Provision of research and design of pilot schemes to minimise livestock pollution to the water environment in Scotland

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Anaerobic digestion, storage, oligolysis, lime, heat and aerobic treatment of livestock manures

Final report

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Executive summary

The objective of this study was to explore alternative treatment strategies for the prevention of water pollution from faecal micro-organisms originating from livestock manures.

Seven methods for minimising pollution potential - anaerobic digestion, extended storage, oligolysis, lime treatment, pasteurisation, liquid composting and composting of solids – have been examined with an emphasis on reducing faecal micro-organisms. These methods also affect other characteristics of manures, therefore their effects on odour, organic matter and plant nutrients in manures are also described.

Treatment of livestock manures can be practised on individual farms or in a centralised plant. The decision depends on the complexity of the treatment method and the economics of the process. Generally, simple methods like storage, lime treatment and aerobic treatment can be practised on individual farms while anaerobic digestion and pasteurisation, to be economical, are more suitable either as a centralised process or a process to be used by a contractor. Although lime treatment and aerobic treatment methods can be used in a centralised process the economics of manure transportation has to be considered.

Anaerobic digestion (AD) of liquid livestock manures is a complex solution. An adequate (i.e. decrease of 10^4/g) pathogen and faecal micro-organism kill can be achieved either with thermophilic systems, or by using pasteurisation of manure during the treatment process. Anaerobic digestion offers several other major benefits including reduction of odour offensiveness and pollution potential (BOD). Treated manure is less dense and is homogenised with the nutrients contained in the treated material being more immediately available to plants.

Past experience suggests that, for anaerobic digestion to be reliable and economical, a large capital investment is necessary and a premium contract for the sale of electricity is required. These characteristics favour the use of a centralised plant. To achieve financial viability, capital grant funding is desirable. Also, a supply of organic waste (up to 50% of all treated waste) from industrial food processors is necessary. Food processing waste not only increases the biogas output but the revenue from the gate fees adds to the revenue stream.

It was estimated for the Ettrick Bay water catchment area that an AD plant would cost approximately £5 million. The economics of the plant would depend on the availability of organic wastes from food processors. A requirement of between 3,000 and 11,000 tonnes per annum of this waste would be needed to make the plant self sufficient excluding farmers from having to pay any fee for slurry processing and transport. To optimise the waste management, additional storage for treated slurry may be required on the farm.

A full assessment of the viability of an AD plant for Ettrick Bay and for the River Irvine catchment, would require further investigations, particularly in respect of discussions with the Farmatic Biotech Energy UK Ltd (a subsidiary to German Farmatic engineering company) personnel and a survey of organic wastes availability from local food processors.

Extended storage decreases the viability of faecal micro-organisms. To achieve a significant difference in their numbers (10^2 or 99% reduction) an extensive length of storage, possibly 6 months or more may be required. This would not be practical or economically viable. Although the duration of storage is positively correlated with the faecal micro-organisms kill, thus decreasing the manure potential for faecal water pollution, there are other environmental disadvantages, namely increased offensive odour and release of methane (greenhouse effect gas) and ammonia. The cost of storage (180 days @ £5.50/m^3) may not justify the effect on the faecal micro-organisms decrease.

Oligolysis produces unconvincing results in the reduction of faecal micro-organisms in livestock manures. Although some positive results have been achieved in odour reduction, the main objective cannot be fulfilled with this method.

Lime treatment decreases the numbers of faecal micro-organisms and, in particular, kills most pathogens and parasites. Land application of lime treated slurry therefore minimises the risk of pathogens reaching the aquatic environment or being spread to animals and humans via aerosols. Also, it minimises the perpetuation of diseases through ingestion of pathogens by animals from the slurry applied to land.

The method is simple and it is relatively easy to operate it. The end-product of lime treatment also has a value as a liming agent, has minimal odour and can be easily handled and stored.

There are some disadvantages including the cost of lime and additional handling, loss of nitrogen (up to 50%) and increased total mass of material to be applied on the land. Most of all, due to its alkaline content its use on land is restricted by the pH level of soil and the soil buffering capacity.

The minimal cost of treatment using a simple treatment plant was estimated at £4.40/m^3 of treated manure.

Pasteurisation is a method of effectively killing pathogens and faecal micro-organisms. This method, based on manure being heated usually to 70^{o}C for 30 minutes, does not stabilise manure, on the contrary, odours and ammonia are released during treatment and the biochemical oxygen demand (BOD) may even increase.

Pasteurisation is a very effective method which can be employed during a disease out-break. Its use as a routine manure treatment may not prove practical and economical due to the capital (£40,000 to £100,000 or more) and running costs (£3.60 or £1.50/m^3 respectively) and mostly for the increased odour and pollution potential.

The objectives of **aerobic treatment** of manures are the reduction of offensive odour and biological oxygen demand, pathogen elimination and nitrogen control. This treatment is a process which can be used for both, either for liquid slurries and it is termed **liquid composting**, and farm yard manures and it is called **solids composting.** During **liquid composting** at thermophlic temperatures the faecal micro-organisms are eliminated within hours but, due to the process management requirements, longer treatment periods (days) and a two stage process would be required. The process is simple and it can be used on single farms thus eliminating the costs associated with manure transport to central plants as for AD treatment. The additional benefit, extractable heat energy, can be utilised and help to offset the treatment costs.

The treatment of 1,800m^3 of cattle slurry would require about £40,000 for the treatment reactor and running cost would be approximately £6.30/m^3, most of it (£4.00/m^3) required for electrical energy.

Solids composting can effectively decrease the numbers of viable faecal micro-organisms in livestock manures. To provide consistent control, in-vessel composting may be required but the capital and running costs of this would put it out of reach for a typical cattle farm. (The indicative cost of a plant would be around £0.75 million and the treatment cost of a tonne of manure would be in excess of £50). Although other benefits, like odour removal, reduction of waste weight and volume and decreased organic pollution potential, would be achieved, the need to add bulking material like straw, wood chips, etc., could be so great as to make the process impractical. Also, moving from slurry to a straw-based system would result in the loss of between 5 and 15% of cow places resulting in an additional cost of £1000/cow place for the 'displaced' cows.

Cost of cattle slurry composting in simple windrow or aerated pile systems can range from £2.30 to £9.60 per tonne, depending on the management and pollution control requirements.

Table 1. Indicative effects and costs of livestock slurry treatment systems

Treatment	Pathogen control (log_{10})	Other benefits[#]	Capital cost (£ 000's)	Running costs (£/m^3)
AD with pre-pasteurisation, centralised plant	>4	1,2,3,5,6, 7	5 000	0.0 -17
AD farm scale plant	1-4	1,2,3,5,6, 7	60	3 - 15
Extended storage	1-4	(1)[†]	40	3 - 5.5
Lime treatment	>4	1	22	4.5
Pasteurisation	>4	-	40-100	1.5 - 4
Liquid composting	2-4	1,2,3,4,5, 6,7	20-30	4 - 6.5
Solids composting	2-4	1,2,4,5	25 – 100	3 - 10

NOTE: These costings are based on a 100 dairy cow farm except for centralised AD and pasteurisation. Centralised AD is based on calculation for Ettrick Bay and pasteurisation costs are based on processing approximately 15m^3 of slurry per day.

[#] Other benefits - include 1-reduction of slurry odour, 2-slurry organic matter stabilisation, 3- increase of immediate availability of plants nutrients, 4-manipulation of nitrogen (NO_3^-, N_2), 5-decreased water pollution potential, 6-improved slurry characteristics (homogeneity, lower viscosity etc.), 7-energy production

[†] Odour of stored slurry may increase and methane gas can be released to the atmosphere

1 Introduction

Livestock manures are an important part of the nutrient chain in agriculture. Management of manures is maintained at the simplest level by frequent application to grassland and arable land in the raw form. Pollution of the environment, which can arise from poor manure management, is minimised by utilising adequate manure storage and land application methods (PEPFAA, 1997). Despite all precautions, the high concentration of organic matter, nutrients and pathogens in manures can negatively affect the environment, and so other, more complicated and expensive methods may be employed. These are physical, biological and biochemical processes, which are predominantly used for solids removal from slurries, offensive odour reduction, manipulation of nitrogen and phosphorus, manure stabilisation and for reduction of pathogens. The value of by-products like compost, biogas and heat can offset the cost of treatment.

Seven methods for minimising pollution potential (anaerobic digestion, extended storage, oligolysis, lime treatment, pasteurisation, liquid composting and composting of solids) were therefore examined with a special emphasis on eliminating faecal micro-organisms. Since these methods also affect other characteristics of manures, their effects on odour, organic matter and plant nutrients are described too.

Anaerobic digestion

Anaerobic digestion is one of the most important biological methods used for stabilisation of liquid organic sludge from sewage works, highly concentrated effluents from biochemical and food processes. It is becoming more common now for processing of livestock wastes and solid municipal wastes.

Objectives of anaerobic digestion

The main objectives of anaerobic treatment are minimisation of waste pollution potential and the provision of renewable energy.

For the purpose of this report the control of pathogens and faecal indicator organisms is the primary objective whilst the other benefits listed below are of a secondary importance.

- Reduction of offensive odours by decreasing the concentration of volatile fatty acids and other odorous compounds
- Stabilisation of organic matter and hence reduction of COD and BOD
- Reduction of pathogens and faecal indicators by amount depending on the particular process
- Increased immediate availability of nutrients by converting less available organic nitrogen to ammoniacal nitrogen and decreasing C:N ratio by converting carbonaceous compounds to methane and carbon dioxide gases
- Improved characteristics of liquid manure homogeneity and flow by decomposition of solids and decrease of viscosity resulting in better and faster infiltration of digested slurry into the soil
- Production of energy in the form of methane to produce electrical energy and/or heat through combustion.

3.1 Anaerobic digestion - the process

Anaerobic digestion is a natural process which takes place in the absence of oxygen. Controlled digestion is normally accelerated by increasing reactor temperature into the mesophilic range (normally for anaerobic digestion between 30-37^{o}C), or into the thermophilic regime (normally for thermophilic anaerobic digestion between 55-65^{o}C). The decomposition of organic material consists of three basic processes (Dohanyos *et al.*, 2000).

1.1.1 Hydrolysis

The first step in anaerobic decomposition is enzymatic hydrolysis. It occurs in the substrate, outwith the cells, by the action of extracellular enzymes produced by bacteria. The result of hydrolysis is the formation of sugars from carbohydrates, amino acids from proteins, and fatty acids from lipids. Soluble organic compounds are fermented to a relatively small variety of end products. These include formate, acetate, propionate, butyrate, lactate, succinate, ethanol, carbon dioxide, and hydrogen gas.

1.1.2 Acetogenesis

Products of hydrolysis are degraded by acetogenic bacteria to their final metabolic products of volatile fatty acids (predominantly acetates), CO_2 and hydrogen. During this phase a fast growth of acetogenic bacteria occurs, thus mixing of the substrate positively affects this process.

1.1.3 Methanogenesis

Production of methane and CO_2 from intermediate products is accomplished by methanogenic bacteria. Approximately 70% of the methane is formed from volatile fatty acids (Smith and Mah 1978). The remaining 30% is produced from hydrogen and carbon dioxide. Methanogenesis is critical to the entire digestion process, since it is the slowest biological reaction of the digestion. Overloading of the reactor, temperature changes or large ingresses of oxygen usually result in cessation of methane production, an increasing fatty acids concentration and results in the production of only CO_2.

Since the anaerobic digestion process is usually carried out in a single reactor/vessel the processes described above run concurrently. The characteristics of i) the final treated stabilised sludge/slurry and ii) the biogas, are therefore the result of this complex anaerobic decomposition.

i) Liquid waste stabilised by anaerobic digestion has the same volume as the raw waste, but the solids content is reduced by up to 50% and the digested waste odour is substantially decreased. The extent of pathogen inactivation in the sludge depends largely on the treatment temperature and the process arrangements.

ii) Biogas composition is dependent on the type of digested substrate. Livestock wastes normally produce biogas which contains 55-75% methane. The remainder is mainly CO_2. Both gases are odourless but the biogas has a strong smell caused by hydrogen sulphide (1-10g/m^3) and other volatile chemicals - mainly very odorous mercaptans. Hydrogen sulphide is a very corrosive component of biogas. In boilers it can be oxidised to form sulphuric acid which can dissolve the metal parts of the heat exchangers and chimneys. In internal combustion engines, hydrogen sulphide reacts with copper alloys and rapidly destroys the bearings and other engine parts. Removal of hydrogen sulphide is therefore a prerequisite for safe biogas utilisation. Several methods are used. The most common method uses a reaction with iron salts. More recently a technique using small streams of air bubbled through the top layer of digested slurry in the digester has been used to promote growth of *Thiobacillus spp.* These oxidise hydrogen sulphide to elemental sulphur which is retained within the treated slurry.

Biogas is an energy source. In smaller anaerobic digestion/biogas plants, the gas is usually purified and burned in boilers to help maintain the digestion process temperature. Hot water heats the digester to mesophilic or thermophilic temperatures and can also be used locally for space or process heating. In larger units, the gas can be used by internal combustion engines or gas turbines to produce electricity using an electricity generator. Heat developed during electricity generation can also be used to heat the digester.

1.2 Anaerobic digestion in livestock agriculture

Anaerobic digestion was originally developed to provide treatment for sludge generated by sewage treatment and for effluents with a high concentration of dissolved organic matter like spent fermenter broth resulting from production of citric acid. Adaptation of this process for livestock manures was driven by the requirements for finding new sources of renewable energy as well as to decrease of the pollution potential of manures. Various researches were conducted into laboratory and pilot scale treatment systems (Hobson and Robertson, 1977, Hobson et al., 1981) and large full scale systems (Pain et al., 1984). Although the process proved to be effective for the required objectives, the economics and the system operation usually left something to be desired. Thus, only a few companies became specialists in agricultural digestion systems. In the UK there are only a few farm anaerobic systems, whilst Denmark (Appendix 1), Italy and Germany have tens of anaerobic digesters for farm waste, although the largest ones, usually co-process other waste from the food processing industry. In large systems, like the Trebon plant in the Czech Republic, the excess biogas is used for generating electricity which is used predominantly on-site to avoid disadvantages associated with selling power to the electricity grid. In Germany and Italy the concern about the environment in has led to the increased use of anaerobic digestion of livestock wastes. The respective Governments (Italy, Germany, Netherlands) offered incentives to sell the electrical energy to the national grid for between €0.103 to €0.13 per kWh (Piccinini 1996). In the Netherlands during the 1980's and 1990's, anaerobic digestion was intensively researched and many slurry digesters were built on dairy and pig farms. Although the environmental benefits of AD were recognised, the economics (low price for natural gas) and technical problems contributed to the closure of most of the digesters in the Netherlands. Only recently has AD attracted more interest, mainly because the environmental advantages of this process have been recognised.

Regulations requiring an increase in the recycling of wastes, tapping renewable energy resources and protection of the environment from pathogenic and faecal organisms, motivated several organisations to review the practicality of anaerobic digestion of livestock wastes. Two companies, Holsworthy Biogas Ltd and German installation contractors Farmatic Biotech Energy built the UK's first centralised anaerobic digestion (CAD) plant in Devon for 146,000 tonnes/year of cattle, pig and poultry manure together with organic waste from local food processors (Appendix 2). Here waste is firstly mixed and pasteurised by heating to 70^{o}C within an hour. The mixture, cooled by a series of heat exchangers, is then pumped to one of two 4000m^3 reactors where it is digested for an average duration of 20 days. Treated waste is stored and redistributed back to farmers as a fertiliser. Following desulphurisation, which removes hydrogen sulphide (H_2S), the biogas generated by digestion is used to produce electricity and heat.

Silsoe Research Institute, in a 42 months project, has undertaken an evaluation of the process and the plant performance. This DEFRA funded project (Assessing the environmental impact of centralised aerobic digestion (CC0240)) will produce the environmental Life Cycle Assessment (LCA) of the above CAD. It will compare this technology, cost effectiveness and environmental impact with other manure management strategies.

Literature research

1.3 Pathogen control by anaerobic digestion

Livestock slurries and sewage sludge can be processed by anaerobic digestion at mesophilic or thermophilic temperatures. Due to its stability and lower use of energy, mesophilic anaerobic digestion is used more often than thermophilic digestion. Although a reduction in pathogen concentration is achieved in both systems, the pathogen inactivation effect is lower in mesophilic digestion. Bendixen (1999) analysed large-scale digesters in Denmark. Numbers of pathogens in the waste stream were reduced by 1-2 and by 4 log_{10} units during mesophilic and thermophilic digestion respectively. Kumar et al., (1999) studied the survival of some pathogenic bacteria in anaerobic batch digesters at 18-25°C and 35°C under laboratory conditions. *E. coli* and *Salmonella typhi* survived at room temperature for up to 20 days, but the survival time was reduced to 10 days at 35°C. *Shigella dysenteriae* was a more temperature-sensitive organism, surviving for only 10 days at room temperature, and for 5 days at 35°C. *Streptococcus faecalis* survived the longest period for up to 35 days at room temperature, and for 15 days at 35°C. The investigation by Hu et al., (1996) of the mesophilic anaerobic digestion of sewage sludge on the survival of *Giardia* showed that the concentration of cysts was about 900,000/kg wet weight of sludge after anaerobic digestion, but the cysts infectiveness was not determined.

Thermophilic anaerobic digestion is a more promising process for pathogen inactivation (Bohm et al., 1999). At the Harrogate South Sewage Treatment Works mesophilic anaerobic digestion plant, the entero-bacterial counts were reduced by 90% and enteroviruses by 99%, but no effect was observed on *Ascaris* ova. The thermophilic plant exceeded the disinfecting ability of the mesophilic one and the counts of enterobacteria, thermotolerant coliforms and faecal streptococci were all reduced to below 10^4 per litre. Cytopathic viruses were undetectable and *Acsaris suum* ova lost viability within 4 hours. Plachy (1997) also demonstrated that mesophilic anaerobic digestion with a 30-day residence time had only a minimal effect on *Ascaris suum* eggs, 76.2% were still viable, whereas thermophilic anaerobic digestion at 54°C destroyed all eggs within 10 minutes. Olsen and Larsen's (1987) research of thermophilic digestion (53°C) provided data of the decimation time (T90 or 90% removal) for various bacteria. *Streptococcus faecalis* had a T90 of 1h, *Salmonella typhimurium* 0.7 h, *Salmonella Dublin* 0.6h, *Staphylococcus aureus* 0.5 h and E*. coli* 0.4 h. Another study by Martens et al., (1998) showed that a 30h treatment was required to inactivate *Salmonella*, faecal streptococci and most of the viruses associated with livestock by thermophilic anaerobic digestion in cattle slurry.

Viruses of notifiable animal diseases like classical swine fever virus, Aujeszky's disease virus and foot and mouth disease virus are more difficult to study in large scale plants. The available data are therefore scarce. However, by comparing inactivation kinetics of some indicator bacteria and viruses, it can be shown that the inactivation kinetics of *Salmonellae* nearly corresponded to those of the Picorna viruses. Viruses of this group are known to be comparatively stable in the environment, especially against chemicals. ECBO virus, for instance, is an organism used to test virucidal effects for disinfectants according to the regulations of the German Veterinary Association (DVG, 1988). Thus, inactivation studies using *Salmonellae* in anaerobic treatment plants (a requirement by law in Germany) indicate the inactivation of Picorna viruses or other environmentally less stable viral pathogens which may occur in slurry.

Viruses occurring naturally in raw sludge appear to be inactivated by the digestion process much more slowly than laboratory strains seeded into the sludge. The close association of naturally present viruses with the organic material in the sludge may be the reason for more difficult inactivation (Goddard et al., 1981). These results also indicate that there may be a general problem in trying to extrapolate data obtained using sludge seeded with virus with those obtained using naturally occurring organisms. Ward and Ashley (1976) studied the effect of anaerobically digested sludge on polioviruses at 4 and 28^{o}C and found that virus inactivation increased with time and temperature. The inactivation rate, possibly due to RNA damage, ranged from a 10 fold reduction (or more) per day at 28^{o}C to about 10 fold every 5 days at 4^{o}C. Monteith et al., (1986) seeded a bovine enterovirus and parvovirus into liquid cattle manure and noted that both were rapidly inactivated by the anaerobic digestion process under thermophilic (55^{o}C) conditions, no virus having been detected after 30 minutes. They survived for 13 and 8 days respectively under mesophilic conditions, however.

Anaerobic digestion processes can be combined with aerobic autothermic pre-treatment or thermal pretreatment. These combined processes have a much greater capacity to eliminate pathogens (Ward et al., 1998). Autothermic pre-treatment was shown to have the potential to make anaerobic digester operation more stable compared to anaerobic digestion alone. Autothermic pre-treatment consistently reduced faecal coliforms to below detection limits, and they remained at low levels throughout the digestion process.

Co-digestion plants process livestock slurry with other organic wastes, particularly from food processing, which could be contaminated with pathogens including those of notifiable diseases. To assure that the treated material is free of these pathogens an additional treatment step is required which involves heating of the feed stock to 70^oC for 1 hour. This combined treatment inactivated the tested micro-organisms *Faecal Streptococci*, Equine Rhinovirus, Bovine Enterovirus, *Salmonella senftenberg* by 4 to 7 log_{10} units while Bovine Parvovirus was reduced only by 3 to 3.5 log_{10} units.

The removal of pathogens can be described by the first order equation (Dohanyos et al., 1998):

$$dN/dt = - K_bN$$

Where N is the number of cells and K_b is the rate of biomass degradation. Because K_b increases with increasing temperature, the time required for inactivation of most pathogens would be a few weeks at 20^oC, a few days at 35^oC and a few hours at 55^oC. Bendixen (1995) described the effect of digester temperature on the 90% (T_{90}) decrease of pathogens in a mixture of livestock slurries (Table 4.1.1).

Table 4.1.1 Time (d) required to decrease pathogen activity by 90% (T_{90}) at various temperatures in the anaerobic digester (Bendixen ,1995).

	Digester temperature (^{o}C)						
Pathogen	**5**	**20**	**35**	**40**	**45**	**50**	**55**
Bacteria							
Salmonella sp.		14	2.4				0.03
E.coli		14	1.8				0.02
Faecal *Streptococci*			2				0.05
Viruses							
Foot & mouth	>98	14	1	0.5	0.2	0.05	0.05
Aujeszky's	98	14	0.2	0.1	0.04	0.01	0.01
Parasites							
Nematode eggs			21-35				0.2

Studies by Haas et al., (1995) and Pesaro et al., (1995) have showed that temperature is not the only pathogen inactivating component during anaerobic digestion. The combination of other factors, like the pH and the concentration of free ammonia, contributes to the degree of inactivation.

4.2 Organic matter, odour, nitrogen and phosphorus in digested wastes

The final result of organic matter digestion (fermentation) is the production of methane and carbon dioxide as described above. Organic material is mineralised to a degree dependent on the material degradability and the anaerobic process parameters.

Livestock excrements (pig, cattle and poultry) are substrates with a high percentage of biologically degradable organic compounds. They contain all the nutrients required for anaerobic digestion organisms. Waste from cattle and sheep even contain the methanogenic bacteria required in the AD process. The highest proportion of organic matter biodegradable by AD is in poultry waste (65%), with less in pig waste (50%) and even less (25-40%) in the waste of cattle where the material has already undergone methanogenesis in the ruminant stomachs (Dohanyos et al., 2000). The average characteristics of pig, cattle and poultry waste are indicated in Table 4.2.1.

Table 4.2.1 Average characteristics of pig, cattle and poultry excrements as a percentage of total solids concentration.

Parameter (%)	**Pig**	**Cattle**	**Poultry**
Organic matter	82	84	75
Suspended matter	86	81	82
COD	133	140	135
BOD_5	35	20	35
Total nitrogen	7.5	4.0	7.0
Ammon. nitrogen	4.0	1.2	4.5
Phosphorus	2.5	1.2	2.0
Potassium	3.0	4.0	2.0
Volatile fatty acids	0.7	0.2	N/A

Odour from livestock slurry is substantially decreased by anaerobic digestion. Compounds associated with offensive odours, including volatile fatty acids (VFA) and small but potent molecules of mercaptans, are degraded into methane and carbon dioxide by anaerobic bacteria during the process. Volatile fatty acids may be reduced by 93% (Summers and Bousfield, 1980) and phenols and p-cresol virtually eliminated (van Velsen, 1979). The remaining odour in the treated material is caused by low residual concentrations of VFA's and by hydrogen sulphide. From field studies (Pain *et al.*, 1984) it was found that the odour concentration (223 odour units/m^3 of air) of air collected after land application of anaerobically digested pig slurry, was about five times lower than the odour of air (1,100 OU/m^3) collected from above the field sprayed with raw slurry.

Changes in the pollution potential of livestock slurries caused by the biological anaerobic decomposition during the digestion process (Table 4.2.2) were described by Hobson et al., (1977). Anaerobic digestion was carried out in pilot and farm scale digesters.

Table 4.2.2 Reduction (%) of BOD_5, COD, total solids (TS) and volatile fatty acids VFA) in pig, cattle and poultry slurry as a result of mesophilic anaerobic digestion process.

Parameter	Pig	Cattle	Poultry
BOD_5	75	55	80
COD	50	35	50
TS	40	30	60
VFA	73	70	80

The quantity of total nitrogen in the waste was not changed, except for a small percentage of ammonia being transferred to the biogas. Nitrogen in the organic material available for biodegradation was mostly reduced to ammonium ions thus increasing ammoniacal concentration in the waste to a rather high value (4-6g NH_4^+-N/l), particularly in digested poultry wastes (Dohanyos et al., 2000).

Phosphorus, which is mostly associated with solids, was partially released into the liquid phase by anaerobic digestion.

The anaerobic digestion process therefore substantially decreases offensive odour of wastes, decreases the C:N ratio and increases the concentration of immediately accessible plant nutrients.

1.4 Process requirements

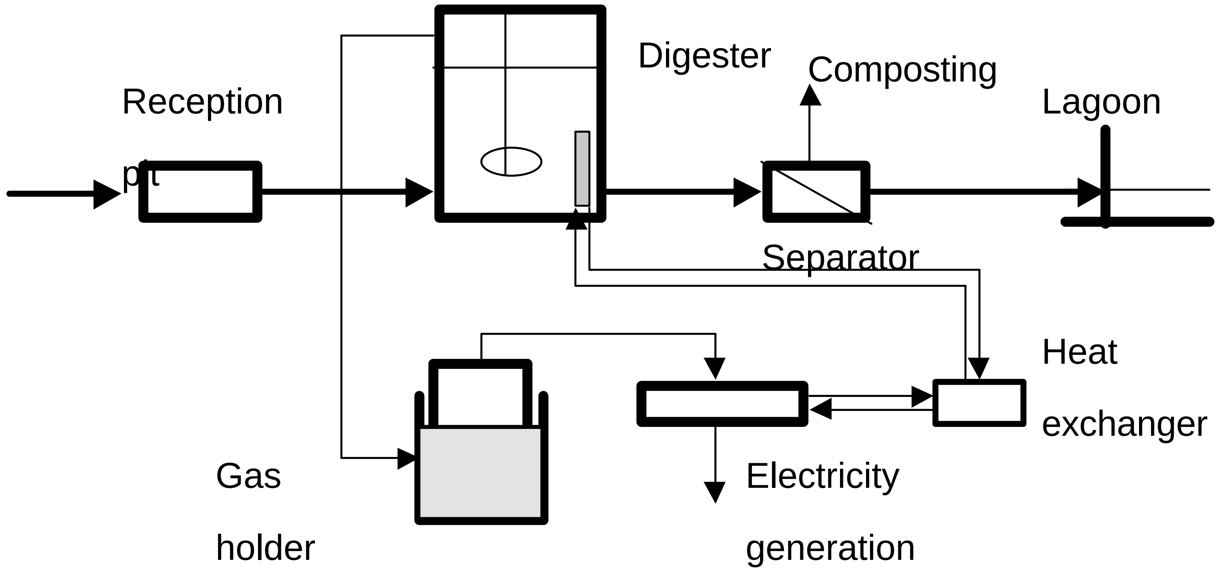

Figure 5.1.1 Schematic of anaerobic digestion system for treatment of livestock slurry.

The basic system for anaerobic digestion of livestock wastes comprises several units which are required for successful process operation.

- A reception pit/tank used for short duration storage is usually equipped with a powerful stirrer for slurry homogenisation. Slurry is mixed and homogenised here and pumped to the digester on a regular basis to maintain the predetermined treatment (residence) time in the digester.

- The digester is a gas tight tank usually thermally insulated, and constructed with the aim of preventing sedimentation of slurry particles. It is equipped with a mechanical or gas mixing system which keeps the slurry in a homogenous state, thus optimising the digestion process and minimising any gradients of temperature, solids, substrate, and gas concentrations in the digested mass. Furthermore, the digester will also have a system (a heat exchanger) for maintaining the process temperature at either around 35^{o}C or 55^{o}C.

- The digested slurry can be then stored in a tank or a lagoon prior to land application; or it can be separated, usually by a centrifuge, to produce compostable solids and liquor rich in plant nutrients.

- The biogas generated from the anaerobic process is accumulated in a gas holder. Biogas is normally de-sulphurised, to remove hydrogen sulphide, and used in a boiler for heating the digester contents and for producing hot water for space heating in adjacent buildings. When large volumes of biogas are produced, it can be used in internal combustion engines which, through an electric generator, can supply electrical energy for the plant and for the farm or local houses. The excess can be sent to the electrical grid if the necessary export arrangements are put in place. Heat from the internal combustion engine is usually enough to maintain the temperature of a digester at the required level.

The process of anaerobic digestion of livestock wastes can be affected by some factors, which are the result of the livestock waste characteristics.

1.4.1 Temperature

Temperature is one of the most important factors of an anaerobic digestion process. It affects all phases of the digestion. As with other biochemical processes, the rate of reaction is accelerated at higher temperatures. The optimum temperature for AD is a compromise between the optimal biochemical temperature and the economics for heating the digesters. The highest heat energy input is required for raising the temperature of the input slurry to the process temperature. It is therefore obvious, that a high water content of the slurry will have a negative affect on the process energy balance.

It was found (Jonas et al., 1980) that biogas production was effectively increased when the digestion temperature of pig slurry was increased from 33°C to 39 to 42°C. Similarly Feilden (1981) recommends the optimal temperature for maximum gas production for livestock wastes to be digested at 40 to 44°C.

Recently, in some of the centralised AD plants in Denmark, the treatment temperature has been maintained in the thermophilic range of between 55 and 62°C. This higher temperature has had a positive effect on the biogas yield and has increased pathogen kill.

1.4.2 pH

The optimal pH for anaerobic digestion, particularly in the methanogenesis phase is between 6.5 and 7.5. At these levels the volatile acids have no significant toxic effects upon methanogenic bacteria at concentrations up to 1,000 mg/l. Since the acetogenic phase of the digestion has a higher reaction rate than the methanogenic, accumulation of organic volatile acids (VFA) can occur in the reactor causing a decrease in pH and a further increase in VFA concentration. This can be a consequence of overloading the biomass with organic material (slurry) or from the effect of inhibitors like antibiotics or disinfectants. When the process is not corrected and the concentration of VFA is not reduced to tens or hundreds of mgVFA/l, the production of methane can stop and only carbon dioxide is produced.

1.4.3 Ammonia

Ammonium ions play an important role in the anaerobic digestion process. Ammonium ions are rapidly formed in a digester during the decomposition of proteins. Since the anaerobic micro-organisms grow relatively slowly they require only a low ratio C:N:P=100:1:0.2. In livestock slurry, mainly pig and poultry, the ratio can be as high as C:N=100:5. Therefore the ammoniacal nitrogen concentrations can reach levels of 2 to 6gNH_4^+-N/l. This shifts the pH level upwards to over pH 8 and free ammonia is released. This has a toxic effect on the production of biogas. Free ammonia levels should be maintained below 80 mg/l while ammonium ion can generally be tolerated up to 1,500 mg/l as NH_4^+ -N. Despite that, it has been found that with acclimatisation (usually several months), stable operation can be achieved for ammonia nitrogen concentration up to 8,000 mg/l (van Velsen 1979).

1.4.4 Sulphides

Sulphides are produced in anaerobic reactors by the reduction of sulphates present in the influent and by degradation of proteins. If the concentration of soluble sulphides exceeds 200 mg/l then the metabolic activity of methanogenic bacteria will be strongly inhibited, leading to the failure of the process (Lawrence and McCarty 1964). Because heavy metals form highly insoluble precipitates with sulphide, the addition of a metal, such as iron, provides a simple means of reducing the soluble sulphide concentration. Sulphides can also be present in the gaseous phase (biogas) in the digester. Therefore the concentration of soluble sulphides depends upon the pH of the liquid phase, the presence of heavy metals, and the composition of the gas phase.

1.4.5 Treatment time and organic loading

Treatment time (residence time) and the organic loading of the biomass together with the hydraulic loading of the digester affect the reduction of organic matter in the treated slurry (stabilisation) and the production of biogas. As an informative guide the following table describes some of the parameters normally applied in AD of livestock slurries. Slurry solids concentration used in AD plant is assumed to be between 4 to 6% in dry matter.

Table 5.1.5.1 Informative technical parameters used in AD of livestock slurries (Dohanyos et al., 2000).

Parameters	**Pig slurry**	**Cattle slurry**	**Poultry slurry**
Treatment time (d)	13-17	16-21	23-25
Treatment temperature (^{o}C)	38-42	38-42	38-42
Maximum organic loading (kg.org.matter/m^3d)	5	4	3
Biogas production (m^3/kg org. matter.d)	0.35	0.20	0.20

1.5 Farm anaerobic digestion systems

Farm anaerobic digestion plants are self contained units processing the waste from the farm, occasionally from near-by farms and some waste from food processing units. The gate fees for imported wastes are important in justifying the AD plant economics.

Table 5.2.1 Indicative requirements for the digester volume and biogas production from livestock wastes (Dohanyos et al., 2000).

Animal	**Animal weight (kg)**	**Excrements (kg/d)**	**Digester volume (m^3)**	**Biogas production (m^3/d)**
Hen	1.5	0.2	0.015	0.015
Broiler	0.8	0.15	0.01	0.012
Piglet	20	1.8	0.03	0.04
Fattening pig	50-100	7	0.14	0.14

Sow	160	12	0.25	0.2
Calf	120	7	0.1	0.08
Fattening cattle	120-350	22	0.4	0.5
Fattening cattle	>350	42	1.3	1.0
Heifer	120-300	20	0.4	0.39
Heifer	300-500	38	1.3	0.85
Milking cow	500-600	50	2	1.2
Bedding straw	1.0	-	0.08	0.2

Generated biogas is normally utilised by the cogeneration unit (combined heat and power - CHP). Both heat and electrical energy are usually utilised on the farm and any excess electrical energy can be, if agreed with the electricity generating company, sold into the electricity grid. The size of the farm AD depends on the quantity of waste produced by the farm. The size of AD plant at the lower end is limited by the increasing costs with decreasing size for the unit volume of the digester, by storage space, and by the increasing heat losses with decreasing volume of digester. Table 5.2.1 gives indicative parameters for the size of digester and rates of biogas production from excrement for various farm animals.

Currently there are hundreds of small farm AD plants in Europe. In warm regions of Europe, like Portugal, Spain, Italy and Greece, the AD plants are not heated to achieve mesophilic temperatures because the summer temperature is high enough to keep the digestion working. In temperate climates in Germany, Austria and Switzerland the heated units process waste from an equivalent of 30 to 400 livestock units (1 livestock unit LU normally corresponds to 400kg of live weight cattle). Examples of Austrian AD plants are given in Table 5.2.2.

Table 5.2.2 Some characteristics of AD plants in Austria (Dohanyos et al., 2000).

Type of waste/excrements	LU	Treatment time (d)	Digester volume (m^3)	Biogas production (m^3/d)
FYM, pig	75	30	120	140
Pig, poultry, food	80	30	100	160
FYM, poultry	30	30	50	70
FYM, poultry, pig, food	70	40	140	140
FYM	120	30	760	170
Pig, food	50	35	70	170

Reasons given by farmers for using on-farm anaerobic digesters were:

- Decrease in import of electrical and heat energy
- Increase in value of livestock wastes as fertilisers
- Decrease in import of mineral fertilisers
- Soil improvement from use of digested slurry
- Decrease of offensive odour around the farm
- Less weed on the fields
- Ecologic aspects like recovery of renewable energy, decrease of methane emissions etc.

1.6 Centralised anaerobic digestion systems

Centralised biogas plants process livestock waste from several farms and also waste from local food processing industries and other industries which produce organic biodegradable waste. In Central and Eastern Europe these units were constructed solely for the treatment of excrements from large pig fattening units with more than 20,000 places, or in combination with the treatment of sewage sludge from large cities.

In Denmark centralised biogas plants (CBP) were conceptually developed in 1980 when a 40% grant was given to farm co-operatives to build CBP (Appendix 1). In 1997 there were 19 CBP in operation and a few others were planned. These CBP process 50 to 500 tonnes of waste and produce 100 to 15 000 m^3 of biogas daily (Al Seadi, 2000). Normally the plants process a mixture of 75% livestock wastes and 25% of other industrial organic wastes (Table 5.3.1). In 1998 the CBP's in Denmark processed 1.2 Mt of waste and produced 40Mm^3 of biogas.

Table 5.3.1 Parameters of some centralised biogas plants in Denmark (Dohanyos et al., 2000).

	CBP's in Denmark				
Parameters	**Sinding**	**Fangel**	**Ribe**	**Lintrup**	**Lemvig**
Input (m^3/d)	132	152	401	385	453
Slurry (%)	70	77	84	67	79
Org.waste (%)	30	23	16	33	21
Dig.temp. (^oC)	52	37	53	37	52
Treatment time (d)	16	21	12	20	17
Biogas (m^3/d)	7100	7100	11800	11400	14800

The sanitisation of wastes in CBP's can be achieved by two means. As demonstrated above, some of the plants process the slurry and additional wastes at thermophilic temperatures. This, and extended treatment times, minimise the viability of pathogens and faecal indicators so the treated slurry can be safely applied onto the land. The thermophilic process has further advantages in shortening the treatment time, thus using smaller size digesters. The production of biogas can also be higher than from the mesophilic process.

A different technique is applied with the mesophilic process to control pathogens and faecal indicator bacteria which would not be destroyed at the lower levels of treatment temperature with this process. The input slurry and organic wastes are heated to 70^{o}C for 1 hour before they are pumped into the digester. Although this requires additional energy, a system of heat exchangers with thermal efficiencies of between 50 to 70% makes good use of this heat. The digestion process, which in the mesophilic and thermophilic range uses about 15 to 30% of produced energy can benefit from the use of heat recovery heat exchangers and the net energy use can be as low as 10%.

The most important aspects in building a large biogas plant are those of the economics of the project. With increasing plant size the specific capital and running cost per unit volume treated decreases. There are other advantages including the possibility of using more qualified plant operators, more efficient use of biogas in the combined heat and power units and a more stable quality and quantity of treated slurry.

Economics of anaerobic digestion

1.7 Energy conversion

The anaerobic degradation of organic substances to its most reduced form, methane (CH_4), is a microbial process. The energy released, originally stored in the substrate, is predominantly recovered by the formed methane.

$$33\text{g org. material} = 22\text{g } CO_2 + 8\text{g } CH_4 + 3\text{g biomass}$$

1.8 Transport of wastes

The co-processing centralised anaerobic digestion plants have one significant economic disadvantage, compared with small on-farm digesters. This is in the relatively expensive transport of low energy content livestock slurry from remote sites to the digester. The cost of waste collection and treated material re-distribution, even when using large $20m^3$ road tankers, can represent 20 to 35% of the AD plant total running cost (Dohanyos et al., 2000). It is therefore important to plan the whole transport system carefully and to minimise travelling distances. Also the slurry pumping systems and management of slurry collection on single farms must be reliable so as to minimise down time. In the case of transporting more dilute slurries, consideration should be given to the use of long pipelines.

The cost of slurry transport in the UK (Scotland) has been calculated for a contractor with a 20 tonne road tanker and a farmer/contractor with a tractor and 8 tonne tanker (A. Jones, personal communication). The average speed of a road tanker is estimated at 25km/h and the tractor/tanker at 20km/h. The road tanker has a capacity of 20 tonnes and the farm tanker 8 tonnes. The total turn-around time (hooking up, slurry pumping at $100m^3$/h and finishing off) for a road tanker will take 44 minutes and for a tractor/tanker 30 minutes (for a return journey). The hourly cost charged by a contractor for a road tanker is estimated at £40/h and for a tractor and a tanker at £32/h. The total costs and transported slurry volumes can be interpolated from the following graphs.

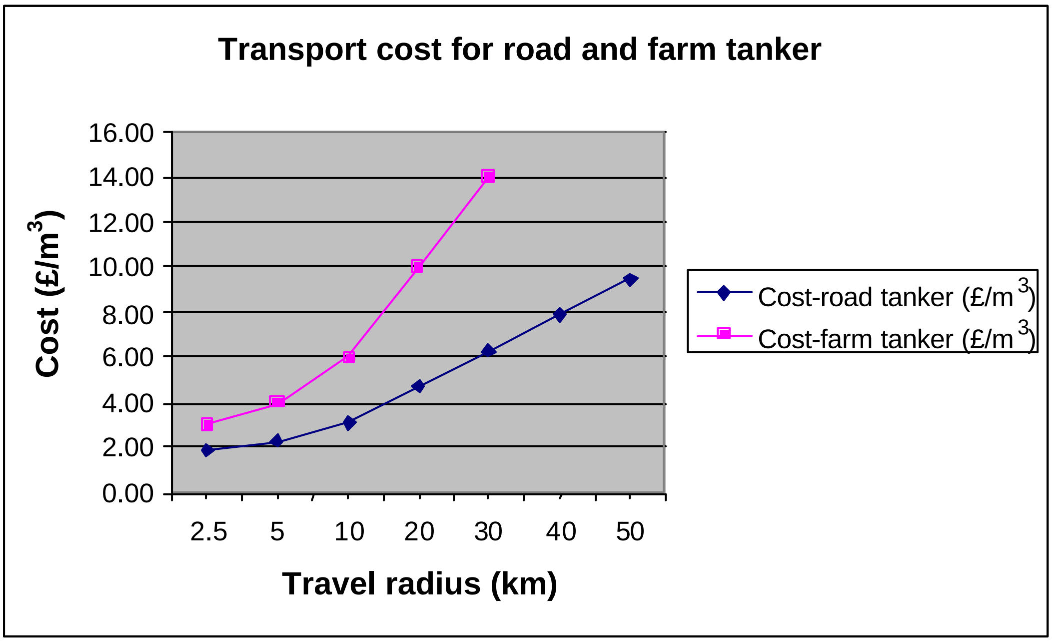

Figure 6.2.1 Transport cost for road and farm tanker

The road tanker has a higher carrying capacity and road speed but for small roads and short distances it would not be effective, thus a tractor and tanker of a smaller capacity would be used.

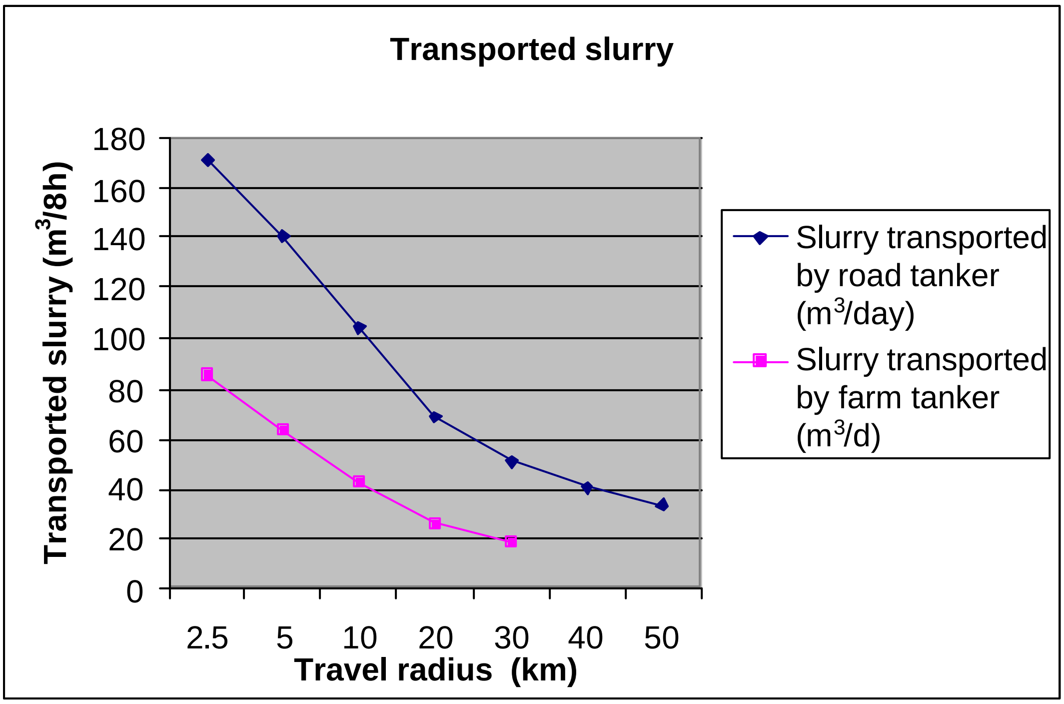

Figure 6.2.2 Effect of travel radius on the rate of transported slurry

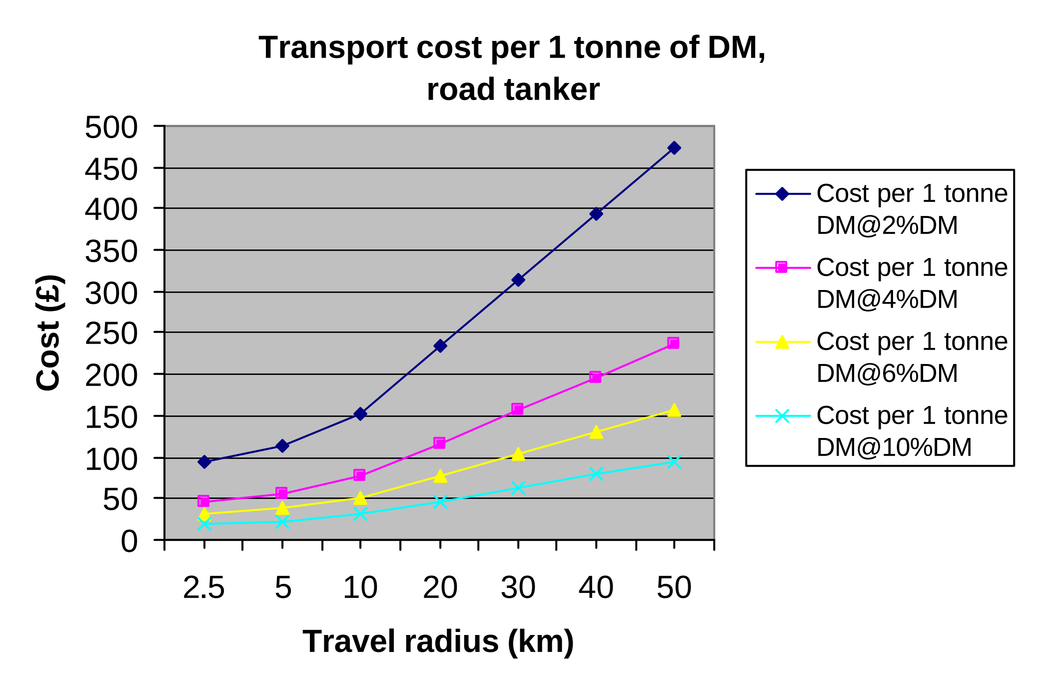

Figure 6.2.3 Cost of transport by road tanker

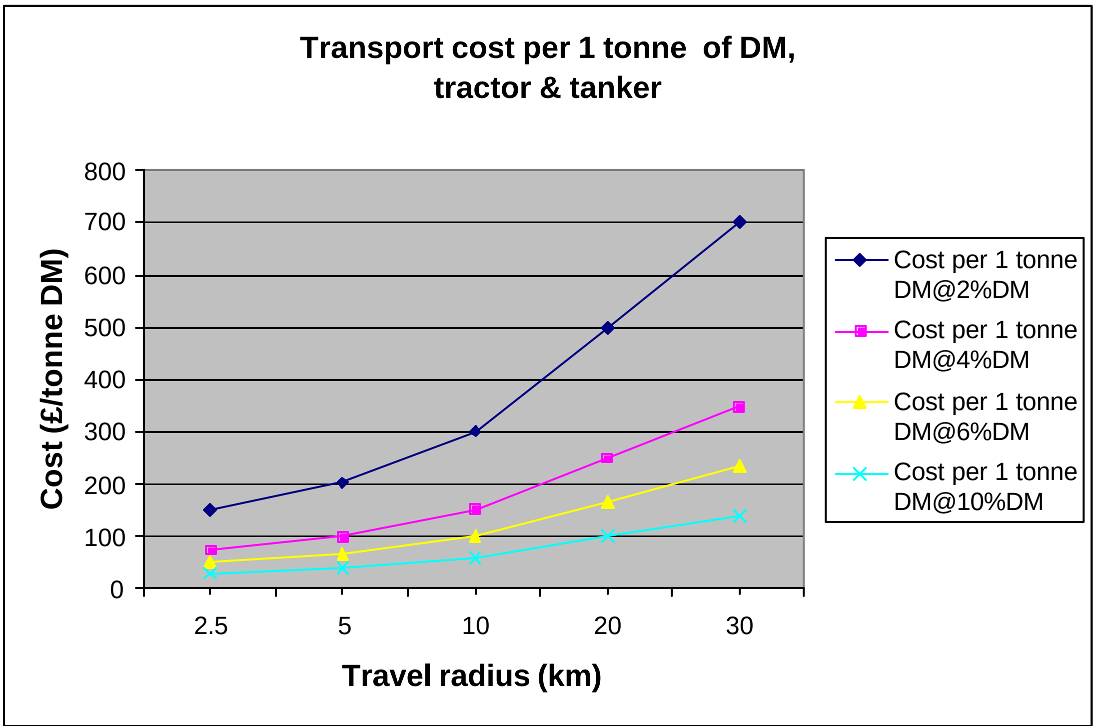

Figure 6.2.4 Transport cost by tractor and tanker

1.9 ***Energy market***

The AD plant will provide biogas which will be used to generate two forms of energy, electricity and heat, in combined heat and power (CHP) units of gas engines. Electrical energy, part of it utilised by the plant (approximately 5%), will be exported to the national electricity grid. Its selling cost will depend on the terms of a contract secured by the plant manager. It could be expected that, due to the different schemes like Non-Fossil Fuel Obligation, the electricity could be sold for approximately £0.05 to 0.06/kWh.

It is expected that the quantity of generated heat will be about the same as that of the generated electricity. The sale of heat for heating large complexes such as hospitals and factories, or providing heat for district heating will bring further revenue to the AD plant operator.

1.10 Costs

Anaerobic digestion is a proven technology but it is not a simple process. It requires storage space for both the raw and treated material, dosing pumps, a gas tight reactor with heat exchanger and mixing facilities, a bio-gas reservoir, boiler and/or internal combustion engine with an electrical energy generator. To make the process economical, with a payback period of less than 5 years, a high percentage of biogas has to be utilised. This target is achievable in larger plants, where electrical energy/heat co-generation is the most practical design.

The data for a simple unheated anaerobic digester was provided by Piccinini (1996). The digester of 1700m^3 treated slurry from pigs of a total live weight of 270 tonnes.

21 000m^3 of biogas produced annually had a value of € 4,900. Since the investment in the anaerobic digester was € 20,600 (year 1988) the pay back time can be calculated as 4.2 years.

The capital and running cost of anaerobic digestion depend greatly on the size of the unit, quality of materials used and management skills. Parsons (1984) stated that for a farm anaerobic digestion unit to produce energy comparable to other sources, the supply of slurry would have to exceed either that from 1,000 cows or 5,000 pigs. (Based on a daily production of 45 m^3 of cow slurry or 22.5 m^3 of pig slurry both with 10% DM).

TEG Environmental Plc estimate a capital cost of £2.75 million per anaerobic digestion unit and a total cost of treatment per tonne of dry solids of £78. This system would not provide the total elimination of pathogens. Anaerobic digestion with pre-pasteurisation, i.e. slurry feed would be pasteurised (see section 3.4 on Pasteurisation) before anaerobic digestion, would cost £3.25 million and the cost of treatment per tonne of dry solids would be £97. Thermophilic anaerobic digestion cost should be between these two. The cost of a large (200 tonnes/day of livestock slurries and other organic materials) Danish-built mesophilic anaerobic digestion plant with pasteurisation planned for Cannington in Somerset is estimated at £4 million.

Nicholson *et al.,* (2000) estimated the cost of an anaerobic digestion plant for a 100 dairy cow herd (4.5 m^3 of slurry per day) to be at least £60,000. The specific cost per m^3 of digester volume was estimated as £750.

The first UK anaerobic digestion plant with process capacity of 146,000m^3 per annum of livestock manure (cattle, pig and poultry) and organic waste from food processing producers with additional manure storage capacity was built for £7.7 million. Although the farmers do not financially contribute to either manure treatment or the transport cost it is expected that the payback period should not exceed seven years.

Boyd (SAC, 2001) drew some conclusions from the most recent estimates of capital and running costs for anaerobic digesters using a combined heat and power system for energy recovery. Boyd used data from British Biogen who estimated the capital costs as £60k to £70k for smaller installations with 10kW_e output and £3 to £4 million for plants with 1MW_e output. Other, slightly higher values, were obtained from Higham (1998) who assumed that a 25kW_e output installation would cost £0.31 million and a large system for production of 1MW_e output would be about £5.65 million. The trends are graphically expressed in the following figures:

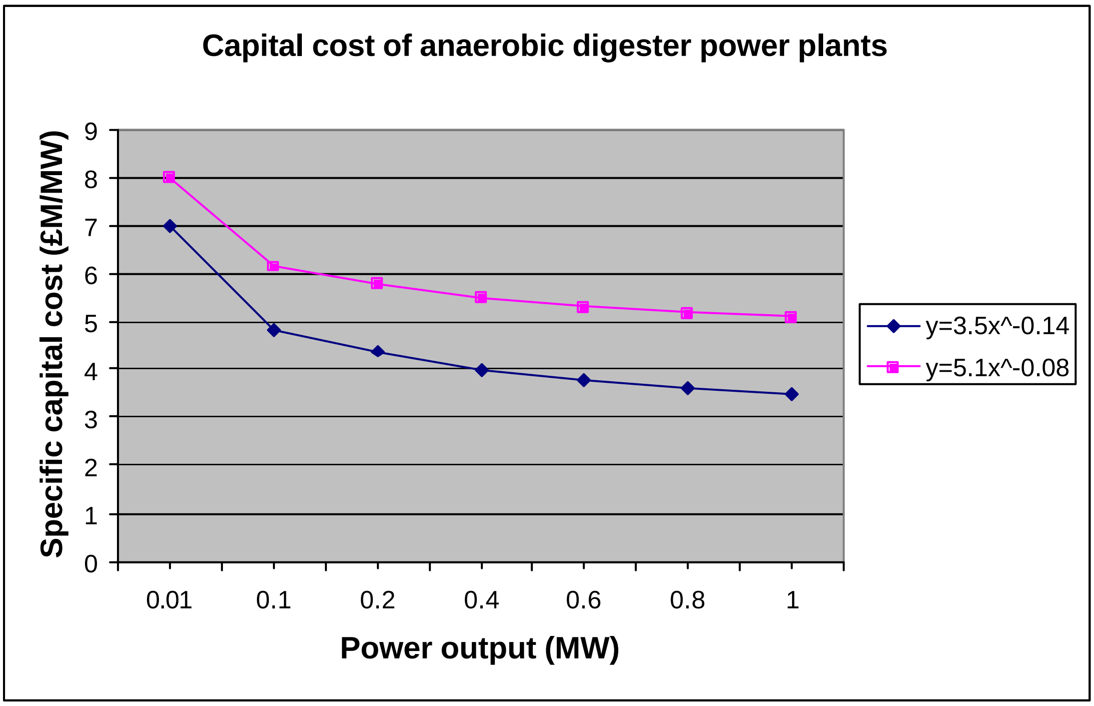

Figure 6.4.1 Capital cost of anaerobic digester power plants

The annual running cost suggested by British Biogas and Higham were combined to produce a trend line and can be expressed as:

Annual operating costs (£M/MW_c) = 0.22 $(MW_c)^{-0.22}$

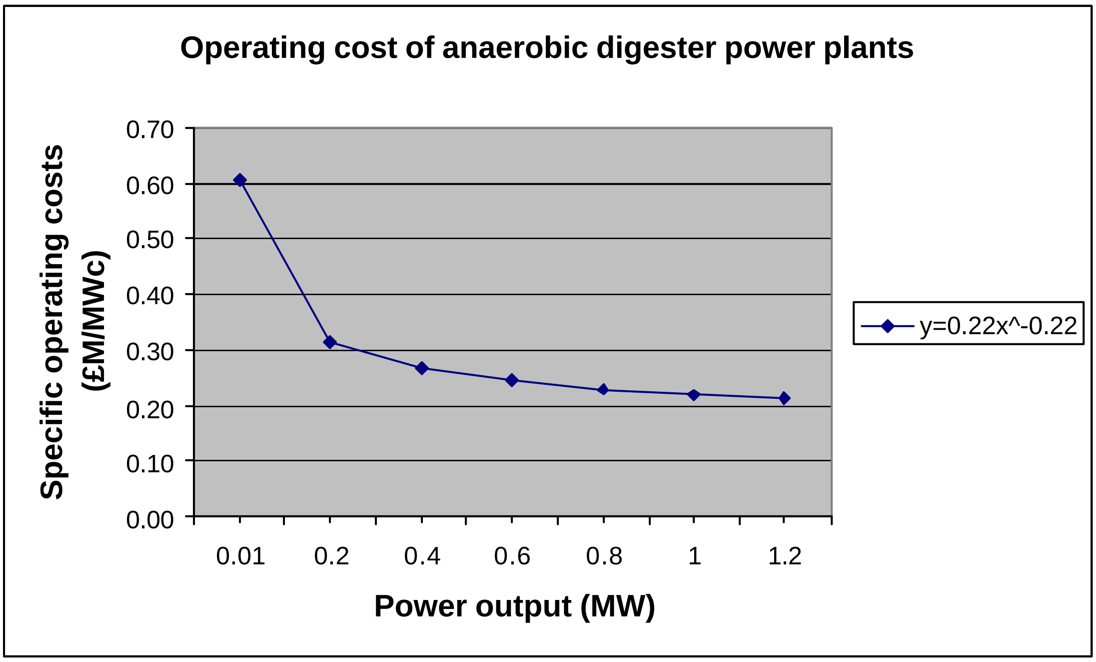

Figure 6.4.2 Operating cost of anaerobic digester power plants

These figures indicate annual operating costs in the range of 5-9% of capital cost.

Example of CAD assessment for Ettrick Bay (Isle of Bute)

The water catchment area of Ettrick Bay accommodates 10 major farms, most of them with dairy cattle. Production of slurry during the winter period was estimated at 13,360 m^3 giving a total daily arising of **73m^3.** With a minimal 30% increase by water dilution, the winter volume could be approximately 17,400m^3. The volume of slurry collected during the summer, about 15% of the winter production, would be approximately 2,600m^3.

Slurry transport cost to the AD plant and back was estimated for tractor and tanker at **£70,000.**

Production of **biogas** was estimated for 1.2m^3/d per cow as **1752m^3/d** for 1460 cows.

Volume of digester approximately 3000m^3.

All gas would be used for electricity generation and the heat from internal combustion engines used for AD heating. The electrical energy would be sold on the open market @ £0.03/kWh.

1m^3 of biogas would have approximately the energy of 23MJ, i.e. 1.5kWh. With the combined efficiency of the CHP unit the plant would give 80kW.

Using the British Biogen figures for **capital cost** the plant cost is estimated as **£5million. Running cost £30,000**.

Plant depreciation over 20 years would cost annually £250,000.

Energy profit over winter £10,000.

Deficit excluding the depreciation cost would be £90,000. If the industrial organic waste would attract the gate fee of £30/tonne then:

90,000/30 = 3,000 tonnes of industrial organic waste would be required to break even.

When the depreciation is included than the overall annual deficit is:

250,000 + 90,000 = £340,000

340,000/30 = 11,333 tonnes of organics to be imported.

The operation of the system during the summer months (cattle slurry would only be available during winter time), the redistribution to land of treated effluent, the actual volumes and dilutions of cattle slurry arising and the number of available suppliers of industrial organic wastes would all need to be surveyed and discussed before any of the suggested figures could be assumed to be realistic.

1.11 *Regulations and planning*

The centralised anaerobic digestion plant requires a large land area for its establishment. The estimated area, excluding access roads, for the Hoslworthy Biogas plant for 146,000 tonnes of livestock manure treated annually, is 120 x 100m, i.e. 1.2ha.

Although specific to the area planning demand, there are general requirements associated with the anaerobic digestion process, waste management and the plant characteristics. The main attention, before the planning permission is granted, will be given to the Environmetal Impact Assessment (EIA). Since the AD plant would be relatively large the EIA, dealing with transport of wastes, effects on water and atmosphere, visual effects etc., it will be further scrutinised by SEPA, Scottish Water, the Local Council and the public.

<u>Access roads</u>

It is envisaged that the plant operator will use 20m^3 tankers to deliver fresh (and re-distribute treated) manure to and from the farms. The 146,000m^3 of manure will be collected and re-distributed by 24 daily transport runs for six days a week and 52 weeks a year. This will demand adequately wide and accessible roads with an adequate surface quality and well managed and clear junctions. Also it will require farmers to keep the farm access roads clean of soil and waste to minimise pollution on the main roads.

<u>Noise and odour</u>

The sources of noise and odour, both the transport and the treatment plant will have to be controlled. The transport vehicles should emanate minimal noise and odour would be kept low by a careful cleaning from manures.

It is highly probable that the transport of manures would be restricted to daylight hours from Monday to Saturday.

The treatment plant will have a covered unloading bay with air extraction and biological filtration. The tanks storing the manure will be covered and the biogas will be contained within the plant, used for electricity generation, heating or burned off in a flare. The biogas engines, pumps, etc., will be in noise insulated enclosures.

Since the treated manure will be of substantially lower odour than the fresh manure, the inhabitants of houses adjacent to the fields where the manure will be applied, will greatly benefit from this process.

AD plant location

The distance from the AD plant to livestock farms contributing manure should be less than six miles. Screening of the plant would probably be required to minimise its visual impact.

Access to an adequate electricity connection and access to a water supply for plant washing etc. will be required.

Safety

Large quantities of raw and treated manure will be stored within the plant. In case of accident and leakage of any of the storage tanks or reactors, a bunded emergency storage area based on the maximum tank size will be required.

Separate storage for anaerobically digested slurry

The mixture of livestock slurry and organic wastes processed by anaerobic digestion would be stored before land application to optimize the slurry nutrient utilization and to minimize the environmental pollution. The pasteurized and digested mixture, as the one from Holsworthy plant in Devon, has a low content of organic matter which minimises the growth of pathogens and micro-organisms. Despite that, a separate "clean" storage space is required to prevent re-infection by faecal micro-organisms. A store, separate from the raw slurry store, is therefore required. The cost for this additional storage was covered by a grant received by the Holsworthy plant contractors/operators. In the absence of such a grant, the additional cost may be covered from farmers themselves and from industrial food processing companies, which waste will be treated in the AD plant and applied on the farm land.

Co-operation within farming community and food sector processors

A centralised AD plant will be run by a specialist manager and a plant operator. It will be the function of the manager to co-ordinate the livestock slurry collection and the treated waste re-distribution to farms. Farmers will be required to agree on the volumes and quality of raw slurry they will supply to the AD plant and on volumes of digested waste they will store and apply on their land.

The quantity of organic waste from food processors treated in the AD plant, and therefore the revenue obtained from the gate fees, will determine the cost, if any, to farmers for treating their livestock waste. The type of organic waste from food processors will have to fulfill the requirement given by Animal By-Products Order 1999 and Amendment 2001 as well as there will have to be an agreement with farmers on acceptance of the digested waste as a soil improver and plant fertilizer.

Conclusions

1.12 Advantages of anaerobic digestion

- Effective destruction of a wide range of pathogenic and faecal micro-organisms
- Odour and a range of environmental impacts can be effectively reduced to low levels
- Increasing proportion of immediately available plant nutrients in the treated manure
- Anaerobic digestion is a net energy producing process. Surplus biogas can be used to generate electricity and thus defray the cost of the process. Also, the excess of heat can be sold for heating of large buildings and/or district heating purposes

- By producing energy from non-fossil derived fuel, it reduces the impact on global warming. Similarly it contributes to the reduction of methane emissions from stored and land applied raw manure.

1.13 Disadvantages of anaerobic digestion

- High capital cost; specialist technical input and control is necessary
- Relatively complicated process, the centralized plant has to be run by specialists
- Process needs to be thermophilic or to include pasteurisation of raw or treated manure for the most effective pathogen kill
- No reduction of waste volume nor of the nitrogen content (which may be required in NVZ)
- Often, a high proportion of the generated energy has to be used on site owing to the remoteness of the farm and the relative small size of the operation.

Recommendations

Anaerobic digestion can minimize or completely kill certain pathogens that may be present in liquid waste. This is especially so at higher (thermophilic) temperatures and when the process is run as a semi-continuous, or a two-stage continuous process. A single stage continuous digester will have reduced effectiveness in achieving the reduction in numbers of 4 $\log_{10}$ units that is often required owing to a wide residence time dispersion, or flow shortcuts, leading to a short exposure time for a significant proportion of the effluent. Mesophilic digesters are also less effective, and if used will require longer treatment times. Where there are special microbiological hazards, thermal pre-treatment may be appropriate.

A new approach to the management of livestock manures and energy generation and utilisation has been initiated by a recently established centralized anaerobic digestion Holsworthy biogas plant in Devon, UK (Appendix 2). Although a 50% grant from the EU has been secured for the plant construction and additional manure stores, the next generation of plants should be self sufficient, mainly through the gate fees for accepting food processing waste and from the sale of energy. This plant provides treated manure to the same farms which supply the raw manure. Although these farms financially do not contribute to the treatment and transport costs, they benefit from the more immediately available plant nutrients in the treated manure. Also, the community feels the benefit from the land application of manure with much less odour than the raw manure. Since the treated manure is free from faecal micro-organisms and pathogens and has much lower biochemical oxygen demand than raw manure, there is minimal risk to the quality of field drainage water and consequently to the bathing waters.

Such a plant may be considered for a large and concentrated farming community with an adequately large food processing industry in the plant vicinity. Restrictions imposed by the Animal By-Products Order 1999 and the Amendment 2001 on the kind of waste eligible for bio-processing and a subsequent application on the agricultural land will have to be considered.

Also, it would be beneficial to secure heat consumers like large factories, buildings, hospitals, etc., and a new dwelling estate with a capacity for district heating adjacent to the plant.

A further study, in collaboration with Farmatic Biotech Energy UK Ltd., is recommended to identify a suitable location for an AD plant in Scotland.

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Storage

1.14 Effect on pathogens and faecal indicators

Livestock manures (slurries and FYM) are stored inside buildings, in channels and in outside storage enclosures in steel or concrete tanks, lagoons and compounds (middens). The type of storage and the storage duration of excrements can strongly affect the survival of pathogens and faecal coliforms in the manure. On farms in Scotland there should be enough storage capacity to cater for six months slurry production unless otherwise agreed with SEPA. During storage, the manure undergoes biochemical changes. These mainly depend on the storage temperature, which affects the survival of pathogens. Normally lower temperatures, except freezing, prolong pathogens survival, while higher storage temperatures accompanied by development of free ammonia shorten the pathogens chances for survival.

Most pathogenic bacteria are parasitic and do not multiply outside their host. Pathogenic bacteria excreted to the surroundings enter an alien environment where they can only survive for a limited period of time (Larsen and Munch, 1986). This period of time can be measured in weeks or months, depending on the type of pathogen and in the storage conditions (temperature, moisture content etc). Under normal conditions of storage, pathogens in livestock manures and slurry progressively decrease in numbers over time (Rankin and Taylor 1969; Thunegard 1975). Slight increases in temperature during summer destroy *E.coli* O157 and radically decrease numbers of *Salmonella* after a few months (Nicholson et al., 2000). Similarly Chambers et al., (2001) demonstrated relatively short, approximately one week, survival rates of *E.coli* O157 in dairy and pig FYM and broiler litter.

Cryptosporidium parvum oocysts and their viability declined rapidly in mixtures of manure and bedding in calf pens (Svoboda et al., 1997).

Studies on the survival of *E. coli* O157 during solid manure storage (dairy and pig farmyard manure and broiler litter) showed that its survival was relatively short; approximately one week during summer (Chambers *et al.*, 2001). The rapid die-off observed was probably caused by elevated temperatures (>55^{o}C) and high gaseous ammonia concentrations within the store. In contrast, *E. coli* O157 was found to survive longer in stored dairy slurry and in dirty water, for between 2 weeks and 3 months.

In contrast, Stanley et al., (1998) demonstrated that thermophilic *Campylobacter* could still be isolated from composted bedding. A semi-dry litter from rearing broilers composts readily. Temperature and free ammonia concentration rise in the mixture, with both having detrimental effect on pathogen survival (Himathongkham et al., 1999).

Under practical conditions (farm storage tanks) the total bacterial counts as well as the numbers of Enterobacteriaceae, *E.coli* and faecal streptococci remained nearly unaffected, and even increased, during storage for up to 185 days. Numbers (cfu) of *Salmonellae* exposed to the slurry in semi-permeable membranes, were reduced by more than 10^5. *Yersinia enterocolitica*, was completely inactivated within only a few days, whereas the eggs of *Ascaris suum* as well as the oocysts of *Cryptosporidium parvum* also lost their viability, but only very slowly (Rapp, 1995).

Study by Findlay (1972) showed that *Salmonella dublin* survived storage for between 19 and 33 weeks in cattle slurry. Similarly, Larsen and Munch (1986) found that *Salmonella typhimurium* survived in stored pig and cattle slurry for in excess of 10 weeks with only a small decrease in numbers (from 10^6 to 10^4/ml) at 8°C. *Yersinia enterocolitica* was eradicated by week 6, while *Staphylococcus aureus* was reduced from 10^6 to 10^2/ml in 9 weeks. In the solid fraction of pig slurry, *Salmonella typhimurium* survived for 26 days in summer and 85 days in winter (Placha et al., 2001), and coliforms were reduced by 90% in 35 and 233 days during summer and winter time respectively. *Cryptosporidium parvum* oocysts required more than 90 days to become non-viable in stored cattle slurry at 4°C while at 15 and 20°C they were nearly all killed in 30 and 20 days respectively (Svoboda et al., 1997). In the farmyard, manure stored at temperatures of 4 and 15°C respectively, 30% and 8% of oocysts survived longer than 90 days. When composting was encouraged, and temperatures in excess of 30°C were achieved, there was no survival of oocysts after 35 days.

Viruses can also survive in animal slurries for an extended time, depending on the storage conditions. Pesaro et al., (1995) described the in situ inactivation of picorna, rota, parvo, adeno and herpes viruses in stored liquid and semi-liquid animal waste.

Depending on the ambient temperature, pH and type of waste, the time required for a 10 fold reduction of the titre of infectious virus ranged from 1 week for herpes virus to more than 6 months for rotavirus. These results imply that viruses in slurry may require a more extended time, possibly months, for natural inactivation.

Extended storage can reduce the survival of some pathogens in slurry, although a safe and efficient sanitization of livestock manures by storage cannot be expected (Table 10. 1).

Slurry is normally added in regular intervals into slurry stores. Since new slurry carries fresh and large number of faecal bacteria, all slurry is continuously re-infected. Additionally only a small proportion of the slurry will be stored for a period of time adequate to result in bacterial reduction. To store batches of undisturbed slurry for a long time would be impractical and uneconomical given the small effect of storage on the decrease of faecal bacteria numbers.

Table 10. 1 Pathogen survival in livestock slurry.

Pathogen	Slurry type	Survival time (d)
Salmonellae	Cattle	200-300
	Pig	90-120
	Poultry manure (layers)	5-25
B.abortus	Cattle (10^{o}C)	47-70
	Cattle (20^{o}C)	20
E.coli	Cattle (Winter)	85-130
	Cattle (Summer)	30-120
Foot-and-mouth virus	(Summer)	25-32
	(Winter)	20

1.15 Change in organic matter, odour, nitrogen and phosphorus

Livestock slurries undergo anaerobic changes during storage. The extent of the changes depends on the storage duration and the slurry temperature.

The organic matter in excreted pig and cattle slurry, usually between 70 and 87% of the total dry matter (DM) (Evans et al., 1980, Williams and Evans, 1981, Tsang, 2001) slowly decreases with increasing time of storage. Between 3% and 30% of the DM was anaerobically decomposed in cattle and pig slurry respectively (Tsang, 2001) over 30 weeks of storage at temperatures from 5 to 15^{o}C. The decomposition into smaller molecules like organic acids, monosaccharides and alcohols is accompanied by the generation of carbon dioxide, methane and hydrogen sulphide gases. Up to 30% of organic nitrogen was reduced to ammoniacal nitrogen. Similarly, organically bound phosphorus would be released into the solution through mineralisation.

Molecules of organic acids and sulphurous compounds released to the solution as a result of anaerobic degradation of slurry organic solids are often very odorous. An increase in volatile fatty acids content by 130 to 220% in cattle and pig slurry respectively indicate a large increase in the slurry offensive odour. Since the concentration of other odorous compounds (like mercaptans and hydrogen sulphide) also increases, the storage of slurry, particularly during warm weather, increases significantly the slurry offensive odour. It was demonstrated (Pain *et al.,* 1990) that odour from untreated stored slurry was 10 times stronger than from aerobically or anaerobically treated pig slurry applied to land.

1.16 Costs

Cost of storage tanks for livestock slurry varies with the type of store and its size. The unit cost of steel glass lined towers varies from £18 to £45/m^3 of storage space so a 1000m^3 store can cost about £25,000.

1.17 Benefits and disadvantages of additional storage to the farming community and to the environment

Most Scottish farms will have store capacities for slurries for less than 6 months. Based on the “Farm waste management plan” (FWMP) and an agreement with SEPA, it will probably be the most financially effective system for the farm to comply with SEPA requirements. Management of livestock manures complying with FWMP should minimise pollution of the environment by organic matter and maximise the use of the manure's fertilising capacity. Although such management also reduces the risk of spreading pathogens and faecal bacteria, their control is not optimal. As described above, extended storage decreases the viability of faecal bacteria, but to achieve a significant difference in numbers of bacteria (10^2 or 99% reduction) an extensive length of storage, possibly one year or more may be required. Additionally the batches of slurry may have to be stored separately so that the fresh incoming slurry does not re-infect the stored slurry.

1.18 Justification of the process for farm use

Extending slurry storage capacity on farms has the advantage of partially sanitizing the slurry. This partially decreases the risk of contamination of drainage water and further receiving waters with faecal bacteria and pathogens. Although improvement in bacteriological quality of bathing waters might be achieved, it may be overshadowed by disadvantages caused by the requirement for larger slurry storage capacities:

- The capital cost and ensuing maintenance cost for storage would substantially increase

- With increased storage capacities, the surface area of a store would increase, thus large volumes of rain water would be collected giving rise to the cost of slurry disposal. To minimise the water ingress from the rain a permanent covering of stores may be required. This could nearly double the cost of storage enclosures

- Although a larger slurry storage capacity may optimise the management of slurry utilisation, it could lead to complacency and create critical situations with large stores overflowing during times when land application is not possible. The results could be worse than those otherwise avoided

- The impact on the global environment should also be considered. Slurry storage, which is anaerobic, promotes development of methane gas, which has 30 times the greenhouse effect of carbon dioxide. Increased storage time would increase the amount of methane generated from the livestock slurries.

In conclusion, to extend slurry storage periods may not be economical as a means of faecal bacteria decimation.

Oligolytic treatment (oligolysis)

The principle of oligolytic treatment of livestock slurry is based on the effect of electrolytically generated ions of copper (Cu) on slurry. Cu ions are released from copper electrodes suspended in the slurry in a storage tank by a direct electrical current of low voltage (between 1.5 and 24 Volts) which is passed between them. To aid better distribution of Cu ions in the slurry, the polarity of current is changed regularly. After a month or more, about a week before slurry land application, the copper electrodes are exchanged for iron electrodes. By then passing electrical current through them, the copper ions in the slurry get attracted to the iron electrodes surface. This practice removes up to 75% of copper from the slurry.

The copper ions in the slurry have two functions. They have a bacteriostatic effect, thus the function of bacteria in slurry should be minimised, i.e. the breakdown of organic matter and production of further odorous compounds should be slowed down. The second effect is that the copper ions react with hydrogen sulphide (H_2S) gas creating solid copper sulphide. By removal of H_2S, the offensive odour associated with this gas is minimised in the slurry.

1.19 Effect on pathogens and faecal indicators

The effect of oligolysis on pathogens and faecal bacteria is documented only sparsely. This may be due to the fact that results have not shown a great deal of success. Experiments with pig slurry treated by oligolysis for three months by Colanbeen and Neukermans (1992) did not produce any significant reduction of pathogen indicators. Similarly, the work at Universities of Padova and Milano (Sorliny et al., 1990) indicated only 2 $\log_{10}$ reduction of faecal coliforms and streptococci. However, more than 10^4 MPN/l were still present in pig and cattle slurry.

In Norway, where the demands on hygiene are very high, the cooperative work between the Agricultural University of Norway and the University of Udine (Italy) examined the effects of long term storage, treatment by thermophilic aeration and oligolysis on cattle slurry (Donantoni et al., 1994). Aerobic treatment with a 5-6 day retention time at temperatures of 48 – 55^{o}C provided cattle slurry with 6.4% DM for storage. In a 30m^3 store the slurry was continuously treated by oligolysis (0.5 -1.25A at 4.2V) and after 23 weeks was then analysed. Although there were less than 10^2

thermotolerant coliform bacteria per gram of slurry, the fresh untreated slurry contained 10^4/g bacteria, stored aerobically treated slurry also contained $<10^2$/g coliforms.

1.20 Effect on odour

The effect of oligolytic treatment on livestock slurry offensive odour has been reported by several researchers. Colanbeen and Neukermans (1992) who treated pig slurry by oligolysis found that the slurry offensive odour was much less than in untreated slurry. Issac et al., (1991) compared the gaseous emissions from stored and treated slurry by oligolysis. They found a 97% decrease of hydrogen sulphide, but no differences in the concentration of volatile fatty acids or phenolic compounds. The odour decrease seems to be caused solely by the decrease of free sulphides rather than by changes in the metabolites already produced by microbes. Remarkably, similar results were achieved by Feddes et al., (1998) who tested oligolysis of pig slurry at six different voltages between 1.5 to 3.5V. The results indicated that all voltage treatments removed over 97% of the free sulphides in liquid pig manure after 168 hours of treatment. The mean concentration of H_2S in the gas released from the treated bioreactors was 91% less than the control. No significant differences in sulphide levels were observed at the applied voltages.

Similarly Donantoni et al., (1994) observed a complete elimination of H_2S from cattle slurry after oligolysis treatment.

Changes in concentrations of organic matter, nitrogen or phosphorus were not reported.

1.21 Costs

An Oligomat system (1990) would cost approximately £3,000 for the unit. The running cost is very small, since the system requires only about 1kWh of electricity per day.

1.22 Requirements for running the process

The promoter of the treatment system, Alfa-Laval's Oligolyt-G, provides an electrical control unit, wires and copper and iron electrodes. Installation of electrodes is designed for oblong or round storage vessels. The control unit, connected to a single phase 240V electricity supply, provides various voltages and currents to the electrodes. The unit runs continuously and automatically changes the polarity of the electrodes at intervals. Installation and running is therefore extremely simple.

1.23 Benefits and disadvantages of the process to the farming community and to the environment

For its relatively low cost and simplicity, this technique could be regarded as a cost effective solution for suppressing pathogens and faecal coliforms and controlling offensive odour of livestock wastes if this can be proved conclusively. However, it does not stabilise slurry, i.e. the concentration of organic matter is not decreased, and it increases the slurry copper content,

1.24 Justification of the process for farm use

Oligolysis has been investigated and research carried out for livestock slurry applications since the 1980. The last extensive research FAIR V CT97-3506 "ELECTROPROJECT" headed “Electrochemical treatment of fresh animal manure for reducing environment and health risk” was undertaken by three universities, University Udine, University Milan and Freie University of Berlin, between June 1998 and May 2001. The final results and/or any scientific papers from this research have not been traced. Additionally the promoter of oligolysis, Alfa-Laval’s Oligolyt-G, has temporarily withdrawn its product from the market because of fluctuations in the effectiveness of this treatment for liquid hog manure.

Since the results of the latest research are not available and the effects are not confirmed, oligolysis cannot be recommended as an effective treatment process.

Lime treatment

Alkaline stabilisation of sludges from waste water treatment plants has been practiced since the 1890's and even more recently, has been a method used for the inactivation of the foot and mouth virus in cattle slurry. The most commonly used alkaline additives, for their low cost, are quick lime (calcium oxide, CaO) and its derivative hydrated lime or slaked lime (calcium hydroxide, $Ca(OH)_2$).

The lime stabilisation process is relatively simple. Lime addition raises the pH of the processed material (sludge, slurry etc.) during the contact time. Adding adequate volume of CaO to the sludge, the pH increases to 12 (or higher) and the temperature rises to between 55 and 70^{o}C. With sufficient contact time and appropriate mixing, pathogens and micro-organisms are inactivated or destroyed. The resulting biosolids also have altered characteristics compared with the original material, through reactions, like hydrolysis and saponification, with the lime.

Slaked lime ($Ca(OH)_2$) is usually added to sludge as a conditioner prior to sludge dewatering, and is used to raise the pH to between 10.5 and 11.5.

1.25 Effects on pathogens and faecal indicators

Lime treatment can achieve the stabilization requirements for the enhanced reduction of pathogens when the pH value is higher than 12 for two hours and maintained at >11.5 for a further 22 hours. The temperature should also be kept at 70^{o}C for a minimum of 30 minutes.

By increasing the pH of the sludge mixture to pH>11.5 with slaked lime, microbiological activity is suspended and pathogen numbers decrease by two or more log_{10} units (99.0%) within a few hours. Most bacteria and viruses were undetectable within 24 hours (Farrell et al., 1974; Pike and Carrington, 1986). Carrington et al., (1998) suggested that after two hours at pH>12.5, many pathogens will be reduced to insignificant numbers. Plachy (1996) demonstrated that *Salmonella typhimurium* was eliminated in 60 minutes from sludge after the addition of hydrated lime. Strauch and Bertoldi (1986) suggested that two months storage of limed sludge (pH>12.5) would minimise the epidemiological risk from *Ascaris suum* and *Taenia* *saginata*. With more experience of the process, Strauch and DeBertoldi (1986) suggested that the storage of limed sludge should be three months.

Gaspard et al., (1997) demonstrated that in seven samples from ten treatment plants there was a decrease in helminth eggs, although in the remainder, the numbers of eggs were left unchanged following treatment with lime. However, using quick lime and waste cement kiln dust mixed with sludge (the N-Viro process) effectively destroyed pH-insensitive pathogens. With a minimal retention period of 12 hours the treatment produced a pH of 12, and temperatures in excess of 52^{o}C,. (Hampton, 1992).

It has been observed that lime treatment reduces not only pathogen levels in slurries, but also reduces viruses. Derbyshire and Brown (1979) experimented with porcine enteroviruses type 2 and 3 and bovine enterovirus, which they seeded into pig slurry to a level of about 10^4 IU. Adding calcium hydroxide brought the pH up to 11.5. They observed that bovine enterovirus was inactivated within one hour; no porcine enterovirus type 2 was found after three hours, and no porcine enterovirus type 3 after 24 hours. Koch and Euler (1984) investigated lime treatment for inactivating Aujeszky's disease virus (ADV) in pig slurry. It was necessary to add about 30 kg lime per cubic metre of slurry and maintain the pH value above 11.5 for complete virus inactivation. With increased total solids in the slurry, more lime was required. They speculated that the high pH itself was not the cause of the inactivation, but that ammonia release due to increased pH provided the virucidal mechanism. Turner and Williams (1999) evaluated calcium hydroxide and sodium hydroxide against African swine fever (ASF) and swine vesicular disease (SVD) viruses in pig slurry. 1% (w/v) of NaOH or $Ca(OH)_2$ caused the inactivation of ASF virus within 150 seconds at 4^{o}C, although SVD virus was more resistant, requiring 1.5% and 30 minutes for inactivation.

Results from the lime stabilization of sludge produced on a sewage treatment plant are described in Table 12.1.1. Liquid lime was added at a 25% dry-weight dose and a pH value of 12.5 was achieved.

Table 12.1.1 Reduction of bacteria by liquid lime stabilization at Lebanon, Ohio (U.S. EPA, 1979). (After - WEF 1995).

	Bacterial density, number/100ml				
Type of solids	**Total coliforms**	**Faecal coliforms**	**Faecal streptococci**	***Salmonella***	***Ps. aeruginosa***
Raw sludge					
Primary	$2.9x10^9$	$8.2x10^8$	$3.9x10^7$	62	195
Waste activated	$8.3x10^8$	$2.7x10^7$	$1.0x10^7$	6	$5.5x10^3$
Anaerobically digested biosolids					
Mixed primary and waste activated	$2.8x10^7$	$1.5x10^6$	$2.7x10^5$	6	42
Lime stabilized biosolids					
Primary	$1.2x10^5$	$5.9x10^3$	$1.6x10^4$	<3	<3
Waste activated	$2.2x10^5$	$1.6x10^4$	$6.8x10^3$	<3	13
Anaerob.digested	18	18	$8.6x10^3$	<3	<3

Lime stabilisation is therefore capable of reducing faecal coliforms in the primary sludge by 5 $\log_{10}$. But some damage must have been inflicted on faecal coliforms by anaerobic digestion so that their removal was still higher at 6 $\log_{10}$. Faecal streptococci are more resistant to the treatment conditions and a reduction of only 3 $\log_{10}$ was achieved.

Other studies (Westphal and Christensen, 1983, cited in WEF 1995) indicate even better effects. Liquid and dry lime stabilisation (pH >12 at two hours) reduced faecal coliforms by $>5\log_{10}$ in two hours and by $>6\log_{10}$ after seven days of storage of treated sludge. Faecal streptococci were similarly reduced by $2.5\log_{10}$ after two hours and $>4\log_{10}$ after seven days.

1.26 Change in organic matter, odour, nitrogen and phosphorus

Effects of alkaline stabilisation on organic matter have not been reported although it is supposed to hydrolyse and saponify to various degrees. Although this degrades organic matter, at least partially, the contained nitrogen and phosphorus availability to plants as a nutrient is not always increased.

Temperature rise during the addition of quick lime and the pH increase to over 12 will release most of the ammoniacal nitrogen from slurries. Since about 50% of total livestock slurry nitrogen is in ammoniacal form, the losses in fertilising value of such treated slurry would be considerable. Fenlon and Mills (1980) observed in the laboratory trials conservation of urea in slurry after addition of 1% lime. But in the field trials the losses of nitrogen were high and eventually after five to six weeks the slurry became neutral, bacterial numbers and odour increased and urea broke down to ammonia and carbon dioxide.

Some odorous slurry components are likely to escape during increased temperature and ammonia vaporisation will occur. Therefore the exhaust gases from the slurry and lime mixing stage require control and ammonia extraction is required.

1.27 Costs

Capital cost of a farm treatment unit is dependent on the size and the complexity of the control equipment. The most sophisticated and large central plants would cost between £0.5 to 0.8 million while the simplest farm system consisting of a tank ($600m^3$, £16k), a pump (£3k) and a stirrer (£3k) would cost approximately £22,000.

The specific cost was estimated by TEG Environmental plc at £69–£81 per treated tonne of product. This assumes the addition of 600 kg (60%) of CaO to give an enhanced treated product. CaO cost varies between £45 and £85 per tonne. Similarly, the N-Viro process would cost £65/tonne of treated material dry solids (Boon and Thomas, 1994).

Nicholson (2000) estimated that for the farm system the cost of treated material (Table 12.3.1) would be much lower but the lime/slurry ratio was much higher at 1/50.

Table 12.3.1 Estimate of lime treatment costs for store size 600m^3.

Parameter	Cost (£)
Hire of stirrer – 2 days @ £150/day	300
Cost of swing loader – 1day @ £150/day	150
Labour - 20 h @ £5.50/h	110
Total cost excluding lime	560
Cost/m^3 excluding material (Total / 600)	0.93
Cost of lime / m^3 treated (1:50)	3.50
TOTAL COST / m^3 TREATED	**4.43**

1.28 Requirements for running the process

A farm system for lime treatment of slurries would additionally require storage for lime and a storage/disposal system for treated slurry. Protection against alkaline dust and exhaust gases for plant operators would be required.

A large centralised plant may include additional equipment for continuous treatment like bulk storage of lime with a lime delivery system to a mixer/blender processor, load–out conveyor etc. Exhaust gas control in buildings by simple ventilation may be adequate, but more sophisticated systems, including alkaline dust neutralisation and ammonia absorption may be required in some instances (WEF, 1995).

1.29 Benefits and disadvantages of the process to the farming community and to the environment

Lime treatment decreases the numbers of faecal bacteria and, in particular, kills most of the pathogens together with parasites. Land application of lime treated slurry thus minimises not only the hazard of pathogens reaching the aquatic environment and being spread to animal and humans via aerosols, but also minimises the perpetuation of diseases through ingestion of pathogens by animals from soil on the slurry applied land.

The method is simple and it is relatively easy to operate. The product of lime treatment has a value as a soil liming agent and has minimal odour. Also it can be easily handled and stored.

There are some disadvantages including the cost of lime and additional handling, loss of nitrogen as ammonia (up to 50%) associated with the pH increase and increased total mass of material to be applied on the land. Most of all, due to its alkaline content its use on land is restricted by the pH level of soil and the soil buffering capacity.

1.30 Justification of the process for farm use

The use of a slurry liming process may be justified on such farms where the risk of spreading pathogens and faecal indicator bacteria into the aquatic environment is imminent but not a continuous threat. Otherwise the high alkaline content would severely restrict the utilisation of treated slurry. Although the majority of Scottish soils are acidic their buffering capacities would not be able to accept limed slurry on an annual basis.

Pasteurisation

The process of pasteurisation involves the heating of slurries/sludges to a relatively high temperature but below water boiling point and often below the point of protein denaturation. Typically, the temperature range is 55 to 70°C. The Code of Practice (DoE, 1989) specifies a four hour treatment at 55°C or 30 minutes at 70°C for sludge (Fig 13.1.1). Another treatment - sterilization - uses much higher temperatures, usually at or above the boiling point of water. Often it is carried out at an increased pressure to enable the rise of temperature to in excess of 150°C. Under such conditions the destruction of all but the most resistant spores is virtually guaranteed. However, such an approach for livestock manure would be extreme and unnecessary and would require an unsustainable cost at the farm scale.

1.31 Effect on pathogens and faecal indicators

The effect of temperature on the survival of pathogens and other micro-organisms can be described by the exponential law of disinfection (termed "Chick's Law"), where the surviving fraction (Xt) is dependent on the starting population number (Xo) the treatment time interval (t-to) and the specific decay rate, k :

$$\frac{X_t}{X_0} = e^{-k(t-t_0)}$$

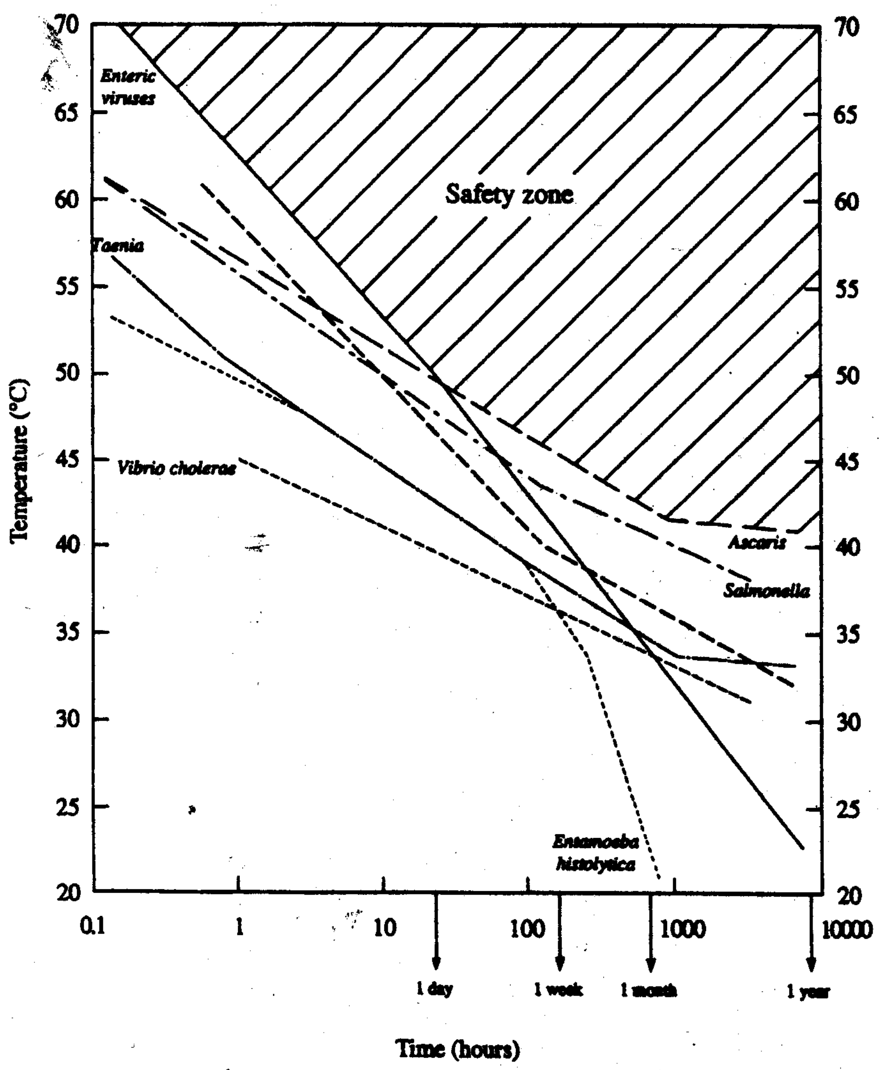

Figure 13.1.1. Time-temperature requirements to produce sludge, that is virtually pathogen-free. (Strauch, 1991).

Heat treatment of waste therefore has a wide application for different species of micro-organisms. Strauch (1991 and 1998) expressed the effect of temperature and time on some species of micro-organisms (Figure13.1.1). The *Safety Zone* is the area of the graph where pathogens would not survive, or the sludge would be virtually pathogen free due to a combination of time and temperature. The lowest safe temperature for the tested pathogens elimination was about 45°C. The length of time required to maintain the sludge at this temperature was over 40 days. By increasing the temperature to 50°C, the time required shortened to just over three days, at 55°C to 15 hours, at 60°C to two hours and at 70°C to seven minutes. This describes ideal conditions, which are rarely achieved in full-scale treatment plants. Practical studies indicate that sludge should be held for four hours at 55°C (Fig.13.1.2) or 30 minutes at 70°C to kill at least 99.99% of pathogens (Carrington et al., 1998). The heat distribution through concentrated sludge and solid materials is more difficult to estimate; therefore the time safety margin should be observed.

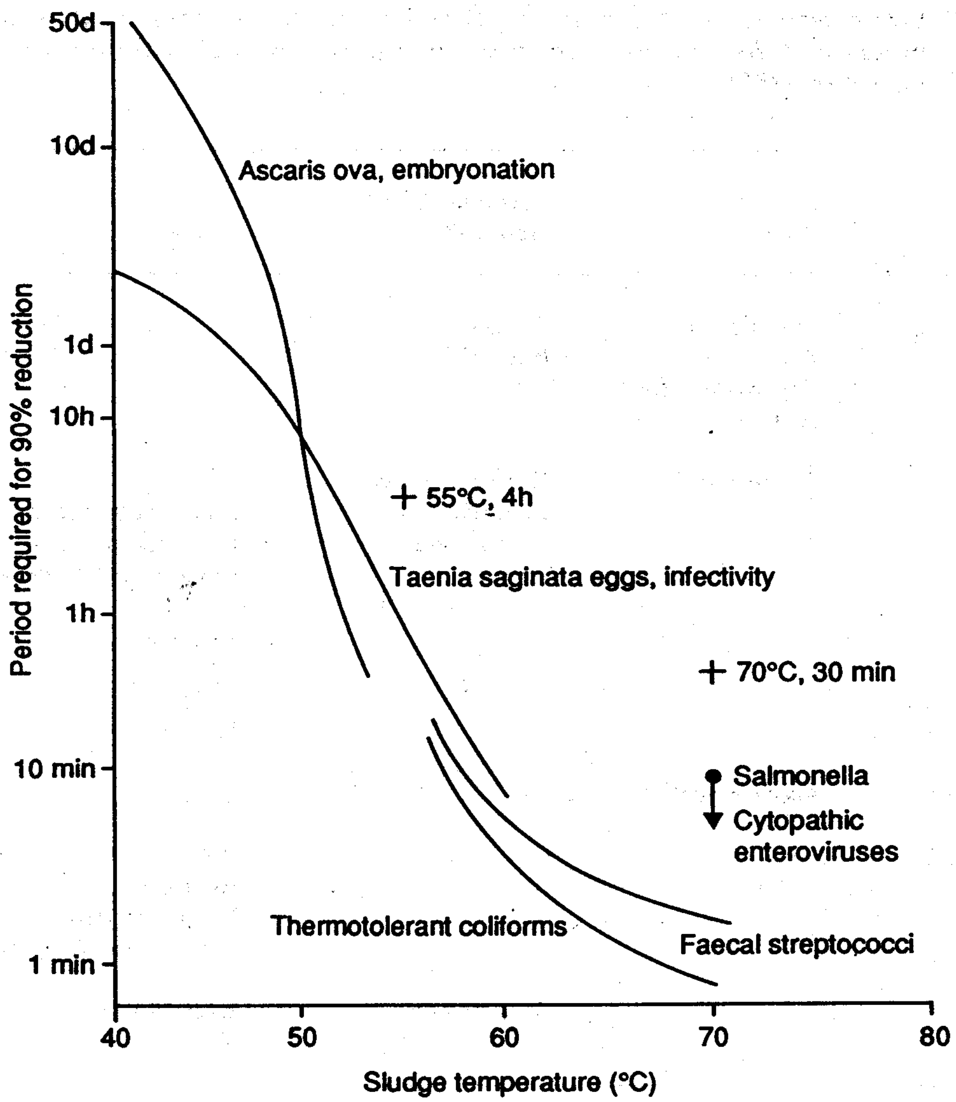

Figure 13.1.2 Effect of sludge treatment temperature upon time for 90% destruction of various pathogens. Crosses indicate temperature/time conditions specified in Code of Practice (DoE, 1989) (Pike and Carrington (1986).

Bruce et al., (1988) demonstrated that by pasteurisation for 30 minutes at 70°C, *Salmonella* and enteroviruses were completely killed in sewage sludge. A similar effect of heat was experienced with intestinal parasite eggs such as *Ascaris suum* and *Taenia saginata* which completely lost viability in 20 minutes at 70°C (Strauch and Berg, 1980). Exposure of *Taenia saginata* eggs to treatments of 60°C for 15 minutes and 70°C for five minutes eliminated their infectivity (Shafai 1975). Pike and Carrington (1985) observed the relationship between temperature and treatment time on the treatment effect. A longer treatment time of three hours was required for pasteurisation of sewage sludge at 55°C to reduce infectivity of *Taenia saginata* eggs by 98.6%.

Viruses are similarly affected by high temperature. Monteith et al., (1986) found that bovine enterovirus was inactivated to below detectable levels in digested liquid manure heated to 70°C, however, some bovine parvovirus was still detected after this treatment. Bøtner (1991) studied the temperature dependent inactivation of Aujeszky's Disease virus (ADV) during anaerobic storage at temperatures ranging from 5 to 55°C. He found that at 5°C, the virus was inactivated after 15 weeks, whereas at 55°C, no virus was detected after 10 minutes. Herniman et al., (1973) examined thermal inactivation of Swine Vesicular Disease virus (SVDV) in both milk and pig slurry. In milk, the virus was inactivated at a temperature of 60°C in two minutes, whereas virus in slurry required a slightly higher temperature of 64°C for two minutes for inactivation.

1.32 Change in organic matter, odour, nitrogen and phosphorus

Pasteurisation is a relatively fast treatment process normally lasting minutes, maximally four hours at 55°C. Except for some protein coagulation and enzymes denaturing, there is little change in slurry organic matter, unlike biological treatments where available organic matter is transformed varying degrees by mineralisation.

Slurry odorous compounds can volatilise due to increased temperature and the vapours developed during pasteurisation will carry an offensive smell. Although pasteurisation prevents, through micro-organism eradication, further development of odours from bacterial anaerobic activity, the original concentration of odorants in slurries remains or is only slightly changed by high temperatures. These changes can also generate an unusual odour, which may be even more offensive than the original odour of fresh slurry.

Also, a proportion of the ammoniacal nitrogen can be released as free ammonia when the slurry pH increases over 7. At higher temperatures, nearly all of the ammonia is in its free ammoniacal form (NH_3) when the pH value exceeds 10, and is therefore liable to escape, as a gas, in the exhaust air. To prevent large nitrogen losses during pasteurisation, unless it is carried out in enclosed spaces, the slurry pH value should be controlled at 7 or lower.

1.33 Requirements for running the process

Pasteurisation can be carried out in batch, semi-continuous or continuous systems. The batch and semi-continuous systems have the advantage of a high degree of control over the bacterial cross-contamination of treated slurry from fresh slurry. However, for large volumes of potentially contaminated livestock wastes these two systems become impractical. In contrast, a continuous process enables high slurry throughputs, consistent treatment and lower treatment costs with additional savings from heat recovery. The main drawback of the continuous process is the backmixing of slurry leading to some contamination of the final product by micro-organisms from the raw slurry. To minimise this it is necessary to reduce the residence time distribution, i.e. by using baffles (Fig. 13.3.1) the slurry flow through the reactor approximates a “plug flow”.

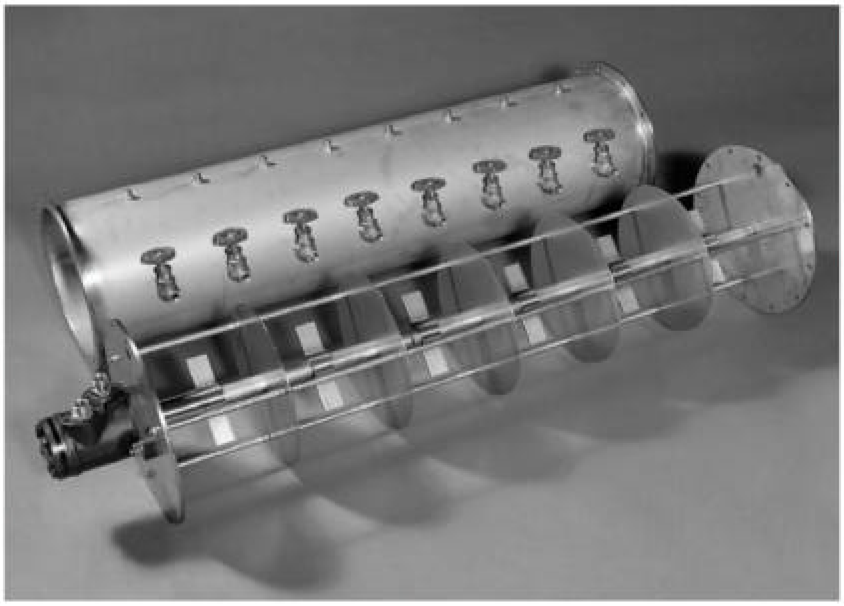

Figure 13.3.1 Baffles and mixing system inside the reactor vessel

Research by Turner et al., (1999) used this approach in a series of pilot scale trials to decontaminate pig slurry inoculated with a range of viruses including African Swine Fever virus (ASF) virus and Swine Vesicular Disease virus (SVD) and later against classical swine fever (CSF), foot and mouth disease (FMD) and Aujeszky's disease (AD) viruses (Turner et al., 2000).

The cost of treatment is usually the limiting factor. Since heat recovery is most efficient with a continuous process a new pasteurisation treatment system was developed.

The pilot plant used by Turner et al., (1999) is shown schematically in Figure 13.3.2. Cold, untreated slurry was pumped into the heat exchanger (HE1), where it was heated up to the required temperature. This heat was provided by the treated slurry and hot water generated in a boiler V3. The heated slurry passed through the reactor R1 where it was mixed and maintained at the required temperature for the required period of time. The treated slurry then passed through the other side of the heat exchanger and was finally collected in tank V2.

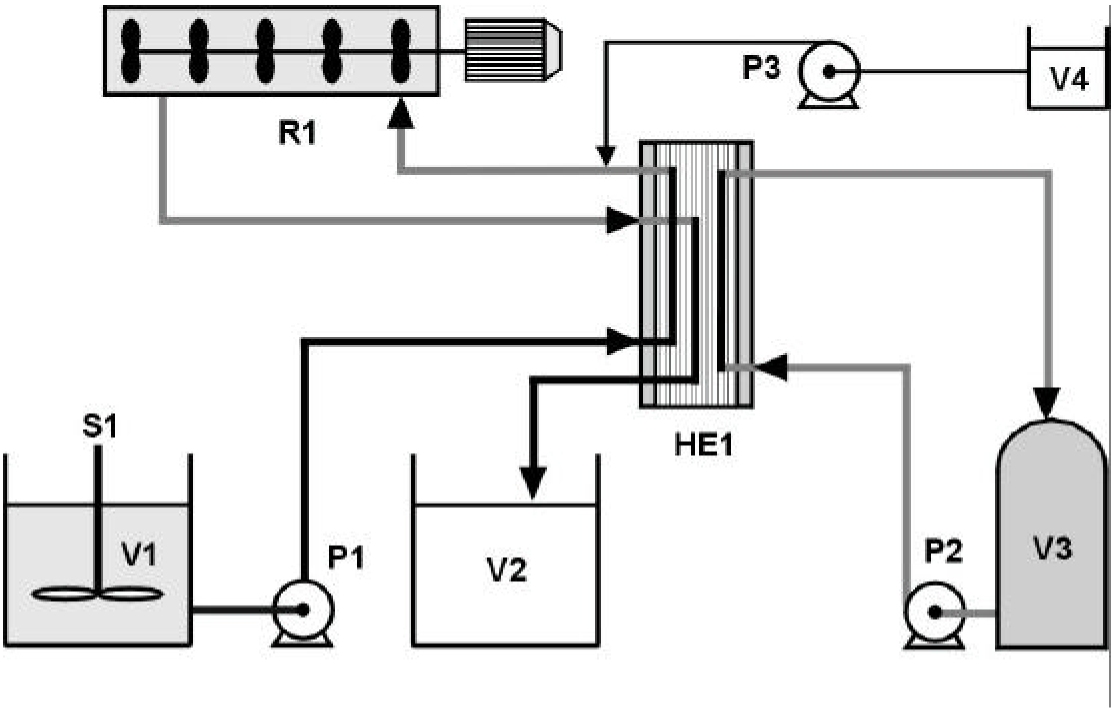

Figure 13.3.2 Schematic diagram of a continuous pasteurization system

Laboratory scale experiments on the survival of selected viruses concluded that a treatment period of five minutes was the minimum residence time for adequate de-contamination. A reduction in virus titre by 4 $\log_{10}$ units was adopted as the criterion for effective decontamination. This 10^4 reduction in titre is the same as that required in tests for commercial disinfectant efficacy prior to licensing by the UK Department of the Environment, Food and Rural Affairs (DEFRA) and this study used procedures and protocols for monitoring virus inactivation that were based on those regularly used for disinfectant testing and licensing. This implied that at least 99.99 % of the slurry needed to be subjected to a minimum treatment time of five minutes.

An extensive range of trials in a bio-secure area was carried out by Turner et al., (1999, 1999a and 2000). The results showed that inactivation of the viruses in raw pig slurry using the thermal decontamination plant occurred as follows:

- Classical Swine fever virus at 51^{o}C

- Swine Vesicular Disease virus at 55°C
- African Swine Fever virus at 55°C
- Aujeszky's Disease virus at 58°C
- Foot and Mouth Disease at 62°C

Inactivation of the viruses in the absence of free ammonia (water or acidified slurry) occurred at slightly higher temperatures:

- Swine Vesicular Disease at 60°C
- Aujeszky`s Disease at 62°C
- Classical Swine Fever at 63°C
- Foot and Mouth Disease at 66°C

Ammonia is thus seen as virucidal, hence contributing to the decontamination process. Thus, the temperature required for inactivation in livestock slurries where free ammonia can be expected is lower, because of the synergistic effect of heat and ammonia. At a lower pH the ammonia is increasingly in the ammonium form and its virucidal activity is much reduced. Because the pH and ammonia content of slurry varies considerably depending on the diet of the animal, environmental conditions and other factors, it is strongly recommended that in the event of an outbreak of one of these viral diseases resulting in the production of contaminated slurry that slurry is heated to above the minimum temperature required for inactivation to provide a safety margin. The following temperatures are thus recommended for this system (Turner et al., 1999 and 2000):

- Classical Swine fever virus: 65°C
- Swine Vesicular Disease virus: 65°C
- African Swine Fever virus: 60°C
- Aujeszky's Disease virus: 65°C
- Foot and Mouth Disease: 70°C

1.34 Costs

The capital cost of a simple reactor for a batch of 10m^3 with a heating system and a mixer is estimated at about £40,000. The treatment energy cost of 1m^3 of slurry @ £0.05/kWh is estimated at £3.60.

A continuous system for processing approximately 15m^3 of slurry a day would cost in excess of £100,000. The treatment energy cost is estimated at £0.40/m^3 with an additional £1.00/tonne of slurry for staff time and unit maintenance.

1.35 Benefits and disadvantages of the process to the farming community and the environment

The pasteurisation system would benefit farms mainly during outbreaks of contagious livestock diseases. Pasteurised slurry can be applied to fields without the risk of further spread and propagation of the disease.

Application of this method to slurries for minimisation of their faecal bacteria content could be beneficial for the protection of bathing water from slurries applied onland during the bathing season.

The impact of pasteurisation on pollutants in slurry, except bacteria and viruses, is minimal. In fact, offensive odours and ammonia are released during the process. Therefore, the risk of environmental pollution by organic matter (BOD) and nutrients to the aquatic environment, and by ammonia and odours to the atmosphere, is not reduced by pasteurisation of slurry.

1.36 Justification of the process for farm use

Despite the proven effectiveness of thermal decontamination techniques, their suitability will only be established if they can be shown to be practical at the farm scale. Unlike biological systems, thermal based systems may be only required at times of particular disease risk to the local livestock farm industry. Although it is unlikely that decontamination of livestock wastes would ever be a standard routine, it could perhaps be justified in areas where the quality of bathing waters is an issue. It may be therefore more practical to deploy mobile units to the farm site (Figure 13.6.1).

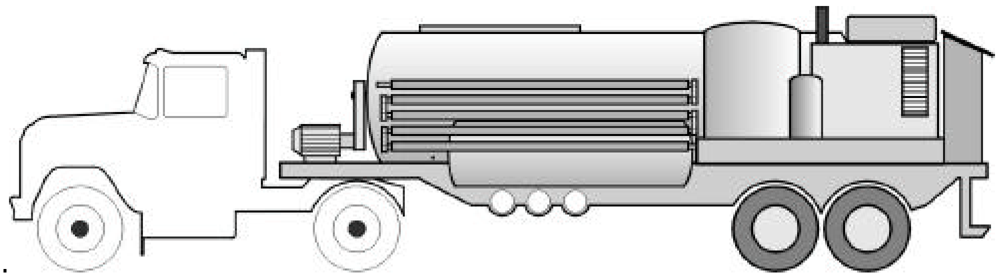

Figure 13.6.1 Mobile pasteurization unit for slurry continuous treatment

The concept of a mobile treatment unit is attractive as it enables the efficient use of limited resources across a wide area. However, such equipment must be fully self-contained and not reliant on local services as would be the necessity for remote farms. The plant would need to carry its own fuel, electrical power source, water and disinfectants for cleaning the equipment prior to moving on to a new farm. This emerges from a detailed design study on such concepts by Burton et al., (1999) which studied all aspects of running such a system safely and reliably in a range of locations. With a throughput of 500 tonnes per day, the proposed unit was designed to run continuously for up to a week, largely automatically. For operation beyond a week the plant would need a re-supply of water and fuel.

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Aerobic treatment – Liquid composting

The main objectives of aerobic treatment are the minimisation of waste pollution potential and, to a lesser extent, the provision of renewable energy.

For the purpose of this report the control of pathogens and faecal indicator organisms is the primary objective whilst the other benefits listed below are of secondary importance.

- Reduction of offensive odours by decreasing the concentration of volatile fatty acids and other odorous compounds
- Stabilisation of organic matter and hence reduction of COD and BOD
- Reduction of pathogens and faecal indicators to levels depending on the process characteristics
- Increased immediate availability of nutrients by converting available organic nitrogen to ammoniacal nitrogen and decreasing C:N ratio by converting carbonaceous compounds to carbon dioxide gas
- Manipulation of nitrogen by oxidising available ammonia to nitrite and nitrate with partial or full denitrification to nitrogen gases
- Improved characteristics of liquid manure like homogeneity and flow by decomposition of solids and decrease of viscosity and hence a better and faster infiltration of digested slurry into the soil
- Production of excess energy in the form of low level heat.

Livestock manures contain a large percentage of organic matter, 75 to 87% of the DM of slurries, (Evans et al., 1980) or more in FYM. This matter is susceptible to rapid biological decomposition through anaerobic or aerobic pathways. The direction depends on the manures handling conditions and the available microbiological population. Although manures have undergone anaerobic metabolism in the animal's gut, a large proportion of micro-organisms contained in manure will not only be strict anaerobes but also facultative bacteria. They, if the conditions are correct, will metabolise the available organic matter through aerobic pathways since this biodegradation path gains 18 times more energy for the micro-organisms than does anaerobic decomposition. It is therefore quite clear that aerobic treatment is a natural biological degradation and stabilisation process of organic material. In nature it is limited by oxygen supply, which particularly for manures, has to be very intensive to satisfy the bacteriological demand. The lack of oxygen creates anaerobic conditions characterised by evolution of odorous volatile compounds. To prevent this, liquid manures are aerated using mechanical or compressed air devices while FYM is agitated or aerated in heaps or enclosed compartments during composting.

As with all biochemical reactions, the reaction rate increases at higher reaction temperatures. The heat needed to increase the temperature in slurries or compost material is normally generated by the exothermic (heat producing) metabolism of aerobic micro-organisms present in the feedstock (slurry, FYM). It is important that dilution of slurries or water ingress into FYM is kept to a minimum, since the heat generated in dilute liquid materials is mainly dissipated to the bulk of the liquid and to the environment so the temperature increase may be very low. If concentrated materials are aerated in an insulated reactor, the specific heat evolution is larger and heat losses are smaller, thus the temperature can rise up to the thermophilic range – when the process is sometimes called autothermic. Aerobic treatment/stabilisation of solid materials is termed “composting”, or “liquid composting” when liquid or semi-liquid materials (slurries) are treated.

1.37 Liquid composting - the method

The objective of liquid composting/aerobic treatment is to decrease the pollution potential of wastes which can then be safely stored, utilised or disposed of without causing pollution of soil, air or water.

The process is based on the biological oxidation/stabilisation of the organic matter, in this case, contained in livestock slurries. Firstly, the micro-organisms already present in the slurry metabolise the dissolved (available substrate) components from the slurry. These components, organic acids, phenols, indoles, low molecular weight proteins, small molecules of sulphur compounds etc., are the cause of the slurry offensive odour. The concentration of these dissolved compounds is reflected in the high BOD_5 of the liquid slurry phase (supernatant) with levels reaching 10,000mg/l.

Secondly, other organics, large molecules of suspended material, are hydrolysed by bacterial enzymes. This degradation is much slower than the first step. Thirdly, nitrogenous compounds, like urea and proteins, are decomposed into carbon dioxide and ammonia which is further oxidised to nitrite and nitrate. These oxidised forms of nitrogen can be finally reduced to nitrogen oxides and nitrogen gas.

The final product of livestock slurry aeration/liquid composting is treated slurry without offensive odour, with much lower BOD, lowered or completely eliminated pathogens and faecal bacteria, lower solids concentration and a higher ready availability of plant nutrients. Although the liquid phase of treated slurry can be further improved to the level which may satisfy discharge to watercourse standards, the cost of additional treatment is too high to be justified and the treated slurry is therefore applied on to agricultural land.

The process described here is suitable for individual farms or co-operatives, but does not include complicated and sophisticated methodologies required to treat slurry to the level of discharge standards.

1.37.1 Oxidation of carbonaceous matter

As already mentioned the aerobic treatment process has two distinct phases:

i) oxidation of carbon and

ii) nitrification (oxidation of nitrogen).

The carbonaceous compounds are degraded and about 50% is oxidised to carbon dioxide, while another 50% of the carbon is used for the biosynthesis of biomass. Also water is created and energy is released (Equation 1).

Eq.(1) $$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{Energy}$$

Approximately 60% of this energy is used by micro-organisms to synthesise biomass while the rest is lost in the form of heat. This quantity of heat has been measured and expressed as the amount of heat released by the biomass which used 1kg of oxygen for the metabolism of carbonaceous compounds (Svoboda and Evans, 1987). This heat, which is approximately 4kWh/1kg O_2, increases the temperature of the aerated slurry. In thermally insulated systems, with concentrated slurry and efficient aerators the slurry treatment temperature can reach over 50°C. This auto-heating process has been utilised for various purposes, as described further below, but mainly for slurry sanitation (pathogen destruction) and the utilisation of generated heat.

1.37.2 Nitrification

Nitrification of ammonia nitrogen can be described by a two step reaction as follows (Sharma and Ahlert, 1977):

Eq. (2) $NH_4^+ + 1.5\,O_2 \rightarrow 2H^+ + H_2O + NO_2^- + 58$ to 84kcal (mol^{-1})

Eq. (3) $NO_2 + 0.5O_2 \rightarrow NO_3 + 15.4$ to 20.9kcal (mol^{-1})

Similarly the heat evolution has been expressed as a function of oxygen consumed and a value of 1.2kWh/kgO_2 was established.

Since the micro-biological nitrification process is sensitive to dissolved oxygen concentration, residence time and temperature controlled during the treatment of slurry, a model has been developed to describe the forms of nitrogen resulting from various levels of aeration and residence time (Fig.15.1.2.1).

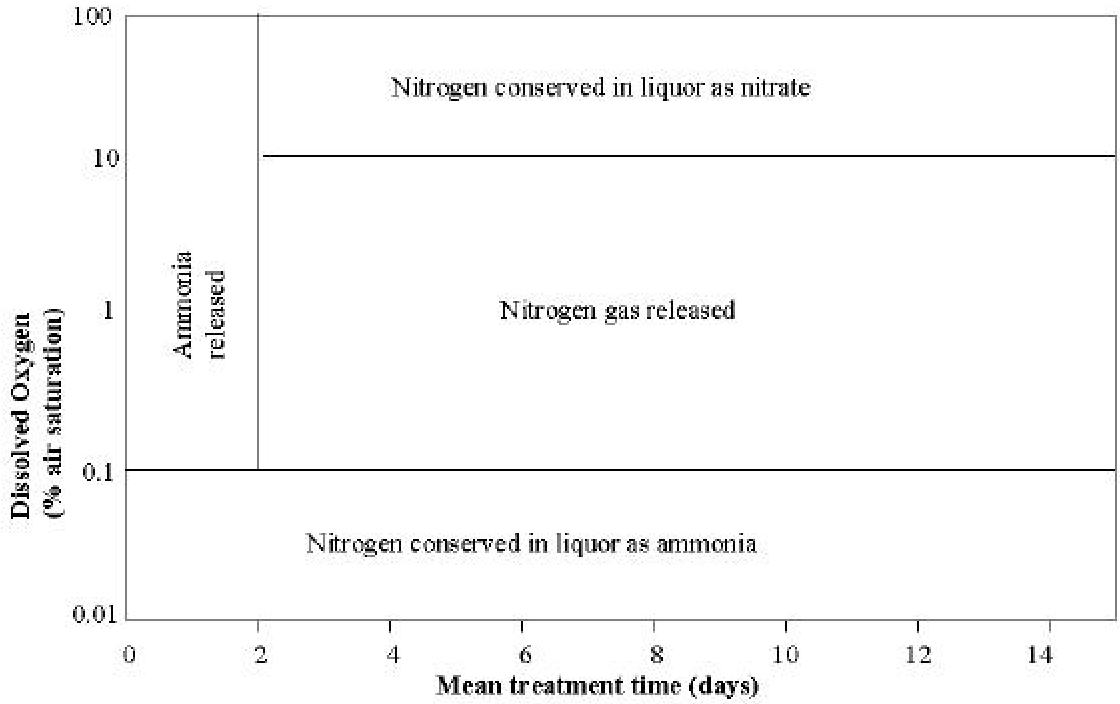

Figure 15.1.2.1 The effect of the dissolved oxygen level and treatment time on mineral nitrogen during mesophilic continuous treatment of piggery slurry (Evans et al., 1986)

Microbiological oxidation of ammonia is limited by the following treatment parameters:

i) Treatment time

ii) Treatment temperature

iii) Dissolved oxygen (DO) concentration

iv) pH level

1.37.2.1 Treatment time

Ammonia oxidising bacteria like *Nitrosomonas spp.* and *Nitrobacter spp.* require a relatively longer generation time (time required for multiplication) than other bacteria, heterotrophs, which oxidise the carbonaceous components of slurries. In a continuous culture treatment (described below), the minimal generation time has been found to be about 2.5 to 3 days at mesophilic temperatures (15 to 40^{o}C). At shorter treatment times, the nitrifying bacteria are washed out from the system and the nitrification process is terminated.

1.37.2.2 Treatment temperature

Nitrifying bacteria are more sensitive to extremes of temperature than are heterotrophs. The rate of nitrification is minimal at less than 5^{o}C and the bacteria stop nitrifying at temperatures higher than 45^{o}C.

1.37.2.3 Dissolved oxygen concentration

DO concentration in aerated slurry affects the speciation of inorganic nitrogen (Fig. 15.1.2.1). Nitrifying bacteria start to oxidise ammonia when DO reaches between 0.1 to1% of saturation. At lower DO levels only ammonia and organic nitrogen will be present in the slurry. At higher DO concentrations, and treatment times longer than 2.5 to 3 days, most of the available ammonia nitrogen will be oxidised to nitrite and nitrate. Although nitrate can reach high concentrations in treated slurry, it was found that in full scale treatment reactors, where anoxic zones exist, varying quantities of nitrate are reduced to nitrogen oxides and nitrogen gas.

1.37.2.4 pH level

Low and high pH levels negatively affect nitrification rates. At pH levels lower than 5.5, usually resulting from oxidation of ammonia to nitrite, the un-dissociated nitrous acid inhibits nitrification (Prakasam and Loehr, 1972). Similarly pH levels over 9, caused by high ammonium concentration, inhibit nitrification by increasing the concentration of free ammonia. The recommended pH levels for optimum nitrification are between 7.2 and 8.2 (Alleman, 1985).

1.37.3 De-nitrification

The process of de-nitrification is characterised by the reduction of oxidised nitrogen (nitrite, nitrate) to di-nitrogen gas and/or to nitrogen oxides, mainly nitrous oxide (Equation 4).

Eq. (4) $NO_3^- \leftrightarrow NO_2^- \rightarrow N_2O \rightarrow N_2$

Although this process happens only when the DO levels in treated slurry are low (Fig.15.1.2.1), it was found in practice (Svoboda, 1993) that conditions in the treatment reactor are far from ideal and the losses of nitrogen through de-nitrification occur regularly. This is beneficial for nitrate vulnerable zones (NVZ's) where an excess of nitrogen from land applied slurries can be effectively halved by slurry aerobic treatment with a nitrification/de-nitrification process.

Nitrate in treated slurry can also be effectively exploited for maintaining offensive odour free slurry in the storage phase subsequent to treatment. Nitrate acts as an oxygen supply for aerobic bacteria in treated slurry and thus it limits, for various durations, the development of odorous substances by anaerobic bacteria.

1.38 Aerobic treatment of slurry in livestock agriculture

The intensification of livestock agriculture has brought significant changes to the management methods for animals' excrements. Bedding materials are used minimally and slurry is produced instead of FYM. The large volumes of diluted slurries produced have become a problem with respect to pollution of air and water. This has led to biochemical technologies like anaerobic digestion and aerobic treatment being developed to minimise pollution.

Laboratory, pilot and full scale aerobic treatment systems have been developed, mainly for pig slurry. The reason for this is that piggeries are generally geographically concentrated, have inadequate land for slurry application, and produce slurries with offensive smell and high water pollution potential.

In the early days of development, full scale systems used open channels or lagoons for aeration (Robertson 1977), while recent systems are both more complex and efficient using steel tanks reactors and additional equipment. Aeration technology, being relatively simple, can be used on individual farms (Evans et al., 1979, Hughes, 1984) or as centralised treatment plants, as it is in Holland for veal slurry (Starmans, 2001), or for pig slurry (the FAL systems in Germany or the PROMEST in Holland). There are various treatment plants in Portugal, Spain, Italy and France, Czech Republic, Slovakia, Russia etc., either on large pig farms, or in a central position for collecting slurry from many smaller farms.

Treatment of slurry is carried out to different degrees, depending on the country, regulations for direct watercourse discharges, irrigation requirements or land application restrictions. The common objectives are the reduction of offensive odour and biological oxygen demand, pathogen elimination and nitrogen control.

Treatment plants with very sophisticated equipment aimed to provide a very high degree of treatment have not always been successful. The PROMEST plant in the Netherlands was closed with huge financial losses when trying to economically treat up to $6Mm^3$ of pig slurry annually.

1.39 Literature research

1.39.1 Pathogen control

Aerobic treatment of livestock slurry can be carried out over a very large temperature range, (from 5 to 70^{o}C) and has a detrimental effect on the survival of pathogenic and faecal organisms. The rapid death rate is affected by grazing, high competitiveness and activity of aerobic micro-organisms, high temperature and extreme pH values resulting in free ammonia or un-dissociated nitrous acid. Particularly, the high temperature and high concentration of ammonia are utilised in the auto-thermal aerobic pre-treatment stage to anaerobic digestion.

Strauch *et al.,* (1970) observed that 24 hour exposure to aerobic treatment of infected pig slurry at 40°C significantly reduced the number of *S. dublin*. Complete inactivation of *S. enteriditis* occurred after 40 hours at 42°C and pH 8.0 during aerobic treatment. Kabrick and Jewel (1982) found that *Salmonella spp.* numbers were reduced to undetectable levels – at least three decimal reductions - in an aerobic reactor at 35°C in 24 hours, while at higher temperatures of up to 60°C *Salmonella* spp were eliminated in several hours.

Aeration of pig and cattle slurry substantially decreased the time required for the decimal reduction of five strains of *Salmonella spp.* (Munch et al., 1987). A decimal reduction occurred in 0.3 and 1.0 week at 18 to 20°C and 1.0 to 2.5 weeks at 6 to 9°C in aerated slurry and in 1.0 to 3.0 weeks at 18 to 20°C and 3.0 to 8.0 weeks at 6 to 9°C in anaerobically stored slurry.

The effects of aerobic stabilisation on *Ascaris suum* eggs were described by Plachy *et al.,* (1995). The mesophilic temperature treatment reduced the viability of eggs to 37%, while the thermophilic treatment completely destroyed them. The authors demonstrated that pH increase (pH 5.0 to pH 9.0) had a negative effect on egg survival, similar to the temperature increase. In contrast, higher organic solids prevented *Ascari* egg destruction. Strauch *et al.,* (1985) support the theory that sludge particles positively affect survival of pathogens.

It can be seen that the thermophilic aerobic treatment is an effective method for the control of eggs of parasites and bacterial and viral pathogens. Batch experiments were carried out in a 550m^3 insulated reactor by Bohm (1984). Infectivity of foot and mouth disease virus was completely lost 24 to 44 hours after commencement of aeration. To reach the final temperature of 50°C from about 15°C took about 40 hours. To inactivate the viruses of pseudorabies and swine vesicular disease Bohm (1984) recommends retention times of 50 a 48 hours respectively, during which times temperatures of 40°C should be reached.

Hojovec (1990) reported a decrease in the total bacterial count (TBC) of piggery slurry treated by aerobic thermophilic stabilisation. Slurry was aerated in laboratory, pilot scale and full-scale plants at average temperatures of 60°C for an average of eight to ten days. The TBC decreased from an average of 10^{11} to 10^{5}/ml and the coliform count was reduced from 10^{6} to 10^{3}/ml and to nil after 24 hours of aeration.

Enteroviruses and rotaviruses can both survive for periods of several weeks or months in slurry stored at ambient temperature, but show greater death rates at elevated temperatures and in aerated slurry. Strauch (1986) considered aerobic thermophilic stabilisation as a disinfection process. Sludge is virtually disinfected in a two stage, batch and continuous system with a minimum treatment time of five days, and a treatment temperature between 55 and 60°C.

Oechsner and Ruprich (1989) reported similar results from a two stage, batch and continuous treatment of piggery slurry. In the second reactor, in which the temperature reached 68°C, faecal streptococci were eliminated in two days, while in the first reactor with a maximum temperature of 55°C, four days were required. During continuous treatment, with a three day residence time in each reactor, faecal streptococci were always present in the first reactor, being introduced with each daily fresh slurry input, whereas they were not present in the second reactor.

Survival of *Cryptosporidium parvum* in cattle slurry can be very effectively decreased by aeration. The viability of oocysts was lost within four days at 15°C, with a thermophilic treatment temperature of 50°C, the most effective rendering oocysts non-viable within 15 minutes (Table 15.3.1.1) (Svoboda *et al.,* 1997).

Table 15.3.1.1 Time required for different temperatures to render *Cryptosporidium* oocysts non-viable in cattle slurry.

Temperature (°C)	**Treated slurry**	**Stored slurry**
4	-	>3 months
15	<4 days	>30 days
20	-	>20 days
30	16 hours	-
50	15 minutes	-

1.39.2 Effect on organic matter, odour and nitrogen

Livestock slurries can be aerated for various a) times, b) DO concentrations and c) temperatures. Also the aeration can be run as a batch or a continuous process. All of these parameters affect the characteristics of the treated slurries. The most efficient is a continuous culture process, and therefore most research has been devoted to it. It has been found (Evans et al., 1983) that with self heating continuous aeration it can be performed at mesophilic temperatures (25 to 45°C) and thermophilic temperatures (50 and >50°C). A series of laboratory experiments provided data allowing the generation of mathematical equations describing the characteristics of treated pig slurry at those temperatures (Table 15.3.2.1).

Table 15.3.2.1 Equations for calculation of residual COD, BOD_5 and BOD_5 of supernatant ($g.l^{-1}$) of treated slurry at treatment temperatures 25 to 45°C and 50°C, where TS_f, TSS_f, COD_f and BOD_f are concentrations of fresh slurry and R the mean treatment time (Evans et al., 1983).

Parameter	Temperature 25 to 45°C	Temperature 50°C
TS	$[0.262/(1+0.4R)+0.744]\ TS_f$	$[0.450/(1+0.7R)+0.579]\ TS_f$
TSS	$[0.282/(1+0.4R)+0.696]\ TSS_f$	$[0.405/(1+0.7R)+0.563]\ TSS_f$
COD	$[0.333/(1+0.4R)+0.535]\ COD_f$	$[0.429/(1+0.7R)+0.445]\ COD_f$
BOD_5	$1.568/R+0.152\ BOD_f$	$1.568/R+0.152\ BOD_f$
$BOD_{5(sup)}$	$0.11/R$	$0.0427/R+0.007\ BOD_{f(sup)}$

TS ....Total solids

TSS ....Total suspended solids

COD ....Chemical oxygen demand

BOD_5 ....Biochemical oxygen demand (5 days)

$BOD_{5(sup)}$......Biochemical oxygen demand of supernatant

As an example of assessing the changes of biodegradable organic material in pig slurry at mesophilic temperatures the following calculation is used.

Pig slurry with 10% DM will have a BOD_5 of 35g/l. Mesophilic aeration for five days will reduce BOD_5 according to the equation in Table 15.1.6.1 as follows:

$BOD_5 = 1.568/R+0.152\ BOD_f$

BOD_5 = 1.568/5 + 0.152 x 35 =5.63 g/l

The residual BOD_5 will be therefore 5.6g/l which is 16% of the original BOD_5. This decrease of organic matter is reflected in changes in the offensives of the odour of the slurry.

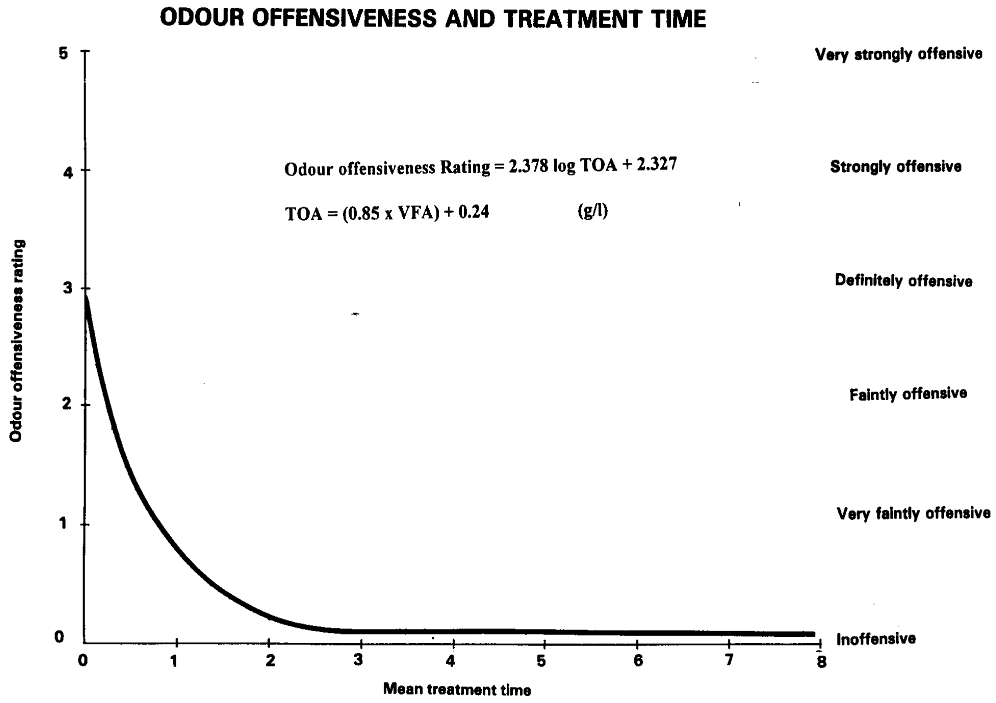

Figure 15.3.2.1 Effect of aerobic treatment time on offensive odour changes in pig slurry (TOA – Total Organic Acids, VFA – Volatile Fatty Acids) Odour Offensiveness was determined by an odour panel for strengths from 0=Inoffensive to 5=Very strongly offensive)

It has been firmly established from comprehensive studies with pig slurry that continuous aerobic treatment can render strongly offensive odours to inoffensive levels within two to three days at mesophilic treatment temperatures. Thermophilic treatment is slightly less efficient in the removal of odorous compounds (Evans *et al.*, 1983).

The storage duration of previously aerobically treated pig slurry without offensive odour regeneration was described by Williams *et al.,* (1989). The time (in days) to reach the concentration of 0.52g/l (offensive odour threshold) for volatile fatty acids, was described by the equation:

$$t_{0.52} = 3.2R + 17$$

where: *R* is the treatment time of slurry in days.

This time is also dependent on the slurry solids concentration; at higher solids content, odours re-develop more rapidly. According to Burton *et al.,* (1998) the odour returned to pig slurry, treated aerobically for 2.4 days, after 28 days of anaerobic storage.

It is important that odour from treated materials is minimised not only during treatment and storage, but also during and after subsequent land spreading. Pain *et al.,* (1990) documented the substantially lower odour threshold values of air samples collected from above fields being applied with aerated and raw slurry. The threshold value for raw slurry was 201.2 units while the aerated slurry value was only 19.6 units.

Nitrogen contained in slurries is normally present in the form of about 50% as organic nitrogen and 50% as ammoniacal nitrogen. This nitrogen composition can be altered with aerobic treatment as indicated in chapter 15.1.2 and 15.1.3 (Sharma and Ahlert, 1977). Some of the organic nitrogen is converted to ammonia during aeration and depending on the process parameters, up to 70% of the total nitrogen can be oxidised to nitrate, and consequently be further metabolised and lost as nitrogen gas (Smith and Evans, 1982; Svoboda, 1995). Such a practice could be exploited in NVZ's with large pig or cattle farms.

1.40 Costs

The cost of aerating livestock slurry is influenced by many factors which are specific to each farm and to the system adopted. These factors include the number of animals, slurry dilution, pre-treatment of slurry and aerator efficiency. The least expensive treatment would be designed for odour control, which can be achieved in short treatment times (Thacker and Evans, 1985) whereas the most costly one would be long term treatment with nitrification (Evans et al., 1982; Williams et al., 1989)

Sneath et al., (1990) assessed aerobic treatment of pig slurry. When slurry was pre-treated by removal of solids by centrifugation and then aerated for a short period of one to two days, the cost of treatment varied between £1.10 and £1.40/m^3. Longer treatment times of three to five days increased the cost to between £1.70 and £4.60/m^3.

At current costs, 1m^3 of pig slurry treated would cost between £3 and £4 (Nick Nicholson, personal communication), and cattle slurry about £6.30 for a five day treatment.

The value of the excess heat energy recovered from the treatment process can be included in the economics of the system which would then be more attractive to farmers. Thyselius (1982, personal communication) reported that the heat energy (at 50^{o}C) recovered from a piggery slurry treatment plant was up to 3.5 times more than the electrical energy used for aeration. Svoboda and Fallowfield (1989) used a heat pump and recovered from a small farm scale reactor twice as much heat energy as the electrical energy used for aeration.

Hughes (1984) installed a heat recovery system into a lagoon of continuously aerated pig slurry from which the solids had been removed. A pay back period for the heat pump and the system of 3.5 years indicates an expected profit from the recovered heat.

Cost assessment

The most recent cost of aeration of livestock slurry was assessed by Nicholson et al., (2002). Cattle slurry would be aerated for a five day treatment time in a 50m^3 reactor. The capital cost of the reactor and other equipment was estimated as £20,000. The annual depreciation and maintenance was £4,120 and the electricity running cost per 1m^3 of slurry was £3 to £4. The reactor would treat 1800 m^3 of slurry in 180 days during the cattle winter housing period. Thus the total specific cost per 1m^3 of slurry would be £6.30 (£2.29 for depreciation and maintenance plus £4 for electricity).

If the treatment could be run continuously for the whole year, then the slurry from a 100 dairy cattle farm (see below) could be treated and the cost would be decreased to about £5.00/m^3.

Volumes of slurry from 100 dairy cattle

	@m^3.d^{-1}		**m^3.d^{-1}**	**m^3.y^{-1}**
100 milking dairy cattle	0.052		5.2	
30 dry cattle	0.035		1.05	
30 calves (FYM)				
SUB-TOTAL			**6.25**	
Slurry production for 180 days			180x6.25	1125
15% for the summer period			0.15x1125	169
wash water (100 dairy)	0.04	4.0	365x4	460
Outside silage clamp 1000m^3 (area of 18m x 30m, annual rainfall 1m, winter collection 70% of annual)				540
TOTAL ANNUAL				**2 294m^3**

1.41 Requirements for running the process

Aeration of livestock slurry is a relatively simple process which can be automated and run with minimum supervision. The core of the process is a reactor (tank or a lagoon) with an aerator either subsurface, floating on the slurry (Fig.15.5.1), or submerged venturi type (Fig. 15.5.2). Slurry is pumped from a reception tank, which already exists on most farms, at regular daily intervals into the reactor, which can be thermally insulated if heat extraction is viable for the farm. Treated slurry is pumped into the final store before the fresh slurry is transferred into the reactor. The aeration process is controlled through DO or Redox probes to optimise aeration and to minimise the electric consumption. Treated slurry is applied to the land with similar equipment to that used for raw slurry.

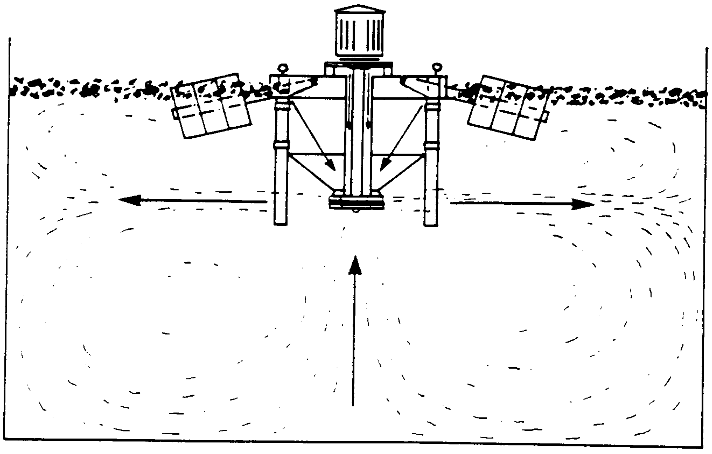

Figure 15.5.1 Sub-surface floating aerator

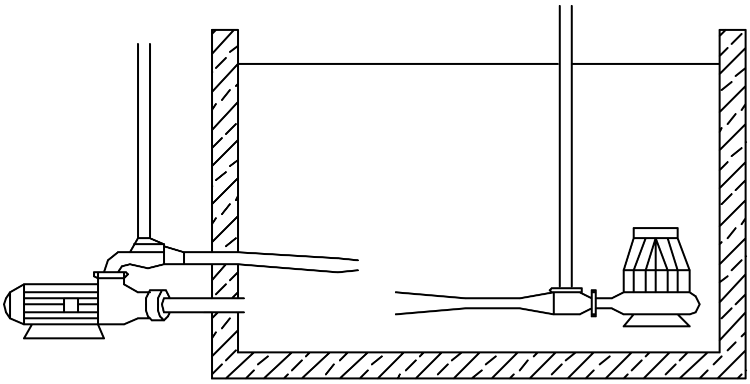

Figure 15.5.2 Venturi aerator fixed (on the left) or submersed (on the right).

A more complicated system would utilise the heat for farm purposes like heating process water, heating piggery weaner housing, a glass house or another facility as suggested in Fig.15.5.3. The value of recovered heat can considerably offset the treatment cost.

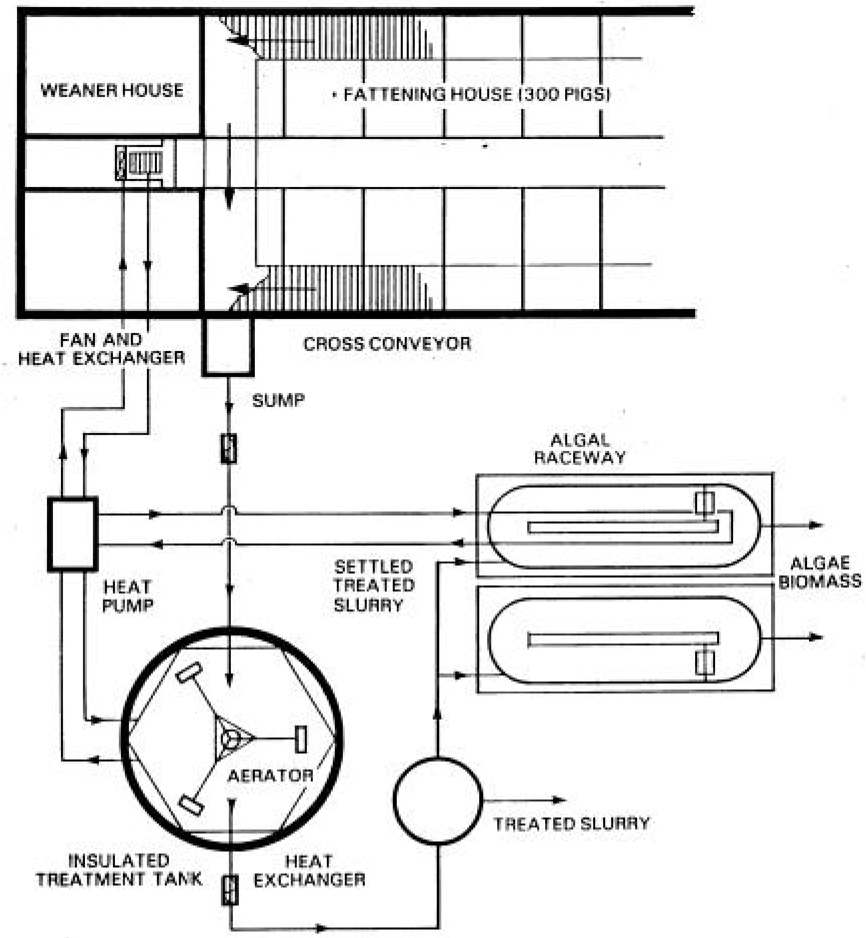

Figure 15.5.3 Integrated system for aerobic treatment of piggery slurry with process heat utilisation in a weaner house and algal ponds.

1.42 Benefits and disadvantages to the farming community and to the environment

There are several advantages for the farmer. Aeration treatment provides an odourless slurry for storage and slurry land application. Also, there is a substantial reduction in the slurry pollution potential (BOD), and an increased immediate availability of plant nutrients. It was demonstrated by Evans et al., (1979) that after installation of the aeration treatment plant the farmer doubled pig production without polluting the ground water through field drainage, which was the case before treatment installation.

The pathogen viability and the faecal bacteria survival indicators are substantially reduced by aeration, particularly if the treatment temperature reaches the thermophilic range.

Mesophilic temperature treatment provides the possibility for nitrogen manipulation. Compliance with NVZ's would benefit from the loss of up to 70% of slurry nitrogen, mainly in the form of nitrogen gas from livestock manures.

Evolved heat from aeration of concentrated slurries can provide a tangible value, which can fully compensate for the electricity used for mechanical aeration.

The disadvantage of the aeration system is as in any treatment process; it increases the cost associated with slurry utilisation.

Overall, the benefits and disadvantages of the process can be compared only with the value the society assigns to the environment which is prepared to protect.

1.43 Justification of the process for farm use

The livestock slurry aeration process, with its simple management, can be easily adopted to any work on livestock farm. In its most simple form, for odour and pathogen/faecal indicators control, it can be run with minimum management input from the farmer. Despite a more complicated design for treatment with heat recovery, it is still a farmer friendly system-as documented by Svoboda and Fallowfield (1989). Nevertheless the cost of this treatment may only be justified if society provides a subsidy to offset the farmers expenditure associated with the treatment and the environment protection.

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Solids composting

Composting of organic wastes is becoming very popular. The reasons for its wide spread application are mainly the environmental protection it brings, and also the commercial application of the compost material. It also reduces land-fill charges which otherwise would be incurred.

Using well defined organic wastes, like livestock manures and garden waste, the process is suitable for producing a peat substitute, soil conditioner or fertiliser, thus providing a renewable resource and directly utilising waste as a saleable commodity.

In European countries, the USA and Japan the composting of domestic refuse and sewage sludge has become part of a programme for the protection of the environment. Land-fill disposal sites are minimised, thus reducing methane and leachate production, and minimising the viability of human and plant pathogens in wastes. In some of the developing countries composts are used for restoration of soil fertility and productivity.

1.44 Feed stock for composting

Composting can be a carried out on a wide range of organic wastes, from highly putrescible fish wastes, animal and food processing wastes, livestock faeces, municipal solid wastes and sludges, to more innocuous material such as crop residues, garden wastes, bark, wood chips etc. Material for composting (the feed stock) is usually obtained by the mixing of nitrogen rich wastes, often with a high moisture content, with dry, structure-providing carbonaceous wastes. The characteristics of the feed stock determine the character of the composting process and the quality of the final product-compost. For a successful and efficient composting, the feed stock C/N ratio should be between 25 to 30:1. A higher ratio will slow down the process, while the composting of wastes with a lower ratio will result in losses of ammonia, often in large quantities, with a negative effect on the environment.

Moisture content is an important factor affecting the transfer of substrate and oxygen to micro-organisms in the compost. Feed stock should contain 50 to 60% of water, although higher values are possible if water is bound within the cells and does not affect the porosity of the compost. This is influenced by the particle size of the feed stock, which is recommended to be between 10 and 50mm to allow the necessary aeration of the bulk. A too high content of water in the feed stock has to be either removed by mechanical separation (sieves, centrifuges), or absorbed by bulking materials which provide carbon and porosity to allow airflow and proper aeration. Straw, wood (chips, shavings and saw dust) and chips made from tyres have all been used as bulking agents.

The homogeneity and particle size uniformity of the feed stock are usually achieved with shredders and mixers which cut the material into a smaller size, mix it and can heap up the feed stock into piles.

1.45 Composting process

Composting is a traditional natural microbiological method used for increasing the stability and reducing the odour of organic wastes. The micro-organisms responsible for the degradation are mixed populations of mesophilic and thermophilic bacteria, fungi and actinomycetes. Composting is an aerobic process requiring a continuous supply of air. Mechanical mixing and/or forced ventilation provide the required oxygen, and remove the heat and moisture which are generated during composting. The temperature within the pile can rise during the first few days of composting to as high as 75^{o}C or more. Such a high temperature suppresses the activity of micro-organisms which compost (break down the organic matter and provide the heat) the organic matter. This effect is usually exploited in composting processes. If the temperature is not suppressed during the initial days of composting, it deactivates most of the pathogenic micro-organisms within the compost. To achieve the optimal composting rate, shortest composting time and fully a resulting composted material, control of temperature at approximately 55^{o}C is required. It is usually achieved by mixing and/or forced aeration of the composting mass.

1.46 Composting systems

Many composting systems have been developed. They range from completely enclosed systems like the Dano tunnel or silo composting, to open systems like windrow composting and static pile processes. The latter types tend to be used most often because of their simplicity and low capital and running costs. For windrow composting, the wastes are piled into long rows (approximately 3m wide at the base and 1.5m high) which are situated outdoors. They are turned periodically, with higher frequency during the first few weeks of very active composting. This type of composting requires larger land areas and a higher labour cost than static pile composting, where oxygen and cooling are provided by forced ventilation from the base of the pile. The aeration at the start and the end of the composting process is initiated by a timer while, during the very active stage, it is controlled by temperature feedback. After the end of composting, indicated by the compost temperature decresing to 25^{o}C or less, the compost should be stored, preferably under cover, for a minimum of a 30 day maturation period, during which phytotoxins are degraded. Separation into various size fractions, and eventual mixing with other additives, are the last processes before bagging or bulk distribution of the compost.

As mentioned above there are main three types of composting systems:

1. Windrow
2. Static pile with forced ventilation
3. In-vessel

Control over the composting process increases from windrow ➔ static pile ➔ in-vessel composting, as does the capital cost. The labour cost decreases in the same succession and the overall running cost mainly depends on the costs of labour and energy.

1.46.1 Windrow composting

The feed stock is piled in long rows (windrows) and turned at intervals using mobile equipment like tractors with front loaders or compost-turners, machines specially designed for compost turning. The most common method, the conventional windrow, is aerated through natural ventilation (convection and diffusion), and also during turning which is also required for more homogenous composting. This process requires an extensive area of ground which can be hard soil, but more ideally a concrete base with the facility for containing the leachate. In regions with high rainfall, leachate production can be reduced and a better control of composting can be achieved by roofing the composting area.

1.46.2 Static pile composting

This process uses an active aeration system. Perforated pipes are laid on the floor or in the floor channels and are covered with porous material like straw, wood chips etc., which aids efficient distribution of air. The feed stock is then piled on the base and covered with a layer of matured compost to provide thermal insulation and partial odour removal. Aeration, controlled by temperature feed-back, is used to sustain the pile in an aerobic state, to maintain the temperature of the pile and to control the moisture content of the pile. The latter helps mainly in the final stage of composting, when the increased aeration rate contributes to compost drying.

1.46.3 In-vessel composting

To ensure homogeneous composting processes with temperature control and therefore inactivation of pathogens and odour reduction, in-vessel composting systems are used. In-vessel composting is usually a multistage process. Pre-composting or full composting is achieved in the first stage in a bioreactor, and the final composting and maturing in windrows. The most common types of reactors are horizontal and vertical plug-flow and an agitated bin reactor. Various systems (*e.g.* Wright Environmental, Sirroco, TEG Environmental, Herhof *etc.*) maintain temperature control and oxygen levels by computerised processors. Also the quality of exhaust gases is improved by passing them through a biological filter for odour and ammonia removal. This type of composting, being well controlled and thoroughly mixed, is faster than the previous systems, but more complicated control and processing mechanisms are expensive and require costly maintenance.

1.47 Literature research

1.47.1 Pathogen control

Various factors affect survival of pathogenic and faecal organisms during the composting process. The most effective system against pathogens is the use of elevated (>50^{o}C) and sustained (one or more days) temperature in the compost pile. When material with a high concentration of nitrogen is composted, it is likely that free ammonia, which is poisonous to micro-organisms, will be generated. Also competition with other micro-organisms for food, grazing by higher micro-organisms and the destructive effect of fungi on cell walls also rapidly decreases survival of pathogens.

Pereira Neto *et al.*, (1987) stated that composting effectively eliminates pathogens, provided the temperature reaches 55-60^{o}C for a minimum period of three consecutive days. Proper turning is important, as it will result in all the composted material being exposed to these temperatures. Particularly in-vessel composting is most effective in providing proper mixing and pathogen inactivation. Strauch (1980) demonstrated that *Salmonella, Ascaris* eggs and enteroviruses can be destroyed when the process is operated correctly. Similarly inoculated compost feed stock with 10^8/g *Salmonella spp.* was pathogen free after ten days of composting (Käck , 1996). Wiley and Westerberg (1969) were unable to detect viable *Acaris* ova one hour after seeding the ova into a high rate composting system operating at 60 to 65^{o}C. Yanko (1987) never recovered viable helminth ova in examining approximately 300 samples of compost although they were plentiful in the compost feed.

Faecal coliforms were reduced from 1.7×10^9/g of DM in solid municipal wastes to less than 100 by composting in a Siloda composting plant. Faecal streptococci were reduced by the same process from 3.4×10^9 to 8.7×10^4/g of DM (Deportes *et al.,*1998). Epstein and Donovan (1992) reported for three different full scale sewage sludge composting facilities, in-vessel, static pile and windrow, a decrease of faecal coliforms from >4.10^3/g to <11, <4.10^3/g and <33/g respectively.

Similarly Käck (1996) showed that composting can decrease numbers of E.coli and fecal streptococci by at least 10^3/g.

Regrowth of *Salmonella* in re-contaminated compost has been studied (Sidhu *et al.,* 2001). Freshly sterilised compost was rapidly colonised with *Salmonella*, while the still active (un-sterilised) compost suppressed pathogen growth by the antagonistic effects of indigenous microflora. Similar effects of viable micro-organisms (possibly fungi) in fresh compost on the survival of helminth eggs were observed by Meeking *et al.,* (1996).

Longer periods of retention in composting environments, such as cattle farm yard manure heaps, are detrimental to the survival of *Cryptosporidium* oocysts (Svoboda *et al.,* 1997).

1.47.2 Effect on organic matter, odour and nitrogen

Compost characteristics relate to the original feedstock characteristics. Therefore, the starting concentrations of carbon and nitrogen will determine the final C/N ratio. While the moisture content decreases from about 70% to less than 30% and the organic content from about 75% to 50%, the concentration of phosphorus and metals increases in relation to the dry matter concentration.

By oxidising the biodegradable carbonaceous compounds to carbon dioxide the compost is biologically stabilised, i.e. when stored without access to air and rewetted, it does not generate any odorous compounds and its biological activity is minimal. Odour is produced mostly at the beginning of composting, when smelly compounds already contained in the feedstock are released in the exhaust gases by the increased temperature and forced aeration or turning. The most obnoxious components of odorous exhaust gas production from a composting mass are sulphurous compounds like methanethiol, dimethyl sulphide, dimethyl polysulphides, carbon disulphide and hydrogen sulphide (Derikx *et al.,* 1990; Smet and van Langenhove, 1998). To minimise the odorous emanations the windrows are covered with mature composted material or the air sucked from static piles is filtered through a biological filter.

Nitrogen losses during composting depend on the material composted, and the C/N ratio. If the starting ratio is lower than 30 or 25:1, there is an excess of nitrogen and losses of up 77% of the total nitrogen, in the form of ammonia, can be experienced (Martins and Dewes, 1992).

1.48 Costs

The windrow composting process requires the least capital investment in the system, but has the highest labour input. An assessment of cost for storage (one store-250 tonnes) and windrow composting is indicated in Table 16.5.1.

Table 16.5.1. Typical net costs per tonne of solid manure for possible pathogen control measures (including depreciation, interest, repairs, labour, tractors, electricity-rounded to nearest £0.10)(Adapted from the scientific report WA0656).

Solid manures	**Measure**	**Pigs/poultry**	**Cattle**
		£ /tonne	
STORAGE	Storage earth-based	£1.30	£1.40
	Storage concrete base-one store	£3.10	£5.00
	Storage concrete base – two stores	£4.30	£7.50
TREATMENT	Composting on earth-base	£2.10	£2.30
	Composting on concrete base-one store	£4.30	£6.60
	Composting on concrete base - two stores	£5.80	£9.60

The cost of in-vessel composting would be prohibitive for farmers if, for example, a Wright Environmental (Canada) system, which provides continuous composting with internal mixing and biofiltration of exhaust gases, were to be used. The indicative cost of plant would be around £0.75 million and treatment of a tonne of manure would be in excess of £50.

Since the treatment of cattle slurry would require the addition of bulking material, like straw, wood chips etc., the advantage of reduced waste weight and volume due to composting would be wasted. For livestock slurries, the necessary addition of other dry matter to reach the necessary solid concentration (25-35 %) can be so high that composting may become impractical. For example, starting with one tonne of livestock slurry with 5 % dry matter content, the feedstock requires an addition of 0.3 tonnes of dry bulking material in order to obtain a mixture with 25 % dry matter (Piccinini et al., 1995). Also by converting the slurry management to straw-based systems between 5 and 15% of cow places would be lost (Nicholson et al., 1992);

this could result in the need to invest an additional £1000/cow place for the 'displaced' cows.

1.49 Benefits and disadvantages to the farming community and to the environment

Compost made from cattle slurry has several advantages for the farmer and the environment in comparison to the raw slurry.

- Odour of compost is inoffensive, and the soil like compost can be stored without producing odours
- Human and plant pathogens and also faecal bacteria indicators are substantially reduced in compost
- The volume and weight of the feed stock are reduced by approximately 30% or more by the composting process
- Compost is a better fertiliser and soil conditioner than raw slurry due to the lower carbon/nitrogen ratio and the higher content of humus.

There are also several disadvantages.

- Capital cost is required for composting equipment, for composting area, for additional roofing of storage space for maturing compost and for the leachate controlling and containing equipment
- Large quantities of dry bulking material are needed for composting of livestock slurries
- There is a risk of decreasing quality of silage due to the herbage contamination with compost solids

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