Sugar Milling Research Institute

Technical Report

No. 2116

Waste Treatment in the South African Sugar Industry

Njodzi Zizhou

Date: 12 August 2011

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OBJECTIVES

- To describe the state of the art in biochemical digestion and its use in the sugar industry
- To place biochemical digestion in the context of the Sugarcane Biorefinery concept

SUMMARY

- The potential of biochemical digestion in biorefinery waste treatment in the sugar industry is reviewed in this report.
- The results of the literature review showed that aerobic and anaerobic digestion can both be used in treating waste resulting from envisaged biorefinery processes.

RECOMMENDATIONS

- The SMRI should gain experience in digestion technology through:
    - Familiarisation visits of current installed processes in the sugar industry
    - Visits to related industries with digestion technologies such as breweries etc.

KEYWORDS

- Major: Aerobic digestion, anaerobic digestion, biological oxygen demand (BOD), chemical oxygen demand (COD)
- Minor: Biogas, digester design, modelling

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INTRODUCTION

Biochemical waste digestion is the engineered conversion of organic matter by microorganisms and is used to stabilize waste prior to disposal as well as to produce nutrient rich products and methane rich biogas for energy generation. The digestate, the solid residue from the digestion process, can be used as a fertilizer and soil conditioner while biogas produced can be used to power the digester or for energy export.

The South African sugar industry is well advanced in the treatment of waste from sugarcane processing. All the sugar mills in South Africa operate some form of waste digestion except Maidstone where a zero effluent system is in place (Jensen and Schumann, 2001). Table 1 shows the current waste handling processes used at the various South African mills.

Table 1: Waste Handling Processes Used in the South African Sugarcane Industry

Effluent Treatment Process	**Mill**
Simple irrigation	Maidstone
Irrigation of dilute stream and anaerobic treatment of concentrated stream	Malelane
Anaerobic followed by irrigation	Amatikulu and Darnall
Anaerobic followed by activated sludge plant	Felixton and UCL
Anaerobic followed by Pasveer ditch	Umfolozi
Anaerobic followed by aerated basin then Pasveer ditch	Pongola
Anaerobic followed by bio filter (taken out) then activated sludge	Komati
Anaerobic followed by trickling filter then Pasveer	Noodsberg
Activated sludge, ash dams on dilute streams	Sezela
Packed anaerobic (ash dam)	Umzimkulu, Gledhow, Eston

Effluent from sugar processing plants is varied and its composition and quantity depends largely on the section of the plant from which the effluent is generated. Normal sugar milling produces liquid effluent with chemical oxygen demand (COD) concentration in the range of 1 500-2 500 mg.L^{-1} composed mainly of easily digestible dissolved sugar at a flow rate of 0.2-0.3 m^3 of effluent per ton cane crushed for factories without cane washing (Purchase, 1996). Suspended solids in this waste range from 0.6-12 g.L^{-1} (Macarie and Le Mer, 2006). The second source of effluent is the back-end or stand-alone refinery where wastewater COD and biological oxygen demand (BOD) are greater than 30 000 mg.L^{-1} and 6 000 mg.L^{-1} respectively (Huang *et al*, 1996). Thirdly, if a factory is integrated as a biorefinery, additional effluent is generated but its quantity and composition is largely dependent on the applicable process. The Sezela furfural plant for example produces effluent with a COD of about 16 000 mg.L^{-1} composed mostly of acetic acid (Purchase and Thompson, 1993).

The sugarcane processing industry is aiming at transforming from producing a single product, sugar, to operating as an integrated biorefinery producing added value products. The introduction of new processes or products within the sugarcane processing industry invariably leads to new sources of wastes. It is therefore imperative that the South African sugar milling industry develops the competence in the treatment and disposal of potential waste streams from an integrated biorefinery. Disposal of this waste to effluent or landfills needs to meet prevailing environmental quality standards. The Environmental Conservation Act of 1989 and the National Water Act of 1998 provide policy guidelines for the disposal of waste in South Africa. Source reduction, recycling, detoxification and neutralisation of wastes are particularly encouraged. Table 2 lists some of the general standards required for effluent disposal in South Africa (Government Gazette No. 9225 (1984): 12-17, http://www.dwa.gov.za)

Table 2: Effluent Standards in South Africa

Parameter	**Units**	**Maximum Allowable**
COD	mg.l^{-1}	75
Oxygen Absorbed	mg.l^{-1}	10
Suspended Solids	mg.l^{-1}	25
Soap Oil or Grease	mg.l^{-1}	2.5
Lead	mg.l^{-1}	0.1
Typical coli	Count per 100 ml	Nil
pH	-	5.5-9.5
Colour, Odour, Taste	-	Nil

AEROBIC DIGESTION

Aerobic digestion is the biological breakdown of organic matter in the presence of oxygen producing mostly carbon dioxide and water. It is commonly used for the stabilisation of sludge from wastewater treatment plants and is therefore frequently a finishing step in the anaerobic digestion process. According to Mebrahtu and Ekama (2008), aerobic digestion reduces volatile and inorganic suspended solids by between 30% and 70% depending on the residence time. This volume reduction is accompanied by a linear decrease in effluent COD and the stabilization of nitrogen and phosphorus to nitrate and orthophosphate respectively. In the sugar industry, aerobic systems achieve a COD reduction of up to 99% (Huang *et al*, 1996).

The major advantages of aerobic digestion over anaerobic digestion are that it is easier to operate, volatile solid compounds reduction is much greater, the sludge is less odorous and excellent as a fertilizer and that the BOD of the supernatant is much lower. The major disadvantages are the cost of supplying oxygen, poor dewatering characteristics of sludge and the strong reliance of the process on temperature. This dependence on process temperature is confirmed by the study of Roš and Zupančič (2002) in which the optimal operating temperature for aerobic digestion of waste activated sludge was determined to be 50°C. The raised operating temperature is however beneficial in that the retention time is much reduced for equivalent volatile suspended solids (VSS) degradation. A 30% VSS reduction was obtained at 20°C in 20 days (Mebrahtu and Ekama, 2008) whereas a 30% VSS reduction was obtained in 5 days at 50°C.

Oxidation

There are two main reactions occurring in aerobic systems: i) direct oxidation of biodegradable materials and ii) endogenous respiration of cell material. These reactions can be represented as:

i) $\text{Organic matter} + NH_4^+ + O_2 \longrightarrow \text{Cellular matter} + CO_2 + H_2O$

ii) $\text{Cellular matter} + O_2 \longrightarrow \text{Digestate} + CO_2 + H_2O + NO_3^-$

Although the second reaction is predominant in the aerobic digestion of sludge, inclusion of primary waste to the digester would obviously shift the system towards the first reaction due to abundance of organic matter. It is for this reason that aerobic treatment is recommended as a finishing step in waste treatment, represented by the second reaction where there is less primary waste.

Nitrification-Denitrification

The proteinaceous material in biological waste invariably contains nitrogen which causes water contamination leading to eutrophication and ammonia poisoning of water bodies. Removal of nitrogen from waste is therefore essential in waste remediation. This is accomplished by the oxidation of cellular matter by nitrifying bacteria during aerobic digestion. Cellular matter is oxidised producing carbon dioxide and ammonia. Nitrification is a two-step process where *Nitrosomonas* bacteria convert the ammonia formed to nitrite which is then converted to nitrate by *Nitrobacter*, both occurring in the presence of oxygen (Idury, 1992). For a cell composition of $C_5H_7NO_2$ the cellular matter oxidation reactions can be extended to nitrification-denitrification systems (Vesilind, 2003) as shown below:

iii) $C_5H_7NO_2 + 5O_2 \longrightarrow 5CO_2 + 2H_2O + NH_3 + \textit{energy}$

iv) $NH_4^- + 1.5O_2 + \textit{Nitrosomonas} \longrightarrow NO_2^- + H_2O + H^+$

v) $NO_2^- + 0.5O_2 + \textit{Nitrobacter} \longrightarrow NO_3^-$

Thus the general nitrification equation is:

vi) $C_5H_7NO_2 + 7O_2 \longrightarrow 5CO_2 + 3H_2O + NO_3^- + H^+ + \textit{energy}$

Denitrification is the conversion of the nitrate to gaseous nitrogen and is accomplished by various microorganisms using nitrate as an electron acceptor. The use of nitrate as electron acceptor instead of oxygen is therefore likely to occur in systems where oxygen is limited. The denitrification equation is represented as:

vii) $2C_5H_7NO_2 + 8NO_3^- \longrightarrow 10CO_2 + 6H_2O + 2OH^- + 5N_2 + \textit{energy}$

Aeration and operating temperature are the main parameters in aerobic digestion. The rate of solids destruction is a function of temperature with higher temperatures increasing the reaction rate. Aeration required is a function of both the temperature and the COD with higher temperatures reducing the available dissolved oxygen (DO). Hence there is an optimum temperature at which solids reduction is greatest for a given sludge COD load.

Aerobic Process Operations

Sugar processing wastewater has high sucrose content and therefore a high COD concentration. Aerobic digestion systems treating sugar processing waste are capable of removing up to 99% of the COD, however this depends on the hydraulic retention time (HRT) (Huang *et al*, 1996). Optimisation of the hydraulic retention time for aerobic systems shows a gradual increase in treatment efficiency with high COD concentration as shown in Figure 1 below:

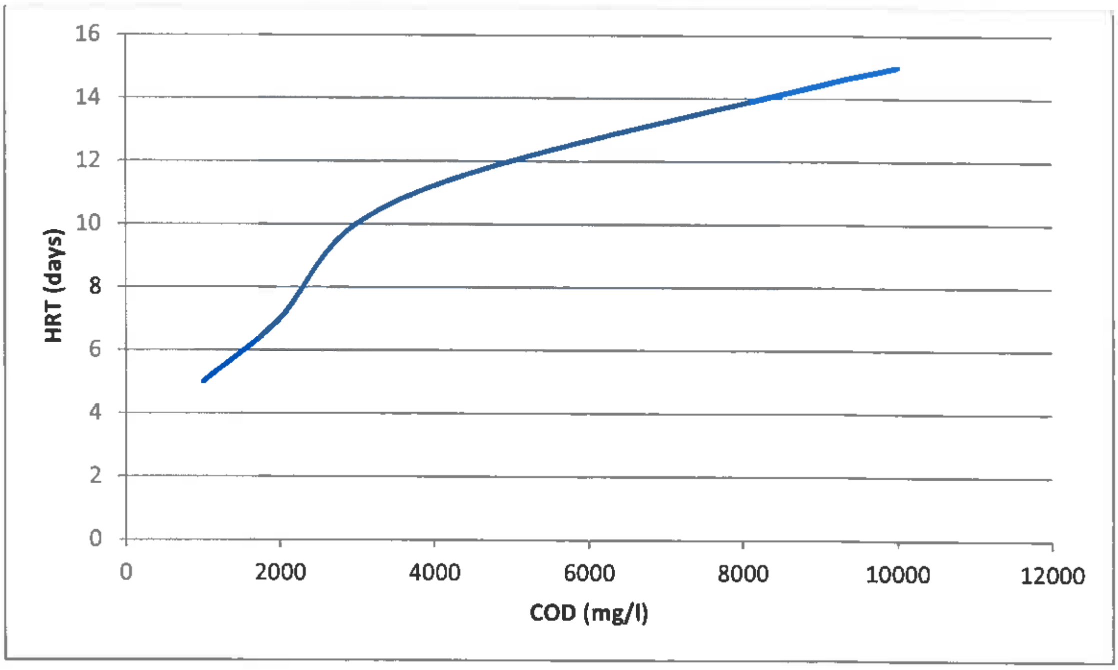

Figure 1: Suitable HRTs for different CODs of wastewater in aerobic systems (data from Huang *et al*, 1996)

Sugarcane biorefinery effluent depends on the type of process in operation. The sugar mill at Sezela operates a furfural plant, producing furfural from sugarcane bagasse. Effluent from this plant consists mostly of acetic acid and has a COD of about 16,000 mg.L^{-1}, total solids of 885 mg.L^{-1} and pH of 2.7 (Purchase and Thompson, 1993). Extrapolating from Figure 1, HRT for this influent should ideally be about 25 days. Investigation into the aerobic treatment of this waste (Purchase and Thompson, 1993) managed to reduce the COD by 40% in a HRT of 1 day. Some components of the effluent were neither known nor readily oxidized showing the importance of investigating the waste characteristics of potential biorefinery wastes on a case basis.

Table 1 (page 3) shows that a number of factories in South Africa operate aerobic treatment systems although these are generally in addition to anaerobic treatment systems. The major aerobic waste treatment processes include activated sludge, Pasveer ditch and trickling filter.

Activated Sludge

Activated sludge waste treatment is the biological treatment of carbonaceous waste with flocculating microorganisms in an aerobic aquatic environment. The process involves aeration of effluent, clarification and recycling of part of the biomass. HRT for dilute wastewaters is in the range of 1-10 days (Sustarsic, 2009). The aeration tank environment is closely monitored for optimal microbial activity with pH maintained between 6.5-7.5, temperature of 15°C-30°C and dissolved oxygen above 1.0 $mg.L^{-1}$ (Sustarsic, 2009). Typical COD removal in such a system is greater than 90%.

The four sugar factories in South Africa that operate activated sludge waste treatment plants are Felixton, Komati, UCL and Sezela. At UCL, the treatment process consists of anaerobic lagoons with outflow to the aeration basin and a final settling tank. The two aerators in the aeration basin are driven by two 37 kW motors with an oxygenation efficiency of 2.05 kg O_2. $(kWh)^{-1}$ supplying 1.75 kg $O_2.m^{-3}.day^{-1}$ (Mattos, 1986). COD concentration of 1 000 -2 000 $mg.L^{-1}$ to the aeration basin is reduced by 80% at a recycle rate of 50-60% and average flow rate of 450 $m^3.day^{-1}$. Combined with 70% COD removal in the anaerobic lagoons, the waste treatment plant achieves close to 99% COD removal (Mattos, 1986).

At Sezela the activated sludge treatment facility processes sugar mill, furfural and domestic waste. The plant consists of an aerated lagoon, activated sludge tank, clarifier and maturation dam as shown in Figure 2. Three aerators each supply oxygen to the 3 250 m^3 aerated lagoon and the 1 600 m^3 activated sludge tank (Nadasen, 1991). Each aerator supplies 50 kg $O_2.h^{-1}$ to achieve dissolved oxygen of 1.0-3.0 $mg.L^{-1}$, thus the Sezela aeration rate to the activated sludge tank of 2.25 kg $O_2.m^{-3}.day^{-1}$ is about 30% higher than at UCL. However, the average hydraulic load at Sezela is 50-66 $m^3.h^{-1}$ which is four times that at UCL. COD concentration averaged 1 875 $mg.l^{-1}$ in 1990 (Nadasen, 1991) and the plant managed to reduce this to 58 $mg.l^{-1}$ in 1990 thus achieving a 97% COD removal. The performance of activated sludge treatment plants is shown in Table 3 below.

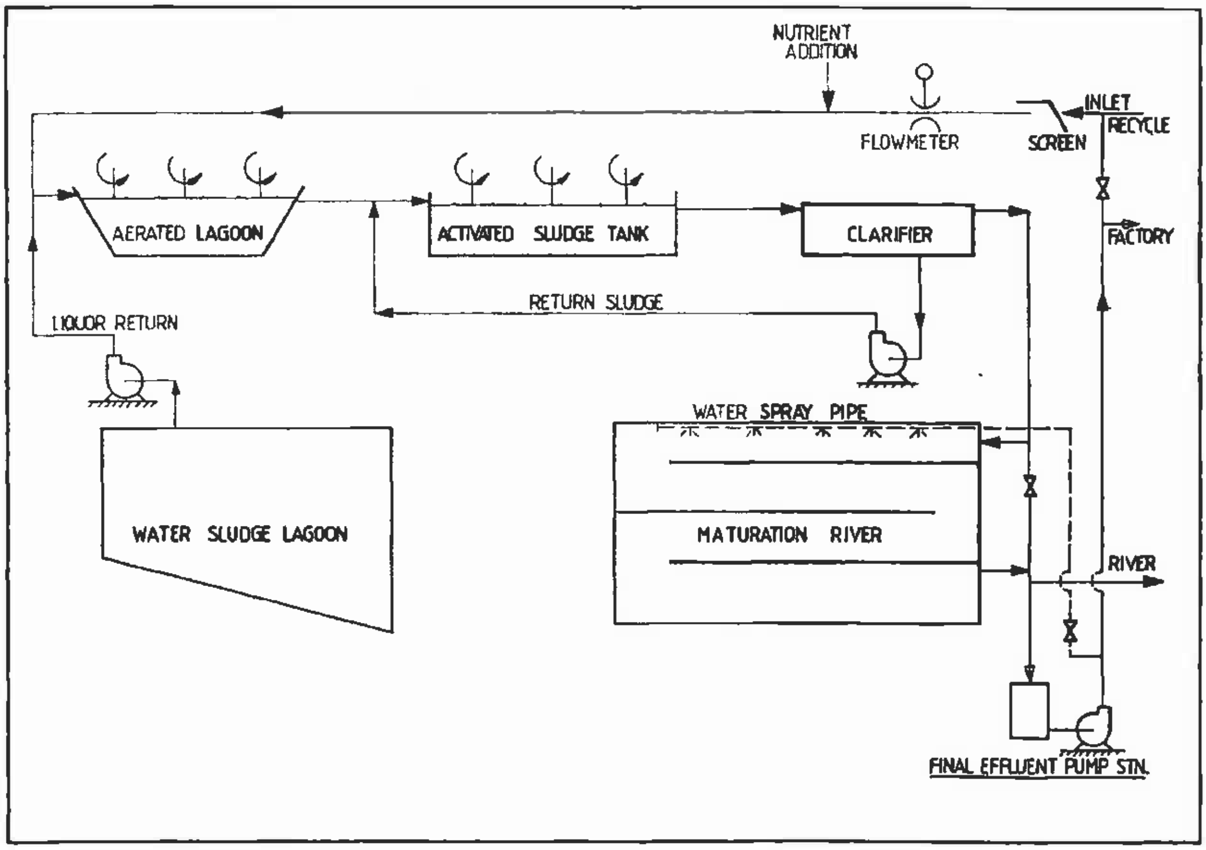

Figure 2: Sezela Effluent Treatment Plant Scheme (Nadasen, 1991)

Table 3: Performance of activated sludge plants at South African sugar mills

Mill	**Effluent to Activated Sludge Plant**			**Activated Sludge Treatment**					
	Flow ($kl.d^{-1}$)	COD ($mg.L^{-1}$)	Load ($kg.d^{-1}$)	Volume (m^3)	HRT (days)	Load out ($kg.d^{-1}$)	COD ($mg.L^{-1}$)	Removal ($kg.m^3.d^{-1}$)	Removal (%)
Sezela	1,500	1,875	2,800	4,850	3	90	60	0.56	97
UCL	450	1,500	675	2,000	4.5	135	300	0.27	80

Pasveer Ditch

The Pasveer ditch is an oxidation system based on the same biological processes as in the activated sludge process. Pasveer ditches are variations of oxidation systems in use in which aeration occurs in an oval shaped channel where oxidation is achieved by recirculation of the effluent. Noodsberg, Pongola and Umfolozi sugar mills have incorporated this system in their waste treatment plants as shown in Table 1.

The Noodsberg ditch was designed to handle a loading of 990 kg $COD.d^{-1}$ at 50 $m^3.h^{-1}$ (i.e. COD concentration of 825 $mg.L^{-1}$) and remove between 440-760 kg $COD.d^{-1}$ (Govender, 1992). However, in practice this was difficult to achieve necessitating the addition of a trickling filter. At Pongola, the Pasveer ditch is used as a finishing stage receiving a load of only 120 kg COD.d^{-1} with an HRT of 1.5 days (Purchase, 1995b). COD loading to the Umfolozi ditch is about 1 100 kg COD.d^{-1} with between 60-70% COD removal (Purchase, 1986). However, this level of performance was not adequate necessitating addition of a packed anaerobic dam to reduce the load to about half (Purchase, 1995c). Pasveer ditches are extended aeration systems, meaning that the aeration rate is low and they therefore require long retention times – i.e. the load per unit volume per day must be low. The major advantage of extended aeration systems is that sludge production is relatively low because much of the sludge growth dies and digests within the system.

Biological Trickling Filter

Biological trickling filters are fixed film systems where a biofilm of aerobic microorganisms degrades the organic constituents in sprayed wastewater. The filter medium is made of rocks, gravel or plastic on which microorganisms attach and grow. Noodsberg is the only sugar mill that operates such a system. At Noodsberg, the trickling filter was added to an existing anaerobic pond-Pasveer ditch system due to plant expansion. The filter medium used consists of two layers of rocks: the top layer with 38 mm diameter rocks has a volume of 360 m^3 and the bottom layer of 152 m^3 has 150 mm diameter hand stones (Govender, 1992). COD concentration of the influent to the trickling filter in 1991 averaged about 1 000 mg.L^{-1} and the filter achieved a removal rate of 40%. The major disadvantage of the trickling filter is its high installation cost and the high hydraulic loading required to unblock excessive microbial growth at high COD concentration.

ANAEROBIC DIGESTION

Anaerobic Digestion Process

Anaerobic digestion is the synergistic breakdown of organic compounds by microorganisms in a low or no oxygen environment producing methane-rich biogas. The process occurs in four biochemical steps carried out by different types of microorganisms. These steps are:

- Hydrolysis
- Acidogenesis
- Acetogenesis
- Methanogenesis

Hydrolysis involves the breakdown of complex organic molecules into simpler molecules. Acidogenesis is the fermentation of these organic molecules in the absence of oxygen. Acetogenic microorganisms convert the fermentation products producing acetic acid. Methanogenic organisms then convert acetic acid to methane gas.

The major advantages of anaerobic digestion are the transformation of effluent into biogas producing more compact sludge than in aerobic digestion. The yield of biomass on COD is about 10% in anaerobic digestion compared to 50% in aerobic digestion (Macarie and Le Mer, 2006). The major disadvantages are that the process is much slower than the aerobic process and subject to failure if proper operating conditions are not maintained. Also the final water quality is often not adequate for disposal.

Hydrolysis

Large macromolecules of carbohydrates, fats and proteins in the waste are hydrolysed to sugars, long chain fatty acids and amino acids. Hydrolytic enzymes secreted by disparate groups of microorganisms hydrolyse their respective polymers. Thus lipases hydrolyse fats to long chain fatty acids, proteases hydrolyse proteins to amino acids and cellulases, amylases and pectinases hydrolyse polysaccharides into hexose and pentose sugars.

Acidogenesis

The products of hydrolysis are fermented to form three, four and five carbon volatile acids. The most common of these intermediates are lactic acid (C3), propionic acid (C3), butyric acid (C4) and valeric acid (C5) (Rapport *et al*, 2008).

Acetogenesis

Fermentation products are further converted by acetogenic microbes to acetic acid, hydrogen and carbon dioxide.

Methanogenesis

Methanogens finally metabolise the acetate, hydrogen and carbon dioxide to produce methane gas. There are three biochemical pathways used by methanogens for the conversion to methane (Rapport *et al*, 2008); acetotrophic, hydrogenotrophic and methylotrophic. Acetate is the substrate for the acetotrophic pathway, hydrogen and carbon dioxide are substrates for the hydrogenotrophic pathway and methylated substrates such as methanol are converted to methane gas through the methylotrophic pathway.

Acetotrophic pathway: $4CH_3COOH \longrightarrow 4CO_2 + 4\ CH_4$
Hydrogenotrophic methanogenesis: $CO_2 + 4\ H_2 \longrightarrow CH_4 + 2\ H_2O$
Methylotrophic methanogenesis: $4CH_3OH + 6\ H_2 \longrightarrow 3CH_4 + 2\ H_2O$

Anaerobic Digestion Technologies

Anaerobic digestion requires feedstock with high moisture content containing proteins, fats and carbohydrates. Cellulose and lignin digest too slowly hence anaerobic digestion is not suitable for such process waste material. Feedstock to anaerobic digestion needs to be managed closely as ammonia production is toxic to anaerobic bacteria (Evans *et al*, 2009). The optimal C: N ratio for bacterial growth is 20-30:1.

Anaerobic Digestion Classification

Anaerobic digestion (AD) systems are classified according to whether they are

- Psychrophilic, mesophilic or thermophilic
- Wet or dry
- Batch or continuous
- Single or multi-step

Psychrophilic, Mesophilic or Thermophilic

Anaerobic bacteria occur naturally and thrive within three temperature ranges. Psychrophilic systems operate at low temperatures ranging from 7-25°C, however, less than 5% of current installed systems operate within this range (Evans *et al*, 2009). The organic feedstock is very dilute and the hydraulic retention time can exceed 50 days. As expected at such low temperatures the biogas generation rate is very slow with a low conversion of solid material.

Mesophilic systems operate at 25-45°C with a retention time of between 20-40 days (Evans *et al*, 2009). In Europe more than 85% of anaerobic digestion plants operate within this range where the greatest number of bacterial species is active. Baez-Smith (2006) has shown that in the distillation of ethanol the liquid residue, vinasse, poses serious disposal challenges due to the high BOD of up to 50 000 mg.L^{-1} and solids concentration of 60 000 mg.L^{-1}. However mathematical modelling of anaerobic digestion of this waste at a mesophilic temperature (40°C) and mean residence time of 10 days results in a 90% BOD reduction as well as substantial methane production to generate electricity(Baez-Smith 2006).

In about 8% of anaerobic digestion systems the temperature range is thermophilic (50-70°C) and the retention time is between 5-20 days. Thermophilic systems have the fastest conversion rate of solid material resulting in the highest productivity of biogas per feedstock. However, the capital costs of thermophilic systems are far higher as more energy is needed to heat them.

Wet or Dry

Wet systems treat dilute feedstock of between 5-15% dry solids. Dry systems treat feedstock greater than 15% dry matter. Dry AD tends to be cheaper to run as there is less water to heat and there is more gas production per unit feedstock. However, wet AD has a lower set-up capital cost.

Batch or continuous

Batch digesters are fed with raw feedstock and sealed for a period of time until digestion is complete at which point they are emptied and a new batch started. In continuous reactors, raw feedstock is added continuously and digested material is also removed continuously.

Single or Multiple Digesters

In single stage digesters all digestion occurs in one unit whereas multiple digesters have several stages arranged in series. Multiple digesters can give more biogas per unit feedstock but at a higher capital cost, higher operating cost and greater management requirement.

Anaerobic Process Operations

All sugar mills in South Africa operate some kind of anaerobic waste treatment except for Maidstone where a zero effluent philosophy is in place. Anaerobic digestion is capable of reducing effluent COD by 80% in a HRT of two days (Purchase and Perrow, 1983), however this may not be enough to produce effluent meeting discharge standards. The major anaerobic methods used in South Africa are the open and packed anaerobic dams. Felixton, Pongola, Noodsberg UCL and Umfolozi operate open anaerobic dams. Boiler fly ash and clarifier smuts are used as packing material in some anaerobic dams to provide an attachment surface for microbial growth. Packed anaerobic dams are operated by the Eston, Gledhow, Sezela and Umzimkulu sugar mills.

Figure 3 shows the structure of an ash disposal dam. As shown in the diagram, the ash dam is not lined with a membrane but the effluent is allowed to percolate through the bed thus achieving physical, biological and chemical treatment of the effluent. Physical filtration of particulate matter occurs through the granular bed whereas the cellulosic ash acts as activated carbon absorbing organic matter in the effluent. Due to the moist conditions and vegetation cover in some places, both aerobic and anaerobic microbes are active within the dam.

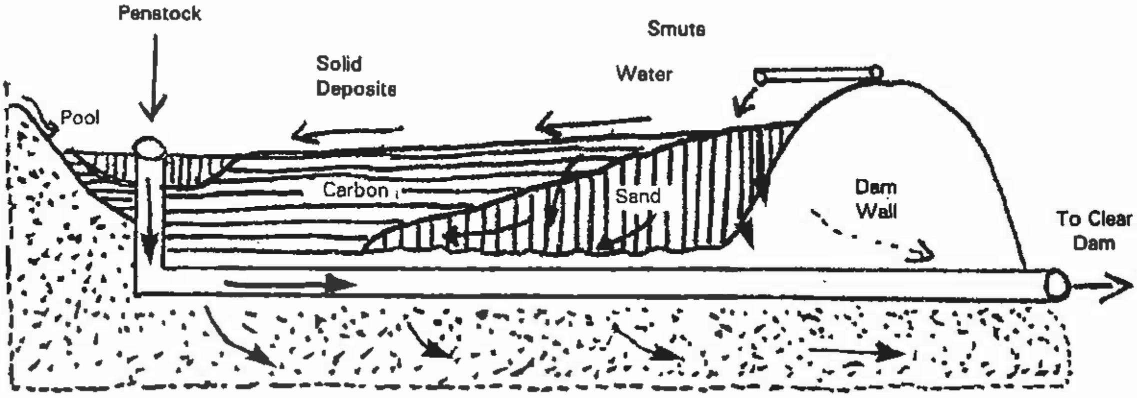

Figure 3: Side view of Ash Disposal Dam (Vermeulen and Vawda, 1989)

The Felixton system consists of three open anaerobic dams of 11 455 m^3 capacity ahead of bio filters (Lewis and Ravnö, 1976; Purchase and Jones, 1987). Effluent flow from the factory is 1 700 kl.d^{-1} with COD concentration of 1 527 mg.L^{-1} and outlet COD of 212 mg.L^{-1} giving a removal of 86%.

At Pongola, the effluent treatment system consisted of three open anaerobic dams and a Pasveer ditch before the third dam was converted to an aerated basin due to plant expansion (Purchase, 1995b). Dam 1 has a volume of 5 100 m^3 whereas dam 2 is 17 500 m^3 and the aerated basin is 9 900 m^3. In all, the three dams remove 70% of the COD, but the anaerobic dams only manage a reduction of 30%. This is mainly due to the short HRTs in the dams where HRT is 2.8 days in the first dam and 9.7 days in the second dam compared to 36 days at Umfolozi.

The Umfolozi system consists of two settling ponds followed by the open anaerobic dam feeding into the Pasveer ditch and maturation dam (Purchase, 1995c). The anaerobic dam has a large volume of 90 000 m^3; however, due to siltation only about 60 000 m^3 is estimated to be available for anaerobic digestion. This is still much larger than dams at other mills as shown in Table 4 below. The removal rate however is still in the same range as the smaller dams.

The packed anaerobic dam at Umzimkulu as shown in Figure 3 has a surface area of 19 000 m^2 and a volume of some 70 000 m^3 (Vermeulen and Vawda, 1989). The dam achieves a COD removal of up to 90% producing an effluent good enough to be discharged to the Umzimkulu river (Govender, 2001).

Factory effluent at Eston is first treated in aeration ponds before further treatment in the packed anaerobic dam which has a volume of some 42 000 m^3. The dam was designed for factory effluent with an average COD of 1 800 $mg.L^{-1}$, flow of 1 320 $m^3.d^{-1}$ (Purchase, 1994) and minimum dam capacity of 32900 m^3 (Bernhardt, 2000). However, an evaluation of the data showed a variation of daily flows from 140-1200 $m^3.d^{-1}$ at a high average COD concentration of 7 800 $mg.L^{-1}$ (Bernhardt, 2000). The dam was performing unsatisfactorily due to channelling, producing return water with a COD concentration averaging 620 $mg.L^{-1}$. This has since been rectified such that the return water is consistently meeting requirements with a 95% COD removal rate (Personal communication, Process Engineer, June 2011).

Table 4 shows the performance of anaerobic dams at Eston, Felixton, Pongola and Umfolozi. Open anaerobic dams have a design treatment rate of 0.08 $kg.m^3.d^{-1}$ whereas packed anaerobic dams can achieve up to 0.6 $kg.m^3.d^{-1}$ COD removal. The loads to the dams at Felixton and Pongola exceed design loads and are therefore expected to fail.

Table 4: Performance of anaerobic dams at South African sugar mills

Mill	Effluent ex-Factory		Anaerobic Dams						
	Flow (kl.d^{-1})	COD (mg.L^{-1})	Volume (m^3)	Load in (kg.m^3.d-^{1})	HRT (days)	Load out (kg.d^{-1})	COD (mg.L^{-1})	Removal (kg.m^3.d-^{1})	Removal (%)
Felixton	1,700	1,500	11,455	0.22	6.7	360	212	0.03	86
Pongola	1,800	1,600	22,600	0.13	12.5	2,000	1,100	0.04	31
Umfolozi	1,650	1,500	90,000	0.04	36	750	450	0.03	70
Eston	1,200	1,800	42,000	0.05	35	90	75	0.05	95

Digester Reactor Types

There are many different types of digester designs. These include but are not limited to:

- Anaerobic Hybrid Reactor
- Anaerobic Sequencing Batch Reactor (ASBR)
- Continuously Stirred Tank Reactors (CSTR)
- Fixed Dome Reactors
- Upflow Anaerobic Sludge Blanket (UASB)
- Temperature Phased Anaerobic Digestion (TPAD)

The volatile solids removal rate in anaerobic digesters is a function of the operating temperature, retention time and type of waste. These different designs of anaerobic digesters and as well as the potential for energy production will be discussed in a review focusing on anaerobic digestion. The major categories of digesters are a covered lagoon, complete mix reactors and plug flow reactors.

Covered Lagoon

A covered lagoon digester is the least expensive type of digester and has a long retention time and a high dilution factor. Lagoons are generally anaerobic systems due to lack of mixing and aeration. These lagoons can either be in-ground, earth or lined with a flexible cover and operate at ambient temperature. Low ambient temperatures are compensated by decreasing the loading rates and increasing the hydraulic retention time. The solids concentration is between 0.5-2% with a hydraulic retention time of 30-60 days (Anon, 2011a). Solids loading into the lagoon is between 3-8 g VS.m^{-3}.h^{-1} which is much higher than an ash dam at 0.1 g solids.m^{-3}.h^{-1} (Vermeulen and Vawda, 1989).

Complete Mix Digester

A complete mix digester is a flow-through continuously stirred tank reactor with temperature control in the mesophilic range. The hydraulic retention time in these reactors is between 20-70 days and concentration of 3-10% total solids (Anon, 2011a). Most aerobic systems are complete mix due to oxygenation requirements.

Plug Flow Digester

A plug flow digester is an unmixed long, narrow (typically a 5:1 length to width ratio) insulated and heated tank made of reinforced concrete, steel or fiberglass with a gas tight cover to capture the biogas in the case of anaerobic digestion. These digesters can operate at a mesophilic or thermophilic temperature with 11-14% solids wastes (Anon, 2011a). Hydraulic and solids retention times are equal at between 15 to 25 days.

DIGESTION MODELLING

Modelling of aerobic and anaerobic digestion is not new, however the variety of models developed in the past were aimed at specific process conditions and hence could not be applied to different operating conditions. The International Association of Water Quality responded to these challenges by setting up task groups to look at modelling both aerobic and anaerobic digestion models. The Task Group on Mathematical Modelling for Design and Operation of Activated Sludge Processes was formed in 1982 with the aim to create a common platform for future model development and specifically to develop a model for nitrogen-removal activated sludge processes. The Task Group on Anaerobic Digestion Modelling was formed fifteen years later in 1997 mainly due to the popularity of activated sludge models.

The activated sludge process is the aerobic digestion of biological waste water using flocculating microorganisms in which the sludge is retained in the system at a high concentration and a highly active state due to high aeration. Aerobic digestion stabilises the organic sludge such that it can be used as a fertilizer or applied to landfills. There are currently four versions of activated sludge models (Henze *et al*, 2000). Activated Sludge Model no. 1 (ASM1) was primarily concerned with single sludge systems carrying out carbon oxidation, nitrification and denitrification. ASM1 therefore excluded phosphorus removal and included only the nitrogenous material in the effluent as well as broad fractions of COD. Activated Sludge Model no. 2 (ASM2) was developed to address the limitations of ASM1 with regards to phosphorus removal from effluent. This was further expanded to include denitrification in relation to phosphorus removal resulting in Activated Sludge Model no. 2d (ASM2d). Activated Sludge Model no. 3 (ASM3) is based on new research of activated sludge processes particularly the possibilities of internal storage in microorganisms and its effects on metabolism. Activated sludge systems produce waste that has higher concentrations of nitrogen and phosphorus.

Aerobic digestion modelling has been focused on the stabilization of waste activated sludge from waste water treatment, thus models available describe the aerobic digestion of activated sludge (Mebrahtu and Ekama, 2008; Roš and Zupančič, 2002; van Haandel *et al*, 1998). Stabilization of this sludge in anaerobic digesters invariably results in liquid effluent high in nitrogen and phosphorus which requires further treatment.

Aerobic digestion modelling is based on the assumption that only the active fraction of sludge comprising live organisms undergoes a first order decay reaction and the inactive sludge material does not. The rate of sludge decay is expressed as:

$$r_d = -(\frac{dX_a}{dt}) = K_d.X_a$$

Where:

X_a = active sludge concentration (mass/volume)

K_d = decay rate constant ($time^{-1}$)

Part of the decayed material remains as un-biodegradable endogenous residue which is a constant fraction (f) of the decayed material. The concentration of active sludge is obtained by integration and the decay constant is determined experimentally and is a function of temperature:

$$X_a = X_{ai}e^{-K_d t}$$

$$(K_d)_T = (K_d)_{T_0}\theta^{T-T_0}$$

Where:

X_{ai} = initial active sludge concentration ($mg.L^{-1}$)

t = the aerobic digestion time (days)

T = operating temperature (°C)

T_0 = ambient temperature set to 20°C

θ = temperature coefficient averaging 1.023 (Roš and Zupančič, 2002)

Hence the reaction rate is increasing exponentially with temperature; however, it is limited by the practical requirements for aerating dissolved oxygen to about 60°C above which oxygen limitation occurs in the digester. Active sludge concentration cannot be determined experimentally and is confirmed by measuring various parameters that are linked to it (van Haandel and van der Lubbe, 2007) and these have been verified to lead to the same value of the decay constant under similar conditions (van Haandel *et al*, 1998). These parameters are:

- VSS concentration
- Oxygen utilization rate (OUR)
- Nitrate concentration
- Alkalinity change

The variation in VSS is a result of active sludge decay and endogenous residue generation whereas oxygen is used for oxidation of decayed organic material and for nitrification. When the sludge is mineralized, the nitrogen is released into the liquid phase and will be nitrified to nitrate. Alkalinity is consumed due to the nitrification of the nitrogen.

Anaerobic digestion is a multi-step process involving a variety of microorganisms in each step. Consequently, anaerobic digestion systems are very complex and difficult to control and operate. Instability in anaerobic digestion systems causes digester failure observed as a drop in methane production, a drop in pH or a rise in volatile fatty acid concentration. It is therefore necessary to determine accurately the control parameters for a digestion system.

Various models of anaerobic digestion systems have been developed and were reviewed by Lyberatos and Skiadas (1999). The major problem with many of these models is that they focused on one step or a combination in the multi-step anaerobic process based on the concept of the rate determining step. However, under different operating conditions, this limiting step is not always the same thus rendering these models insufficient for successful control of digestion systems. It is because of this specificity of anaerobic digestion models that the International Association of Water Quality formed a task group in 1997 for the mathematical modelling of anaerobic digestion (Batstone *et al*, 2002) This group's mandate was to develop a generally applicable model for both different reactor types and various substrates. The result of this effort was the development of the Anaerobic Digestion Model No. 1 (ADM1, Batstone *et al*, 2002) encompassing all the four steps of anaerobic digestion. ADM1 followed on the successful development of models for aerobic activated sludge (ASM1 to ASM3).

The ADM1 is now the recognized definitive model of anaerobic digestion. ADM1 segregates anaerobic steps into biochemical and physico-chemical processes (Batstone *et al*, 2002). Biochemical processes in the anaerobic digester are those that are mediated by microorganisms and include the hydrolysis of organic matter to sugars, amino acids and long chain fatty acids; acidogenesis from sugars and amino acids to volatile fatty acids and hydrogen; acetogenesis of long chain fatty acids and volatile fatty acids to acetate; and the methanogenesis steps from acetate and hydrogen or carbon dioxide. The physico-chemical processes are not biologically mediated and describe ion association or dissociation and gas-liquid transfer. This model has been used to simulate digester dynamics (Zaher *et al*, 2003) and has been modified and adapted to model the net energy production of an anaerobic digester (Lubken *et al*, 2007). Although the ADM1 is fully functional, a number of simplifications were made in its derivation. These assumptions include kinetic equations for intracellular biochemical reactions, thermodynamic boundaries of process pathways as well as exclusion of liquid-solid transformations. These simplifications lend the ADM1 to adaptation for particular digestion systems based on observable parameters. As a result, the successful application of this model is accomplished from pilot studies to determine parameters such as the COD or volatile solids composition of inflow material.

Baez-Smith (2006) produced a mathematical anaerobic digestion model (MADM) of vinasse waste from a molasses-using ethanol distillery. This model is useful as a study of the potential for energy generation from anaerobic digestion. However, because of the assumptions in the model it is unlikely to be useful in practical operations. Firstly the COD range in the model was limited to between 20 000-60 000 mg.L^{-1} but vinasse COD from molasses fermentation has been measured at much higher concentrations (Siles *et al*, 2011) and can be up to 110,000 mg.l^{-1} (Anon, 2011a). Further, the kinetic equation used in the model failed to include dynamic gas transfer rate as used in ADM1 (Batstone *et al*, 2002).

CONCLUSIONS

This digestion technology review focused mainly on the state of waste treatment in the South African sugar milling industry. The report shows that the industry is well aware of the need for waste treatment and willing to employ the latest technology in dealing with the waste.

The integrated biorefinery will involve production of non-traditional wastes which will require an understanding of the waste remediation methods to use as well as the energy requirements. A follow-up report will consider anaerobic digestion and the potential for energy generation.

REFERENCES

Anon (2011a). RCM-DigesterTechnology. Online http://www.rcminternationalllc.com/RCM_Forms/RCM_Digester_Types.pdf (accessed June 2011)

Anon (2011b). UN-Clean Development Mechanism. Online: http://cdm.unfccc.int/Reference (Accessed May 2011)

Baez-Smith C (2006). Anaerobic digestion of vinasse for the production of methane in the sugar cane distillery. *SPRI Conference on Sugar Processing*, 268-287

Batstone D J, Keller J, Angelidaki I, Kalyuzhnyi S V, Pavlostathis S G, Rozzi A, Sanders W T M, Siegrist H and Vavilin V A (2002). The IWA Anaerobic Digestion Model No 1 (ADM1). *Water Science and Technology* **45 (10)**, 65-73

Bernhardt H W (2000). Evaluation of the Eston effluent treatment system. *SMRI Technical Report* 1834

Evans L, Okamura S, Poll J and Barker N (2009). NNFC -Evaluation of opportunities for Converting Indigenous UK Wastes to Fuels and Energy. Online: http://www.nnfcc.co.uk/tools/evaluation-of-opportunities-for-converting-indigenous-uk-wastes-to-fuels-and-energy-report-nnfcc-09-012 (accessed May 2011)

Govender B. (1992). Expansion of Noodsberg effluent plant-utilizing a trickling filter. *Proc S Afr Sug Technol Assoc*, 169-172

Govender S S G (2001). Boiler flyash and effluent disposal at Umzimkulu. *Proc S Afr Sug Technol Assoc*, **75**, 322-323

Henze M, Gujer W, MIno T, van Loosdrecht MCM (2000). Activated Sludge Models ASM1, ASM2, ASM2d, and ASM3. *IWA Scientific and Technical Report No. 9. IWA Publishing, London, UK*

Huang C M, Sheen H K, Chen W C, Wu Z S, Hsieh W D, Chen C H, Li S W and Wang L H (1996). Treatment of wastewater from sugar mill by facultative-aerobic system. *ISSCT*, 232-237

Idury M R (1992). Nitrification and denitrification in the activated sludge process. *MSc Thesis, Rice University, Texas.* (Online: http://hdl.handle.net/1911/13627)

Jensen C R C and Schumann G T (2001). Implementing a zero effluent philosophy at a cane sugar factory. *ISSCT*, **24**, 74-79

Lewis J W V and Ravnö A B (1976). Effluent treatment at Felixton Mill. *Proc S Afr Sug Technol Assoc*, 242-245

Lübken M, Wichern M, Schlattmann M, Gronauer A and Horn H (2007). Modelling the energy balance of an anaerobic digester fed with cattle manure and renewable energy crops. *Water Research* **41**, 4085-4096

Lyberatos G and Skiadis I V (1999). Modelling of Anaerobic Digestion – A Review. *GLOBAL NEST: the International Journal* **1 (2)**, 63-76

Macarie H and Le Mer J (2006). Overview of the biological processes available for the treatment of sugarcane mill wastewater. *International Sugar Journal*, **108 (1292)**, 431-439

Mattos G W P (1986). Operating experience of an activated sludge effluent disposal system. *Proc S Afr Sug Technol Assoc*, 116-119

Mebrahtu M K and Ekama G A (2008). Aerobic digestion of waste activated sludge from biological nutrient removal activated sludge systems. *Water Institute of SA:* 9pp. Online: http://www.ewisa.co.za/literature/files/2008_113.pdf (accessed May 2011)

Nadasen A M (1991). Experience with an activated sludge treatment plant at Sezela. *Proc S Afr Sug Technol Assoc*, 225-227

Purchase B S (1986). Effluent treatment at Umfolozi. *SMRI Technical Note* 2/86

Purchase B S (1994). Options for treatment of factory effluent at Eston. *SMRI Technical Note* 43/94

Purchase B S (1995). Suggestions for increasing the capacity of the Pongola effluent plant. *SMRI Technical Note* 3/95

Purchase B S (1995b). Recommendations for extension to the Pongola effluent plant. *SMRI Technical Note* 20/95

Purchase B S (1995c). Recommendations for ensuring successful effluent treatment at Umfolozi. *SMRI Technical Note* 18/95

Purchase B S (1996). Disposal of liquid effluents from cane sugar factories. *ISSCT* 49-54

Purchase B S and Jones L (1987). Felixton Mill Effluent. *SMRI Technical Note* 26/87

Purchase B S and Perrow S (1983). Suggestions for improving anaerobic digestion of sugar mill effluents. *Proc S Afr Sug Technol Assoc*, 60-63

Purchase B S and Thompson M C (1993). Microbial treatment of SmithChem-Sezela effluent. *SMRI Technical Note* 7/93

Rapport J, Zhang R, Jenkins B M and R B Williams (2008). CalRecycle-Current Anaerobic Digestion Technologies Used for Treatment of Municipal Organic Solid Waste. Online: http://www.ciwmb.ca.gov/Publications/ (accessed May 2011)

Roš M and Zupančič G D (2002). Thermophilic aerobic digestion of waste activated sludge. *Acta Chimica Slovenica* **49**, 931-943

Siles J A, García-García I, Martín A and Martín M A (2011). Integrated ozonation and biomethanization treatments of vinasse derived from ethanol manufacturing. *Journal of Hazardous Materials* **188(1-3)**, 247-253

Sustarsic M (2009). Wastewater Treatment: Understanding the Activated Sludge Process. *Chemical Engineering Progress*, **105 (11)**, 26-29

Van Haandel A and van der Lubbe J. (2007). Handbook biological wastewater treatment: Design and optimization of activated sludge systems. Quist Publishing-Leideschendam. Netherlands

Van Haandel A C, Catunda P F C and de Souza Araujo L (1998a). Biological sludge stabilization. Part 1: Kinetics of aerobic sludge digestion. *Water SA* **24 (3)**, 223-230

Vermeulen P L M and Vawda A S (1989). Efficient and low cost effluent treatment using an ash disposal dam. *Proc S Afr Sug Technol Assoc* 48-51

Vesilind P A (2003). Wastewater treatment plant design. IWA Publishing, Ch15

Zaher U, Rodríguez J, Franco A and P A Vanrolleghem (2003). Application of the IWA ADM1 model to simulate anaerobic digester dynamics using a concise set of practical measurements. *IWA Conference on ENVIRONMENTAL BIOTECHNOLOGY Advancement on Water and Wastewater Applications in the Tropics* December 9th – 10th, Malaysia.