C in the absence of oxygen at a pressure of 1.5 kPa producing char and a raw pyrolysis gas. The char and gas are re-contacted in the second reactor, also operated at 450°C to facilitate the catalysed vapour phase reactions that refine the raw gas, producing mainly hydrocarbons. The catalysts necessary (alumina silicates and heavy metals) are inherently present in all sewage sludges.

The refined vapours are then condensed to 50°C in a direct contact spray condenser using cooled RW as the cooling medium. The char is cooled to 70°C and then used as the main fuel in the Hot Gas Generator (HGG). The condensed products are separated in an

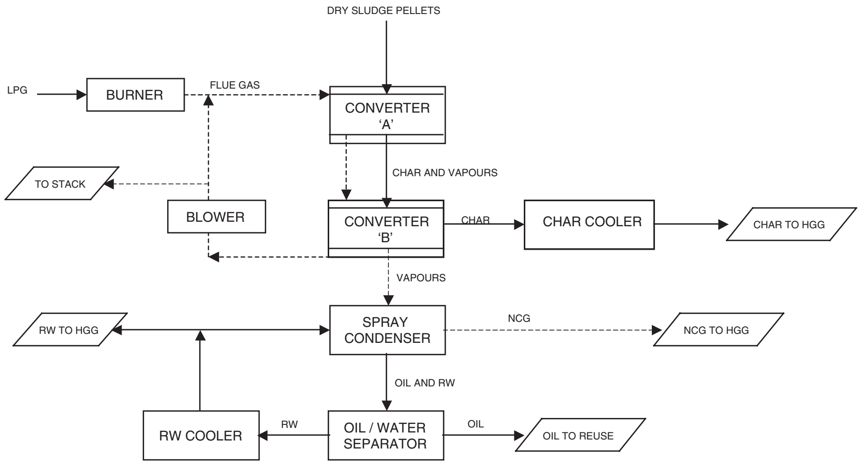

Figure 1 Conversion plant process flow diagram

oil-water separator, with the oil stored prior to use as a fuel off-site. The RW is cooled using once-through secondary effluent and then used to condense the incoming vapours in the spray condenser. Excess RW and the non-condensed gas are combusted in the HGG.

The HGG combusts the three low-grade fuels (char, RW, NCG) to produce all the energy needed to dry the sludge. The flue gas, at a nominal 850°C, transfers heat to a closed-loop of drying air in an air-to-air heat exchanger. Cooled flue gas from the heat exchanger is then cleaned in a venturi scrubber and SO_2 scrubber, before discharge to the atmosphere, via the plant stack (Figure 2).

Energy recovery

The commercial demonstration pyrolysis facility was operated for a 15-month period from September 2000 to December 2001 and plant details and operational results have been reported previously (Bridle and Skypski-Mantele, 2003). In summary, the facility demonstrated that all of the energy in the sludge is recovered in the conversion products (Table 1) and that the integrated facility was a nett exporter of energy (Figure 2).

The Subiaco facility included a fluidised bed combustor (Hot Gas Generator) to combust the char, NCG and RW to provide all the energy required to dry the sludge. The oil was used off-site as an industrial fuel in boilers for steam raising. As can be seen from Figure 2, the facility, when processing 15 dry t/d of sludge, demonstrated a nett energy export of 7.7 GJ per tonne of dry sludge processed. If the oil were combusted in a diesel engine to produce electricity, the process would generate 925 kWh/t of sludge processed.

Substantial monitoring of the Subiaco facility also confirmed the unparalleled control of heavy metals previously demonstrated during pilot plant studies (Bridle *et al*., 1990). In summary the process removes mercury from all the conversion products, with the remaining heavy metals immobilised as sulphides in the char (Bridle *et al*., 1986). Previous work has also shown that organochlorine contaminants in sludge such as PCBs, EDCs,

Table 1 Average conversion product data

Product	Yield (%)	GCV (MJ/kg)	% of sludge energy
Oil	29	30	45
Char	43	18	40
NCG	14	15	11
RW	14	6	4

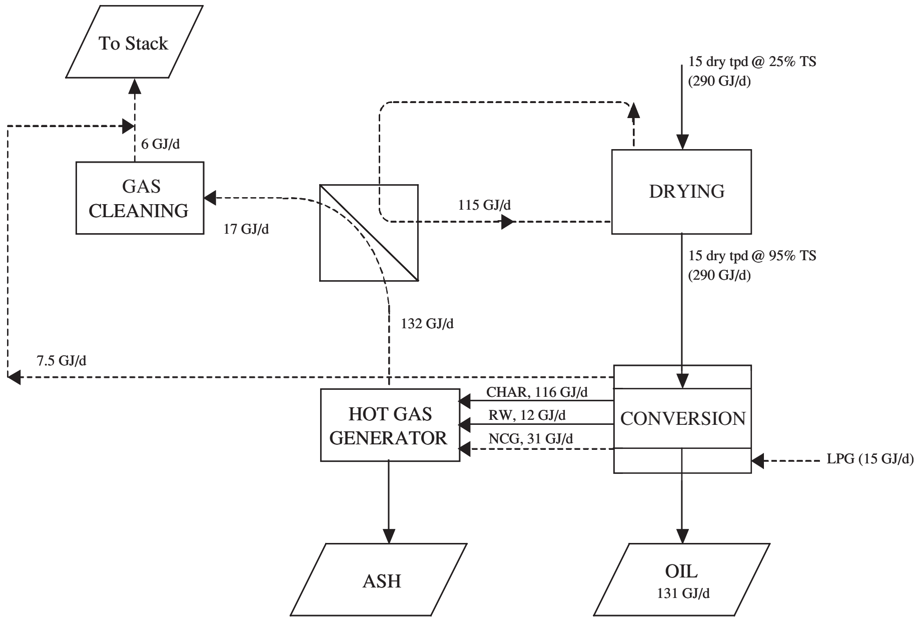

Figure 2 Energy balance for integrated demonstration plant

insecticides and pesticides as well as pathogens and viruses are catalytically or thermally destroyed (Bridle *et al*., 1990). Thus the char should make an acceptable soil amendment product, which also has the added advantage of generating carbon credits, since unlike in sewage sludge, all the carbon is “fixed” and cannot be mineralised.

Nutrient recovery and reuse

Nutrient monitoring of dried sludge pellets and char generated on the same day from the Subiaco demonstration plant has revealed that essentially all of the phosphorus and 55% of the nitrogen is retained in the char (Table 2).

All the char produced by the Subiaco demonstration plant was used as a fuel to provide the energy for sludge drying and hence no attempt was initially made to assess the reuse potential of the nutrients. Consequently, laboratory scale soil incubation studies using char from the demonstration plant were undertaken to determine nutrient availability. These studies were undertaken by Curtin University of Technology and detailed results have been reported (Pritchard, 2003) using small sample volumes of the char, which was retained when the plant was shutdown.

Laboratory scale nutrient availability studies

The objective of these laboratory studies was to determine the availability of the two major plant nutrients; nitrogen (N) and phosphorus (P) in char to assess whether the product could be considered as a fertiliser on agricultural land. It is generally accepted that chemical

Table 2 Nutrient levels in sludge and char

Parameter	% N(db)	% P (db)
Dried sludge	5.3	2.4
Char	6.7	5.6
% nutrient retained in char	55%	100%

elements in wastes can be successfully recycled in agricultural production (Kardos *et al*., 1977; Page *et al*., 1986). The rising costs of phosphatic fertilisers in agriculture and finite natural supplies have ensured that sludge derived P is considered for recycling (Kirkham, 1982). However, there is no data to date that has investigated the nutrient value of char.

To investigate the N and P fertiliser value of char, a soil incubation experiment was run over 56 days with the concentration of plant available P, nitrate (NO_3) and ammonium (NH_4) measured at four sampling dates (7, 14, 28 and 56 days). Char was compared with dried sludge pellets and dewatered digested sludge cake (biosolids) at equivalent total N loadings in soil of 250 mg N/kg. As these products contained different concentrations of P, the total P loadings varied as follows: char 243 mg P/kg, dried pellets 67 mg P/kg and biosolids 147 mg P/kg. The biosolids were sourced from the Beenyup WWTP, Perth, a secondary treatment process using anaerobic digestion and filter belt presses for dewatering. Typical properties of the char, dried sludge pellets and wet sludge cake (biosolids) used in the study are shown in Table 3.

The soil used for these studies was an infertile gravely loam from York, Western Australia and is referred to as a lateritic podsolic. One kilogram of soil samples (<2 mm) were placed in 10 cm diameter non-draining pots and the appropriate quantity of char, dried pellets or biosolids were added to achieve the 250 mg N/kg N loading. The soil was incubated at 25°C and maintained at 17% field capacity during the study. To achieve the 250 mg N/kg soil loading char, dried sludge pellets and dewatered cake (dry) were applied at roughly 4.3 to 4.9 g/kg soil, that is, very similar dry mass rates.

In addition, characterisation of available P by sequential extraction was carried out on the char, sludge pellets and biosolids using the Tiessen method (Tiessen and Moir, 1993) with sub-samples of each material blended with acid washed silica sand to provide final P concentrations of 300 mg P/kg.

The soil incubation study revealed that char would not initially increase soil mineral N values as occurs with pellets or biosolids. However, soil bicarbonate available P levels would increase slowly. At the same mass loading as dried sludge pellets, bio available P was increased significantly from 4 mg P/kg in the control to 29 mg P/kg in the pellets, 32 mg P/kg in the char and 56 mg P/kg in the biosolids at 56 days from incubation ($P<0.05$). At the same P loading rates, char P availability was lower than that from dried pellets or biosolids as per Table 4.

Table 3 Characteristics of nutrient amendments used in the study

Property	Char	Dried sludge pellets	Biosolids (wet cake)
Carbon %	47	44	41
Hydrogen %	2.8	7	
Nitrogen %	6.4	6.3	5.6
Phosphorus %	5.61	1.53	3.0
Potassium %			0.1–0.24
Sulphur %	0.5	0.7	1
Volatile solids %	65	85	85
Ash %	35	15	15
Arsenic mg/kg	2	1	3–5
Cadmium mg/kg	3	1.5	2–7
Copper mg/kg	2,600	1,100	1,000–2,200
Chromium mg/kg	80	36	40–440
Mercury mg/kg	0.2	2.5	2–7
Lead mg/kg	5	50	30–150
Nickel mg/kg	35	15	20–100
Zinc mg/kg	1,700	650	640–1,900

Table 4 Available P recovered as % of total P supplied over time

	Day from incubation			
Product	7	14	28	56
Biosolids	43%	37%	33%	37%
Pellets	35%	37%	41%	40%
Char	8%	8%	11%	13%

The P fractionation data as presented in Figure 3 showed char to have a much lower % of water soluble P than pellets or biosolids as indicated by the resin extraction process, but was similar to pellets in terms of % bicarbonate extractable P. The highest fraction in char however was typically found as Ca bound inorganic P as evident by the HCl extraction. The NaOH extractant indicates Fe and Al bound P, mostly inorganic, with the char similar to pellets.

The data from the laboratory studies suggests that char would provide a source of P for plant growth and could have application on soils as a slow release form of P. Char may suit sandy soils where P leaching to surface or groundwater is an issue. Application of char to land would minimise the risk of nitrate leaching as levels of nitrate and ammonium were not increased in soil at 56 days after application. Another benefit would be that contamination by organics or pathogens is minimised due to the high temperature conversion process. In addition, the remaining heavy metals in the char are speciated as very insoluble sulphides and should not be plant available. This needs to be assessed with further test work. Preliminary calculations indicate that char would have to be applied in excess of 38 t/ha on a typical lateritic soil to exceed the contaminant limited biosolids application rate (CLBAR) of copper based on the maximum allowable soil contaminant concentrations (DEP *et al*., 2002). Other metals of concern such as cadmium would require a char loading of 250 t/ha, with other metals such as zinc, mercury, arsenic, lead and nickel listed in Table 3 much higher than this. Based on typical agronomic application rates to provide total P loadings equivalent to 100 kg/ha of superphosphate (i.e. 9.0 kg P/ha), land application rates of 160 kg char/ha would be required which is below the maximum allowable soil contaminant concentration loading. Overall, the P in char has been demonstrated in the laboratory to be able to be recycled in agriculture; however, plant growth studies to determine the

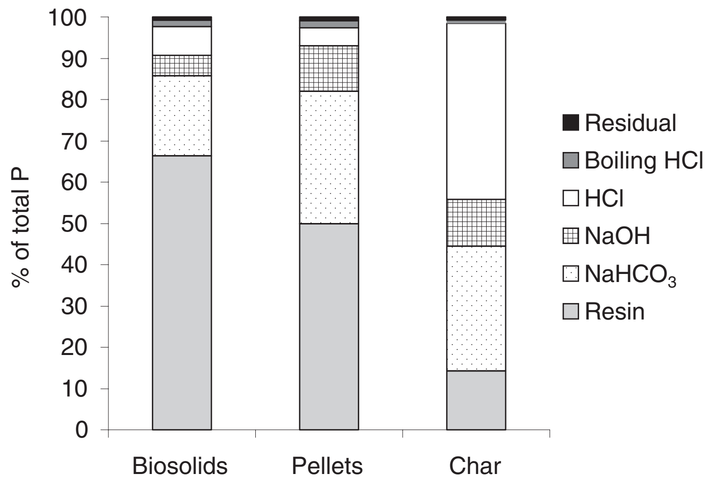

Figure 3 Characterisation of available phosphorus by sequential extraction in biosolids, pellets and char used in the study

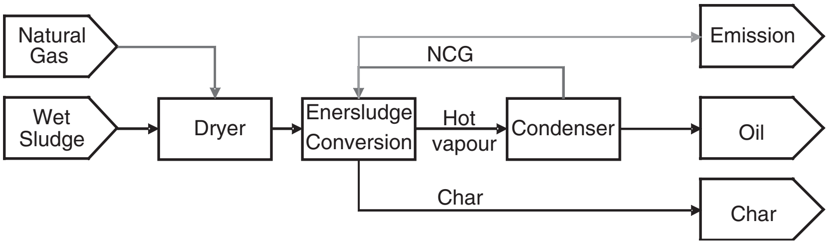

Figure 4 Simple flowsheet for nutrient and energy recovery

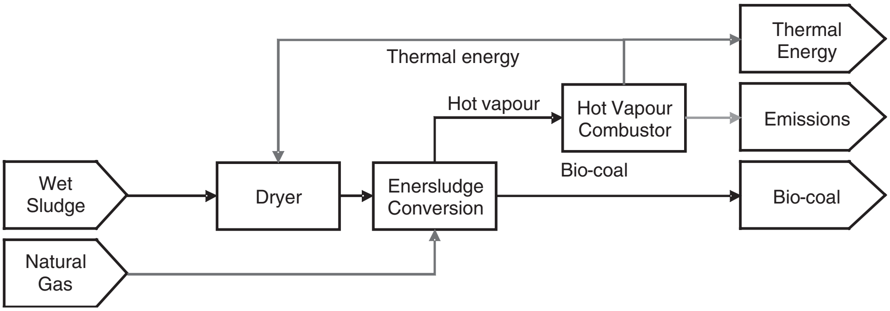

Figure 5 Partially integrated flowsheet

relative effectiveness of char as a source of P, heavy metal bioavailability and effects of other constituents in char on plant growth needs further assessment.

Flow-sheet options for nutrient and energy recovery

As mentioned previously and as shown in Figure 2, the commercial pyrolysis demonstration plant operated at the Subiaco WWTP in Perth was designed to offer only energy recovery in a fully integrated flowsheet. It has now been recognised that two other process flowsheets, much simpler in concept, complexity and cost, can be offered. Both these flowsheets produce a char product, for off-site use as a nutrient supplement or as a fuel.

The simplest flowsheet (Figure 4) uses the conversion system to produce oil for energy recovery and char for use as a nutrient or energy product. This process can be engineered in modular form and a 25 dry t/d module comprises only two 6 m containers. Whole of life costs for a 25 dry t/d "add-on" pyrolysis unit (excluding costs for sludge dewatering and drying) is typically about $US50/t of dry sludge, assuming no energy or nutrient credits.

A slightly more complex flowsheet, still providing energy for the sludge dryer, is shown in Figure 5. This flowsheet dispenses with the expensive and complex Hot Gas Generator to combust char, NCG and RW. Instead, hot vapours at 450°C are combusted in a simple hot vapour combustor to provide the thermal energy for sludge drying. The char is then again available as a nutrient supplement or energy product. Again, this "add-on" pyrolysis unit can be engineered in two 6 m containers for a 25 t/d plant. Whole of life costs for the "add-on" pyrolysis system are typically less than $US60/t of dry sludge, again assuming no nutrient credits.

Conclusions

Pyrolysis processes offer numerous benefits for sludge managers, including the following.

1. Complete energy and significant nutrient (P) recycling from sewage sludge in an environmentally sound manner.
2. Complete control of heavy metals, pathogens and organochlorine compounds present in sewage sludge.

3. Carbon credits, via renewable energy and carbon fixation credits.
4. Lower nett CO_2 emissions from sludge processing.
5. A publicly acceptable sludge disposal system.

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