DESIGN OF A CONTINUOUS FLOW AEROBIC BIOREACTOR FOR ODOUR REMOVAL FROM LIVESTOCK SLURRY

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A thesis submitted to the Faculty of Science of
The University of Glasgow
for the degree of
Doctor of Philosophy

Environment Division
The Scottish Agricultural College
Auchincruive, Ayr

January 2001

Abstract

The primary objective of this study was to develop the most effective abatement strategy for reducing odour offensiveness and emissions, and for reducing the water pollution potential from cattle and pig slurry during storage periods after an aerobic treatment process. A farm-scale treatment plant based on the findings of the laboratory studies, together with the latest research into aeration technology, was designed, constructed, operated and monitored.

An initial study was carried out to investigate the effect of three different temperatures (5, 10 and 15 ^{o}C) on the major odorants in slurries during storage. Odour, and stability of the slurry was measured using Volatile Fatty Acid (VFA), Total Organic Acid (TOA), Total Indoles and Phenols (TIP) and supernatant Biochemical Oxygen Demand (BODs) as odour indicators. Changes in the smell of pig slurry were greater than for cattle slurry, but they both had similar changes in magnitude. The highest production rates of odorous compounds (VFA, TOA, TIP and BODs), in both cattle and pig slurry, occurred during the first 10 weeks of storage; and their production rate increased with temperature, but with only a small effect being observed at 5^{o}C.

Two different treatment process configurations with 1 litre laboratory were studied. The process performed well in terms of odour compound reduction, especially with regard to almost complete (99%) removal of VFA and TIP of both pig and cattle slurries. The concentrations of Chemical Oxygen Demand (COD), Total Solids (TS) and Total Suspended Solids (TSS) reduction were predicted accurately using the input values for cattle and pig slurry in a mathematical model at 15 ^{o}C with 1 and 2 day residence times. Secondly, the changes in slurry characteristics of both feed slurry and mixed liquor (ML) were decreased by increased treatment duration during an aerobic treatment with recycling process. The oxygen requirement for these laboratory treatments was calculated at 4.9 kg $O_2.m^{-3}$ for cattle slurry (with TS 2.25% (w/v)) and 6 kg $O_2.m^{-3}$ for pig slurry (with TS 2.6% (w/v)).

Effective aerobic treatment of pig slurry was achieved, in terms of reduction in odour indicators (VFA, TOA, TIP and BODs), in a continuous farm scale reactor with a slurry recycling process. This treatment plant was built on a commercial pig farm with its existing facilities, and was designed to treat 455 m^3 of separated pig slurry with approximately 1% TS (w/v) to a target total VFA level of 500 $mg.l^{-1}$. The slurry was aerated by pumped recirculation through a venturi aerator where compressed air was entrained, and jet mixing by the returned stream maintained ML homogeneity. Aeration was controlled by a Proportion Integrated Derivatives (PID) control mechanism according to the set Redox value (<100 mVE_{cal}) during the first two trials. During a third trial, aeration was controlled to maintain a redox value between -150 to –200 mVE_{cal} at a fixed airflow of 1.18 $m^3.min^{-1}$. Oxygen consumption was calculated by the difference in total Chemical Oxygen Demand (CODw) between the feed slurry and the ML, with 1.7 kgO_2 being required to remove 1 kg of VFA in Trial 2, and 0.77 kgO_2 in Trial 3, from the reactor. The efficiency of the aerator was measured at different airflow rates with tap water in the reactor, and was found to vary between 0.8 and 1.4 kg $O_2.kWh^{-1}$.

Two aeration strategies (PID and fixed airflow controls) were carried out using similar starting concentrations of pig slurry in full farm-scale treatment trials. An energy cost saving of approximately 45% was achieved with a fixed airflow control compared with PID.

The regeneration of odour, in terms of VFA concentration, was found to be significant during anaerobic storage of treated slurry after both laboratory and farm scale treatment. The rate of odour regeneration was decreased by increased treatment residence times and by longer treatment periods, but increased with an increase in solids concentration.

Acknowledgements

I would like to acknowledge the advice and assistance of the following:

I am most grateful to Drs I.F. Svoboda and G. Sym for their supervision and provision of resources throughout the course of this research and particularly to my supervisor, Dr Svoboda for his inexhaustible advice, encouragement, patience and enthusiasm during the preparation of this thesis.

I would like to thank all the staff at the Farm Energy Centre for their kindly advice and technical support, particularly Mr Tim Pratt, David Burgess, Stephen Bettany and Andrew Kneeshaw. Special thanks go to Mr Pratt for his seemingly inexhaustible supply of technical advice!

I would also like to thank my colleagues in the Environmental Protection Group and Department of Engineering and Mechanism at SAC, Auchincruive for their analytical and technical assistance, especially Messrs J. Clark, K. Avdic, B. Laird and A. Gillespie.

I am also grateful to Professor G.N. Foster for his moral support during the final phase of my work.

I must also thank my family (especially my parents and sisters) for their continual support and encouragement. Also wish to thank all my friends and acquaintances for their spiritual support, particularly, Ah Pit, Wong Chung, Chiu, Pang Pang, Chai-yen, Andre, Jean Marc, Adrianne and the Friday basketball team.

Finally, many thanks to E.A. Technology Ltd (Farm Energy Centre) whose funding made this project possible and a special thank to The Scottish Agricultural College who provided the valuable facilities for the duration of this study. The Scottish Agricultural College receives financial support from the Scottish Executive Rural Affairs Department.

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Nomenclature

β	Beta factor-(Cs in slurry/Cs in clean water)
α	Alpha factor- (K_La in slurry/ K_La in clean water)
θ	Temperature correction factor
a	Specific interfacial area
η	Aeration efficiency
ASP	Activate sludge process
BOD_5	5 day biological oxygen demand
$C(O_2)$	Dissolved oxygen concentration
$C(O_{2,i})$	Dissolved oxygen concentration in the gas-liquid interface
$C(O_{2,l})$	Dissolved oxygen concentration in the liquid phase at equilibrium
$C(O_{2,s})$	Dissolved oxygen concentration was absorbed by microbial floc.
C_L	Local dissolved oxygen concentration in liquid
COD	Chemical oxygen demand
Cs	Saturation concentration of dissolved oxygen
CSTR	Continuous stirrer tank reactor
dC/dt	Rate of change of dissolved oxygen concentration
DO	Dissolved oxygen
FAS	Ferrous ammoniacal nitrogen
GC	Gas chromatograh
hr	Hour
ID	Inner diameter
Kj-N	Kjeldahl nitrogen, (total nitrogen)
K_L	Mass transfer coefficient in liquid phase
K_La	Volumetric overall mass transfer coefficient in liquid phase
$K_La_{(20)}$	K_La at 20°C
$K_La(T)$	K_La at a temperature of T°C
kW	Kilowatt
kWh	Kilowatt hour
ML	Mixed liquor or treated effluent slurry
mV E_{cal}	Mini-volt and electrode potential in Calomel
N	Nitrogen
n	Number of the measurement

NH_4^+-N	Ammoniacal nitrogen
NO_2^-	Nitrite
NO_3^-	Nitrate
O_2	Oxygen
OC	Oxygenation efficiency
OD	Outer diameter
Organic-N	Organic nitrogen
OT	Oxygen transfer
OUR	Oxygen uptake rate
P	Pressure
$P(O_2)$	Oxygen pressure in the gas phase
$P(O_{2,i})$	Oxygen pressure in the gas -liquid interface
PID	Proportion Integrated Derivative
Poly	Polynomial trendline
PLC	Programmable logical controller
Q	Power consumption
r	Microbial respiration rate
R	Residence treatment time
rpm	Revolutions per minute
S.D.	Standard deviation
SOTE	Standard oxygen transfer efficiency
t	Storage time
T	Temperature
TIP	Total indoles and phenols
TOA	Total organic acids
TS	Total solids
TSS	Total suspended solids
V	Volume of aeration tank
VFA	Volatile fatty acids
VS	Volatile solids
VSS	Volatile suspended solids
w	Whole or total
w/v	Weight per volume

Subscripts

f	Feed or input
s	Supernatant or soluble
L	Liquid phase
i	Interface
5	Five days

PART A: BACKGROUND TO THE AEROBIC CONTINUOUS CULTURE TREATMENT AND ITS APPLICATION TO LIVESTOCK SLURRY

1. INTRODUCTION

1.1 Legal constraints and social aspect

Intensive farming practices can lead to significant environmental pollution problems with air, water and soil quality. This result from high production of livestock slurry within small areas and increasing the ratio of the number of farm animals housed to the land area available for spreading (Sutton *et al.*, 1990). In particular, pig farming produces more than 8 million tonnes of waste (MAFF, 1998b), mostly as slurry, each year in the UK.

In recent years, there has been increased pressure on farmers to control pollution incidents arising from the storage and handling of livestock wastes. Environmental Health Officers (IEHO, 1991) reported that odour from storage and land spreading of pig and cattle slurry have been the major causes of nuisance. The number of odour complaints registered by the local authorities in England & Wales (EA, 1991) is shown in Table 1.1. Approximately 64% of the complaints about pig farming were associated with the odour of pig slurry, and 74% of the complaints about cattle farming were due to the odour of cattle slurry (MAFF, 1998a). The impact on the environment from the malodour pollution is minute compared to the damage related to the penetration of wastes into watercourse. Water pollution incidents recorded by the River Purification Boards (Virtue, 1993) and SEPA (1999) in Scotland and are illustrated in Table 1.2. Also, 11% of all reported total agricultural water pollution incidents (E.A, 1998) were caused by livestock slurries. These pollution problems have led scientists and engineers to research and develop new handling and treatment techniques for livestock wastes. Aerobic treatment of livestock slurries has been recognised as one of the most effective processes for odour removal.

Therefore, for the scope of this study reference is made specifically to cattle and pig slurry and is mostly concerned with the reduction in odour offensiveness and with the reduction in the water polluting potential by aerobic treatment.

Table 1.1 Number of public complaints for odours from livestock farming in England and Wales, 1986-1989 (Hissett, 1991).

Cause	1986/87	1987/88	1988/89
Cattle – Building	28	32	29
Slurry /manure storage	75	70	70
Slurry/manure spreading	99	120	130
Pigs – Buildings	115	116	136
Slurry/manure storage	119	119	119
Slurry/manure spreading	292	348	314
Feed products	54	142	24
Poultry – Building	164	133	170
Slurry/manure storage	59	46	51
Slurry/manure spreading	118	84	131
Feed production	18	5	1

Table 1.2. Water pollution incidents from livestock farming in Scotland 1991,1992 and 1999

Source	1991*	1992*	1999**
Cattle housing and yard	30	31	31
Piggery and yard	5	13	8
Slurry store	41	39	29
Dungstead	15	39	29
Dairy premises	34	16	8
Silage effluent	270	138	101

*(Virtue, 1993)
**(SEPA 1999, SAPG)

1.2. Why use aerobic treatment?

The main reason for using aerobic treatment, is in its ability relatively quickly to remove offensive odour as well as to reduce the risk of water pollution (Vetter & Steffen, 1981). Also it can be used to manipulate the nitrogen component of slurries, either to convert surpluses to harmless nitrogen gas, or to stabilise volatile forms, i.e. ammonia emissions (Pain *et al.*, 1989) and to minimise the spread of disease to animals and humans.

Large numbers of aeration processes have been investigated (Evans *et al.*, 1983; Sneath, 1978; Svoboda, 1993, Williams *et al.*, 1989; Burton & Farrent, 1998). Although some of the farms utilised this process, it may not be always represented the

best and final solution mainly due to the economic and management difficulties. It can cause problems for aeration equipment performance due to large variations of biological, chemical and physical characteristics of slurries (i.e. bacteria, COD, BOD, solids). Therefore, choice of aerator is significant. In a review paper of slurry aeration, Cumby (1987c) reported on the performance of aerators. Other experimental data are reviewed to identify the major factors influencing efficiency. Improvements and a development in aerators (Admed, 1974; Sneath, 1978; Bloxham, 1996) and process configuration (Woods & O'Callaghan, 1974; Sneath *et al.*, 1992; Burton & Farrent, 1998) design have come about largely through empirical assumptions, trial and error and some comparative testing. This approach has serious limitations because little knowledge is gained of the fundamental characteristics of aerator performance, which would enable designs to be optimised for livestock wastes. Cumby (1987c) has described a wide range of aerators showing large variation in performance; such equipment is only suitable for specific duties. A similar situation exists with a wide range of options, because the most favour an aerobic treatment process. This may be batch or continuous configuration, may operate at thermophilic, mesophilic and psychrophilic temperatures, high or low aeration rates, and with long or short retention times. These correspond to the initial aerobic reactor design taken into account of oxygen requirement, treatment time, dissolved oxygen level and the reaction temperature. Therefore, in deciding the best process, the problems of waste characteristics and its management must first be accurately identified and the required treatment defined.

1.3 Statement of Hypothesis

The aim of this research was to investigate the design criterion of the practical and most effective continuous biological aeration system for livestock slurries which would minimise offensive slurry odour and provide long term odourless storage. The design of an aerobic culture reactor was based on the hypothesis of laboratory trials and on previous research (Admed, 1974; Sneath, 1978, Morgan *et al.*, 1983; Bruxelmane, 1981; Sneath *et al.*, 1992, Allen, 1996; Burton & Farrent, 1998).

The final aeration system was concluded to use a venturi jet aerator. It is well known that the jet aeration is one of the most efficient systems for waste treatment. The

advantage of aeration by the venturi jet invites its application to the livestock waste and fermentation industrial effluent treatment processes, especially waste treatment since the treatment of waste has no return to waste producing agencies. The advantages other than simplicity are (a) free oxygen from the atmospheric air is used, (b) the venturi system provides both aeration and mixing, (c) venturi system requires less maintenance and is easy to handle.

This project consisted of three practical experiments and had the following objectives:

a) Literature review:

1. Carry out the research of current knowledge on biological aerobic treatment of livestock liquid wastes.

2. Identify the basic engineering systems used in waste treatment, which are used in industries as well as in agriculture, and investigate innovations and assess how these may impact on the system to be considered for full scale process.

b) Anaerobic storage:

1. Investigate the changes of characteristics in liquid phase of livestock slurries under anaerobic storage at different temperatures, which would model the average temperatures in Scotland and England.

2. With respect to the design of a practical on farm system, make assumptions: a) about the design of an 'ideal' system and b) how it would integrate with current on farm slurry storage and distribution system.

c) Laboratory scale reactor:

1. Design the optimal operating parameters for laboratory continuous aeration system, with the aim to develop the most efficient and low capital cost reactor for agricultural sector.

2. Investigate the fundamental quantity of oxygen required for livestock waste treatment by considering the requirements for partially treated and then stored slurries. This study will be based on data obtained from the current and previous experiments with the continuous aerobic system.

d) Full farm scale reactor:

1. Design the aeration components with capability to cope with different strengths and natures of slurries.

2. Design, build and assess a full-scale continuous flow (culture) aerobic reactor for a practical and affordable treatment of livestock slurries in order to reach the target level of odour offensiveness.

2.1 LIVESTOCK SLURRIES

2.1.1 Introduction

An understanding of the characteristics of waste allows a decision to be made on the design and optional type of treatment process. This leads to the option of reuse of waste liquids for transport of raw products, recovery of a specific waste component, irrigation, by-products development, and fertiliser value. The fertilising value of slurries or farm yard manure (FYM) should be recognised in order to minimise inputs of inorganic fertiliser to arable or grass producing farms (Svoboda & Jones, 1999). Livestock manure are continuously produced from livestock farming. The quantity and quality affect the complexity and size of any waste treatment systems as well as any recovery opportunities.

Wastes produced by agriculture or related industries vary in quantity and quality. Food processing effluents are often low strength, high volume liquid wastes. Conversely livestock slurries tend to be high strength, relatively low volume liquid wastes. The total quantities and characteristics from raw manures from piggery, cattle and poultry, consisting of faeces, urine, water and bedding materials can be estimated from the number of animals, their weight, food and water consumption and bedding material requirement (Svoboda, 1989). Characteristics of livestock of undiluted raw waste was described by Svoboda (1995) and are shown in Table 2.1.

Table 2.1 Characteristics of pig and cattle slurry (Svoboda, 1995)

Parameter	units	Pig	Cattle
Total solids, TS	$g.l^{-1}$	100	100
Volatile solids, VS	$g.l^{-1}$	83	85
Total suspended solids, TSS	$g.l^{-1}$	87	84
Chemical oxygen demand, COD	$g.l^{-1}$	134	140
Biochemical oxygen demand, BOD_5	$g.l^{-1}$	35	23
Total nitrogen, Tot-N	$g.l^{-1}$	8	4
Organic nitrogen, Org-N	$g.l^{-1}$	4	3
Ammoniacal nitrogen, NH_4^+-N	$g.l^{-1}$	4	1
Phosphate, PO_4^{3-}	$g.l^{-1}$	4.5	2
Potash, K_2O	$g.l^{-1}$	3.4	5

2.1.2. Slurry characteristics

The properties of livestock slurry can be classified as physical, chemical, and biological; some of them are shown in Table 2.1. Physical properties such as viscosity, density, conductivity, etc. were described by Hester (1987). The chemical composition together with biological properties were studied by many researchers (O'Callaghan *et al.,* 1971; Barth, 1985; Paul & Beauchamp, 1989; Williams, 1981; Spoelstra, 1980). Physical, chemical and biological characteristics are known to be affected by the physiology of the animal, the feed ration and the living environment (i.e. temperature and humidity), and the amount of water added from washing and leakage. For example, the chemical characteristics of pig slurry depend on the composition of the diet as regards to protein, fibre and oil content. Approximately 30 % of the consumed feed is converted to body tissue, and the remainder is excreted as urine and manure (see the slurry production estimation in Appendix A1 & A2). Chemicals used as growth promoters, such as copper, zinc and antibiotics will be presented in the waste either being excreted by animals or derived from feed gaining access from spillage. The volume of slurry arising depends on the quantity and digestibility of food eaten, and volume of water used, i.e. washing and drinking. These factors will affect parameters like concentration of total solids (TS), total suspended solids (TSS), volatile solids (VS), volatile suspended solids (VSS), the viscosity, capillarity suction time (CST) and particle size distribution (Hester, 1987).

Typically, cattle slurry contains 13-20% dry matter (w/v); pig slurry 6% dry matter (w/v) and poultry waste contains the highest dry matter, up to 25% (w/v) (Hester, 1987). Loehr (1984) gave guide values for the average daily production of about 0.005 m^3 slurry per 50 kg pig, of which contained 5-9% total solids, of these, 83% were volatile solids. MAFF (1998b) reported that a 130 - 225 kg sow and litter produced 10.9 litres per day, with a 94 % moisture content. From the data of PEPFAA (SOAEFD, 1997) and MAFF (1998b), an estimation of a typical farm of 200 sows will produce about 12.5 m^3 per day of slurry with approximately 10 % of dry matter (w/v). Typical characteristics of excreta from fattening pigs (average body weight 60 kg) are given in Table 2.2.

An average dairy cow will produce between 14,000 and 18,000 kg of manure per year (Loehr, 1984). The dry matter of the manure will be approximately 140 - 180 kg per 1000 kg, which contain about 4.5 kg nitrogen, 1.8 kg phosphate (P_2O_5) and 4 kg Potash (K_2O) in each 1000 kg of wet manure defecated by the cow. MAFF (1998b) reported that a 450 - 650 kg dairy cow typically produced of 53 litres per day of excreta, which contained 90 % moisture. PEPFAA code (SOAEFD, 1997) and MAFF (1998b) reported that a 100 dairy cattle farm will produce about 3290 m^3 of slurry per year (including washing water and rain water) (Appendix A2).

Table 2.2. Concentration of main components of whole and supernatant pig slurry expressed as a percentage of the total solids value (Evans *et al.*, 1978)

Component	Whole (% TS w/w)	Supernatant (% TS w/w)
Volatile solids	82	9.7
Suspended solids	86	-
COD	133	17
BOD_5	35	12.5
Total nitrogen	6.6	2.1
Organic nitrogen	3.4	0.5
Ammoniacal nitrogen	3.2	1.6
Phosphorous (P)	2.0	0.5
Potassium (K)	2.2	1.8
Copper (Cu)	0.04	0.002
Zinc	0.14	0.003
Calcium	1.5	0.2
Magnesium	0.76	0.04
Chlorine	0.6	-
Sulphates	0.5	-

A more comprehensive list of characteristics was compiled from Portuguese pig farms. A series of 25 farms was randomly selected within the most significant pig producing areas in Portugal (Roberto & Bicudo, 1996). Grab samples were taken at the inlet and outlet of each process unit and analysed in terms of a series of physicochemical and microbiological parameters. Raw piggery slurry characteristics are illustrated in Table 2.3.

Table 2.3. Raw piggery slurry characteristics in Portugal (Roberto & Bicudo, 1996)

Parameter	Mean	Min.	Max.	95% confidence interval
PH	7.72	6.50	9.08	7.44; 8.0
Temperature (°C)	19.2	13.2	25.5	18.0; 20.4
Conductivity ($mS.cm^{-1}$)	15.5	2.0	33.0	12.6; 18.4
Redox Potential (mV)	-300	-431	-2	-363; -237
DO ($mgO_2.l^{-1}$)	0.9	0.0	8.2	0.0; 1.8
TS ($mg.l^{-1}$)	18572	1165	62440	12872; 24272
TVS ($mg.l^{-1}$)	12176	840	44090	7981; 16371
TSS ($mg.l^{-1}$)	13282	310	67350	5709; 20855
VSS ($mg.l^{-1}$)	10490	283	48850	4652; 16328
Alkalinity (mg $CaCO_3.l^{-1}$)	7381	898	22241	5581; 9181
COD Total (mg $O_2.l^{-1}$)	37400	2191	131648	23027; 51773
COD soluble (mg $O_2.l^{-1}$)	15033	1594	62208	8990; 21076
BOD_5 total (mg $O_2.l^{-1}$)	10293	825	41800	1603; 18983
BOD_5 soluble (mg $O_2.l^{-1}$)	5515	635	20950	1366; 9664
N-total (mg $O_2.l^{-1}$)	2380	285	6840	691; 4069
NH_4-N (mg $N.l^{-1}$)	2193	253	9719	1307; 3079
PO_4-P (mg $P.l^{-1}$)	936	23	3340	551; 1321
K (mg $K.l^{-1}$)	1737	153	5860	1212; 2262
Na (mg $Na.l^{-1}$)	395	64	1080	290; 500
Cu (mg $Cu.l^{-1}$)	70	3.6	179	52.7; 87.2
Zn (mg $Zn.l^{-1}$)	26	6.6	62.6	19.5; 32.5
Faecal coliforms (MPN/100 ml)	$2.1*10^7$	$4*10^5$	$1.6*10^8$	$6.4*10^6$; $3.6*10^7$
Faecal streptoccoci (MPN/100 ml)	$2.7*10^7$	$1.2*10^6$	$1.3*10^8$	$1.5*10^7$; $3.9*10^7$
Clostridia (cfu/100 ml)	$4.4*10^5$	$1*10^4$	$3.2*10^6$	$9.2*10^4$; $7.9*10^5$

2.1.3 Slurry storage

Storage of slurries plays an important part in the overall slurry management, particularly in connotation with water pollution. According the Control of Pollution (Silage, Slurry and Agricultural Fuel Oil) Regulations 1991, slurry must be kept in a reception pit or slurry storage reservoir, which is normally a lagoon, pit or above-ground circular tank used for the storage of slurry (MAFF, 1998b). Normally the standard requirement for slurry storage is 6 months in Scotland (SOAEFD, 1997) and 4 months in England and Wales (MAFF, 1995) before spreading, unless the Farm Waste Management Plan (FWMP) can prove that a shorter time storage will not cause pollution. The legislation concerned (MAFF, 1998a & 1998b; SOAEFD, 1997) further assumes, that the storage system was designed and maintained correctly to prevent pollution of aquatic environment. SEPA (1999) reported that there were

23 operational failures and 6 events of a structural failure which caused water pollution from the slurry storage during the year 1999.

Emissions of offensive odour and ammonia from stores of livestock slurries pose another environmental problem. This was brought to attention by a number of researchers (Olsen & Sommer, 1993; Burton & Sneath, 1995; Williams & Nigro, 1997; Burton & Farrent, 1998; Hobbs *et al.*, 1999; Hussey *et al.*, 2000) and studied recently by MAFF (1998a & 1998b). Williams & Nigro (1997) reported that about 9% of ammonia emission from UK agriculture come from slurry storage. There were offensive odour complaints caused by farmyard odour from pig units, and 36% originated from slurry storage. However, slurry storage can be used as temporary holding period for many types of aerobic treatment systems. Especially in the continuous aerobic treatment, storage is an important stage to hold a large amount of raw and treated slurry.

During the aerobic treatment process of animal slurries, anaerobic microbial activity sometimes occurs. This is because of incomplete mixing or aeration deficiency. The predominant groups of bacteria involved in anaerobic metabolism are fermentative bacteria, hydrogen-producing acetogenic bacteria, and methanogenic bacteria. The fermentative bacteria hydrolyse and convert carbohydrates to organic acids, alcohols, hydrogen, and carbon dioxide as well as converting proteins and fatty materials into simpler compounds. The hydrogen-producing acetogenic bacteria convert the alcohols and organic acids produced by the fermentative bacteria to acetate, carbon dioxide and hydrogen. The end products are methane and carbon dioxide which result from the methanogenic bacteria activity. The incomplete methanogenesis, in particular fermentation terminated after the hydrolytic or acetogenic stage, results in formation of odorous organic compounds which give the characteristic offensive smells. This comes from dissolved organic compounds such as mercaptans, hydrogen sulphide, phenols, cresols, indoles and fatty acids, which normally can be found in the piggery slurry, but less in cattle slurry. Another 100 more offensively odorous organic compounds have been listed by O'Neill & Phillips (1992).

Besides, anaerobic degradation of slurries by microbes using chemically bound oxygen will reduce sulphate ions into hydrogen sulphide gas and will form another offensive odorant.

2.2 Aerobic treatment

2.2.1 Introduction

Biological aerobic treatment methods used for treating polluted effluents, municipal sewage, food processing effluents, pharmaceutical waste and other industrial effluents can be effectively applied to the treatment of concentrated animal slurries but modifications or an adaptation of the process are required to accommodate the characteristics of these concentrated wastes. Aerobic treatment was used in different configurations to treat the animal slurries especially the pig slurry, for many years (Baxter *et al.*, 1966, Converse *et al.*, 1971, ten Have, 1971, Owens *et al.*, 1973). The treatment methods have been continuously upgraded and optimised to meet the environmental requirement and economical targets (Sneath, 1978; Ritter, 1990; Burton, 1992 & 1997a). Many reports (Evans *et al.*, 1983; Williams *et al.*, 1989; Burton, 1992; Burton & Farrent, 1995; Burton *et al.*, 1998), indicate that the aerobic biological treatment process was the most effective treatment for odour, high COD and BOD.

Aerobic treatment requires a shorter time than an anaerobic digestion to break down the organic matter. When slurry is sufficiently aerated with air or pure oxygen in the completely mixed system, the high aerobic microbial activity (Hissett *et al.*, 1975) provides an intensive oxidative metabolism. This results in degradation of organic compounds including the reduction of concentration of odorants (Williams, 1981). Furthermore, when the carbonaceous components (BOD and COD) of more readily biodegradable materials are consumed, the stability of slurry is increased (Williams *et al.*, 1989). The amount of pathogens and parasites can also be reduced in the aerated slurry, particularly at elevated temperatures (Robinson *et al.*, 1971; Ruprich and Strauch, 1984; Svoboda *et al.*, 1997).

2.2.2 Objectives of aerobic treatment.

The objectives of livestock slurry aerobic treatment can be summarised as follows:

1) to remove the slurry offensive odour
2) to stabilise the slurry carbonaceous compounds
3) to control the amount of nitrogen
4) to reduce the number of pathogens

The key factor in achieving these objectives is adequate aeration and mixing. Therefore the aeration system must be correctly designed in order to transfer sufficient quantity of oxygen to the slurry to satisfy the oxygen uptake rate of microbial activity in the slurry.

2.2.2.1 Control of odour offensiveness

Livestock slurries contain quantities of compounds which result from anaerobic metabolism of food in the animal gut. Many of these compounds (Ritter 1989), being in their reduced chemical state, are very odorous (Appendix A3) and their odour can be expressed as an Absolute Threshold Concentration (ATC) (Loehr, 1984). The ATC is a minimum concentration of a volatile compound (Table 2.4) detectable by members of a sensory testing panel. This is an olfactometry method but it is rather expensive.

Table 2.4. Absolute threshold concentrations for various compounds
(From Neufield, 1975; Henry & Gehr, 1980)

Compound	Odour description	ATC (p.p.m.)
Ethyl mercaptan	Decayed cabbage	0.00032
Dimethyl amine	Fishy	0.04700
Skatole	Faecal	0.00120
Butyric acid	Sweaty	0.00100
Diallyl sulphide	Garlic	0.00014
Valeric acid	Sweaty	0.00062
Dimethyl sulphide	Decayed vegetable	0.10000
Hydrogen sulphide	Rotten eggs	0.00110
Crotyl mercaptan	Rancid	0.00003

Spoelstra (1979 & 1980) and other researchers (Williams, 1984; O'Neill & Phillips, 1992) have also identified compounds mainly in pig slurry that were considered responsible for the offensive quality of the odours. Some of these odorous compounds, volatile fatty acids (VFA) and total indoles and phenols (TIP), being in relatively large quantities and easily identifiable, were later used as offensive odour

indicators (Williams, 1983 & 1984; Thacker & Evans, 1986). Williams (1981) found that the distributions of VFA components in both separated and unseparated slurry were almost identical; acetic 50%; propionic 18%; Iso-butyric 2%; N-butyric 23%; I-valeric 6%; N-valeric 2%. He also attributed offensiveness to other soluble compounds particularly p-cresol, phenol, skatole, indole, O-ethyl-phenol.

Williams (1984) demonstrated that the VFA concentration is a good indicator of odour offensiveness, and he derived the odour offensiveness rate category scale of 0 to 5 as shown below:

0 Inoffensive odour
1 Very faintly offensive odour
2 Faintly offensive odour
3 Definitely offensive odour
4 Strongly offensive odour
5 Very strongly offensive odour

High odour offensive rating corresponded to the high concentration of VFA. A linear equation (2.1) to describe the relationship of offensiveness odour on a scale 0 to 5 with concentration of VFA was derived from experimental data and developed by Williams (1984). The VFA concentration of 0.23 $kg.m^{-3}$ indicates an acceptable offensiveness (rating 2), whilst at the VFA concentration of 0.52 $kg.m^{-3}$ the offensiveness is classified as already unacceptable (rating 3). Concentrations lower than 0.52 $kg.m^{-3}$of VFA have been used therefore as a limit of tolerable pig slurry odour treated by a continuous aeration (Sneath *et al.,* 1992; Burton & Sneath, 1995).

$$\text{Odour offensiveness} = 1.91 \times \log_e(1.2\ VFA + 0.21) + 3.34 \qquad \text{Equation (2.1)}$$

Biological (aerobic and anaerobic) and chemical treatment processes were identified as possible means for reducing the slurry offensive odours (Williams, 1984; Thacker & Evans, 1986; Pain *et al.,* 1987; Burton, 1997b). Although the chemical processes would be expensive for reducing the odour offensiveness and may induce additional pollution problems, they could be used as a back up or emergency service according

to Burton (1997b), who reviewed different chemical processes for waste management. The odour controlled by chemical additives was proved to be more effective than bacterial or enzymatic preparations (Pain *et al.*, 1987).

Although both the aerobic and anaerobic treatments can remove or reduce the odour offensiveness, aeration is regarded as the most effective option (Pain *et al.*, 1990) for controlling odour offensiveness. Aerobic treatment can be carried out either by a batch, fed-batch or a continuous process. The continuous treatment process which can certainly render piggery slurry inoffensive, is more controllable and effective option, in term of oxygen requirement as it was demonstrated by laboratory (Evans *et al.*, 1986) and pilot scale (Williams *et al.*, 1989) experiments. In a farm scale continuous treatment plant trial (Sneath *et al.*, 1992), it was found out that the VFA concentration of treated slurry was reduced to an average of 1 %, 6 % and 7 % of the raw slurry values, in a 4, 2 and 1 day residence time runs respectively. The reduction of VFA concentration approached 100% in another continuous treatment plant trial (Burton *et al.*, 1998). The Farm Energy Centre trials of different full scale aerators (Allen, 1996) also indicated that the VFA concentration could be reduced in short time. Although slurry offensive odour can be removed in a short time of two to three days of continuous aeration (Thacker & Evans 1986; Williams *et al.*, 1989) a longer treatment is required to stabilise the slurry and thus to prevent a rapid odour regeneration during following slurry storage.

2.2.2.2. Stabilisation of carbonaceous compounds

While readily biodegradable carbonaceous compounds in slurry are oxidised by a short terms aeration a large proportion of less biodegradable compounds, still contained within the slurry, presents a risk of pollution to water from livestock manures when they find the access to aquatic environment. This potential risk can be minimised by reduction of the strength of manures carbonaceous compounds, expressed as COD and BOD.

A laboratory continuous culture system has been developed and modified (Owens & Evans 1972). Aerobic reactors of maximum volume 15 litres were fed with pig, cattle or poultry slurries of about 29 $g.l^{-1}$ of total solids (TS), and the treatment time, temperature, DO concentration and redox potential were all controlled, and the

systems were run on a similar working principle to that of a chemostat (Owens *et al.*, 1973). Williams *et al.* (1989) found that COD and BOD could be reduced by 21-38 % and 46-85% respectively with residence times of 1 to 4.5 day in a continuous aerobic pilot scale system, while the destruction of VS and TS were 2 to 20%. In the same piece of work, they concluded that the stability of the treated slurry was directly related to the residual biodegradable COD. In the Farm scale experiments (Svoboda, 1993) reported that COD was reduced by 40 to 50 % at low aeration rate. In another farm scale treatment plant trial (Bicudo & Svoboda, 1995) with intermittent-cycle extended-aeration rate, a 95% BOD_5 removal was observed.

In a batch culture experiments piggery slurry was treated at temperatures between 5 to 50°C and Hissett *et al.* (1982) showed that the oxygen demand peaked at the first 6 to 24 hours of aeration. The peak respiration rates of more readily biodegradable components were recorded between 35 °C and 40 °C, then decreased at 50 °C. This decrease occurred because of the presence of a less diverse microbial population at 50°C which was unable to degrade those organic components normally removed at lower temperature (Hissett *et al.*, 1982). It meant that the oxygen supply would be difficult to control in order to satisfy the oxygen demand of micro-organism at any time. On the other hand, a continuous culture system can be controlled more steady and easier than the batch (Chapter 2.3). The oxygen demand fluctuation and the culture of micro-organisms well adapted to the concentration of substrate and DO is developed, but the oxygen transfer would be also depended upon the various components (i.e. solids concentration) of the wastes.

In a continuous aerobic farm scale treatment, its process performance in term of COD reduction compared well with predictions made using data from laboratory and pilot-scale experiments (Evans *et al.*, 1983).

2.2.2.3. Modelling of carbonaceous compounds removal

The laboratory experiments with a continuous culture aerobic treatment of pig slurry (Evans *et al.*, 1979) generated results which were used to develop a mathematical model. It was derived on the basis of Monod kinetics (Monod, 1949), making an assumption of a constant specific decay rate for the endogenous respiration by micro-organism for the same range of temperatures. This model describes the effect of treatment time on characteristics of treated slurries (Evans *et al.*, 1979). The main characteristics parameters were TS, TSS, COD and a 5-day BOD of whole and separated slurry. They are inversely proportional to the mean residence treatment time at a particular treatment temperature range. These equations were further developed (Evans *et al.*, 1983) to describe the effect of treatment temperatures (Chapter 2.3), in addition to the mean residence treatment times, on the residual slurry quality and oxygen requirement. Equations for the three temperature ranges, psychrophilic, mesophilic and thermophilic, are described below.

Psychrophilic 15 °C

$$TS = [0.318/(1+0.14R)+0.707]\ TS(f) \qquad \text{Equation (2.2)}$$

$$TSS = [0.542/(1+0.14R)+0.526]\ TSS\ (f) \qquad \text{Equation (2.3)}$$

$$COD = [0.547/(1+0.14R)+0.379)\ COD(f) \qquad \text{Equation (2.4)}$$

$$BOD_5 = 2.969/R + 0.202BOD(f) \qquad \text{Equation (2.5)}$$

Mesophilic 25 -45 °C

$$TS = [0.262/(1+0.4R)+0.744]\ TS(f) \qquad \text{Equation (2.6)}$$

$$TSS = [0.282/(1+0.4R)+0.696]\ TSS\ (f) \qquad \text{Equation (2.7)}$$

$$COD = [0.333/(1+0.4R)+0.535]\ COD(f) \qquad \text{Equation (2.8)}$$

$$BOD_5 = 1.568/R + 0.152\ BOD(f) \qquad \text{Equation (2.9)}$$

Thermophilic 50 °C

$$TS = [0.450/(1+0.7R)+0.579]\ TS(f) \qquad \text{Equation (2.10)}$$

$$TSS = [0.405/(1+0.7R) +0.563]\ TSS\ (f) \qquad \text{Equation (2.11)}$$

$$COD = [0.429/(1+0.7R)+0.445]\ COD(f) \qquad \text{Equation (2.12)}$$

$$BOD_5 = 1.567/R + 0.152\ BOD(f) \qquad \text{Equation (2.13)}$$

The residual supernatant of 5-day biochemical oxygen demand (BOD_5s) of treated slurry was simply expressed as:

At 15- 45 ^{o}C

$$BOD_5s = 0.11/R \qquad \text{Equation (2.14)}$$

At 50 ^{o}C

$$BOD_5s = 0.042/R + 0.007\ BOD(f) \qquad \text{Equation (2.15)}$$

Where :

R = Mean treatment residence time, d

TS(f) = TS concentration in feed slurry, $g.l^{-1}$

TSS(f) = TSS concentration in feed slurry, $g.l^{-1}$

COD(f) = CODw concentration in feed slurry, $g.l^{-1}$

BOD(f) = BODw concentration in feed slurry, $g.l^{-1}$

Provided the dissolved oxygen concentration in the slurry was maintained above 1% of air saturation the oxygen flux to the microflora was sufficient and thus the degradation of carbonaceous compounds was mainly controlled by residence time and reaction temperature (Williams *et al.*, 1989).

2.2.3 Effect of treatment parameters

The effect of aerobic treatment on the characteristics of treated livestock slurry, as described by the model equations (Evans *et al.*, 1979, 1980, 1983), is clearly dependent on the three main factors: the mean residence time (treatment time), reaction temperature and the dissolved oxygen level in a continuous culture reactor.

The key part of design of treatment facility to aerobically process is the aeration stage. However, the design of many farm scale aerobic systems has often failed to use knowledge of the microbiology of the process (Loehr, 1984). The aeration capacity and the degree of degradation have frequently been underestimated or excessive. Therefore the effect of the treatment has been governed by a number of factors which were investigated and described in this section. The optimum microbial population and metabolic activity are then considered by the factors of mean residence time, reaction temperature and dissolved oxygen level in the continuous culture reactor.

2.2.3.1. Mean residence time

The residence time of slurry in the reactor is the key to the aeration process and is directly related to the size of a reactor and a continuous flow rate of slurry. The Monod model kinetics (Monod, 1949) described residence time as a function of microbial kinetic growth rate. The equations derived by Evans *et al.* (1979 , 1980 & 1983) and Williams *et al.* (1989) describe the degree of a breakdown of the organic matter (i.e. COD, BOD, TS) as inversely proportional to the residence time (Chapter 2.2.3). Burton *et al.* (1997a) reviewed the typical range of residence times from just below one day up to 30 days. With the minimum residence time, the reduction in concentration of organic matter can be achieved but only with little stabilisation and the offensive odour is likely to regenerate in a few days. Williams *et al.* (1989) found out that the treated pig slurry can be stored up to 10 days and 25 days without regeneration of odour after treatment at residence time of 1 and 4 days, respectively. Thus they correlated residence treatment time with the storage time (t) by a general equation:

$$t = AR + B \qquad \text{Equation (2.16)}$$

where t is the number of days that the treated slurry can be stored until regeneration of offensiveness odour to an acceptable level (as indicated by a VFA level above 0.23 $kg.m^{-3}$), R is the residence treatment time in day, A and B are constants which are dependent on the strength of slurry and aeration level used.

The drawback of the continuous culture system is associated with the problem of the biomass "washout" as it can be encountered with residence times less than 3 days. Particularly nitrifying bacteria (Smith & Evans, 1982) could be flushed out faster than they can grow. Thus a high aeration intensity (kg $O_2.h^{-1}.m^{-3}$ of reactor volume) is required to ascertain the rapid breakdown of the reactive materials in the process. Also, at the longer residence time, with low aeration intensities are generally provide sufficient amount of oxygen for biomass. However, one of the major disadvantages of longer residence time is that a larger reactor vessel is required and mixing may be insufficient.

2.2.3.2 Treatment temperature

The temperature dependence of the biological reaction rate constants is very important in assessing the efficiency of a biological treatment process. Temperature has a significant effect on metabolic activities of the microbial population (Monod, 1949; Stanier, *et al.*, 1986) as well as profound effect on such factor as oxygen transfer rate (Robinson, 1974; Cumby 1987a) (Chapter 2.4). Evans *et al.* (1983) found out there has been little effect on the breakdown of organic material during continuous treatment processes treating livestock slurries at temperatures between 25 and 45°C (mesophilic range). They suggested that a continuous culture process is controlled by nutrient limitation rather than by the metabolic rate of individual microbes. This work also showed that there is a substantial benefit, particularly during cold weather, from allowing the reactor content to self-heat and reach an equilibrium within the mesophilic range. The temperature increase of the reactor content is due to the heat released from aerobic metabolism (Cooney *et al.*, 1968). It has been demonstrated by several researchers (Hughes, 1984; Hemmersbach *et al.*, 1985; Baines *et al.*, 1986; Svoboda & Evans, 1987; Svoboda & Fallowfield, 1989; Svoboda, 1993) that about 15 MJ of heat can be released by aerobic bacteria from every kg of oxygen consumed (normally measured as COD). When minimally diluted pig slurry is aerated in an insulated reactor, using an efficient aerator the slurry temperature can reach over 50°C (Woods *et al.*, 1979; Svoboda, 1993).

At these higher treatment temperatures exceeding 40°C, referred to as thermophilic temperatures, typically 55 to 75 °C (Stanier *et al.*, 1971) the aerobic treatment can

offer a number of merits. (1) useful heat extraction, from treatment of pig slurry was confined to research and demonstration projects on some farms (Hughes, 1984; Baines *et al.*, 1986; Svoboda & Evans, 1987). These investigations were suggesting its practical use for larger farm. (2) A rapid pathogen reduction in slurries was demonstrated (Ginnivan *et al.*, 1981; Evans *et al.*, 1983; Oescher & Ruprich, 1989; Burton and Sneath, 1995; Skjelhaugen, 1999) at higher treatment temperature of thermophilic region. (3) The enhanced breakdown, in terms of COD removal had been proved by a numbers of researchers (Evans *et al.*, 1983; Burton & Farrent, 1995; Skjelhaugen, 1999). Evans *et al.* (1983) demonstrated that approximately 10 % more COD was removed at 50°C than 25 to 45°C which was due to increased cellulolytic activity.

Aerobic treatment at thermophilic temperatures have also some disadvantages when compared with mesophilic temperature treatment option : (1) Heat losses from the system are higher therefore the reactor requires insulation, i.e. increase of the capital cost. (2) The break down of cellulolytic material, which is otherwise degraded slowly at mesophilic or psychrophylic temperatures, thus posing a minimal pollution thread, requires additional oxygen to that of mesophilic treatment temperatures (Svoboda and Evans, 1987). (3) Nitrification of available nitrogen cannot be accomplished (Smith and Evans, 1982). (4) The soluble BOD of treated slurry at thermophilic temperature remains higher than when treated at mesophilic temperature which reflects in higher odour offensiveness (Evans *et al.*, 1986).

2.2.3.3 Dissolved oxygen (DO) level

The choice of aeration level is important in a design of an aeration system. The desired aeration levels are maintained in order to meet the treatment target levels, so that the treatment is more effective and not wasteful of energy. Aeration level is often defined by the concentration of dissolved oxygen, maintained in the aerated slurry. Cumby (1987a) reviewed the parameters affecting the dissolved oxygen level. It can be affected by a number of factors particularly temperature (Chapter 2.2.3.2), but also solids concentration and liquid surface tension. The DO level can be monitored and controlled by the measurement with DO or redox probes, a constant value is an indication of steady state system.

The aeration level can be divided into high, intermediate and low level (Burton, 1992). The high aeration levels are typically above 10% of dissolved oxygen saturation, intermediate corresponds to the levels between 1 to 10% (equivalent to redox values of -90 to +160 mVE_{cal}), and the low aeration level is when redox value below -90 mVE_{cal}. When the redox value is below -300 mVE_{cal}, the system becomes anaerobic. The result of a continuous treatment process can be affected by aeration levels in three aspects (Smith & Evans, 1982; Evans *et al.*, 1986; Williams *et al.*, 1989; Burton & Sneath, 1995; Burton, 1997b; Burton & Farrent, 1998):- (1) the extent of microbial activity; (2) determination of the fate of nitrogen; (3) the storage period of treated slurry free from offensiveness odour. This project is most concerned with the third aspect. Thacker & Evans (1986) reported that the odour became inoffensive when slurry was aerated with DO at 0.1% of saturation and redox value about 0 mVE_{cal} at 15°C for 2 days in a continuous culture reactor. The odour offensiveness increased as the redox potential values decreased (Evans *et al.,* 1986). By decreasing the redox potential from 0 to -500 mVE_{cal}, BOD_5s and TOA exponentially increased from values of around 50 $mg.l^{-1}$ to 2 $g.l^{-1}$ respectively (Evans *et al.*, 1986). The BOD_5 increased by up to 8 $g.l^{-1}$ over the value expected in slurry treated at DO concentration over 1 % saturation. Williams *et al.* (1989) further confirmed that the aerated slurries would have greater stability at a higher aeration levels than at the lower one.

2.3. Biological culture treatment processes

2.3.1. Introduction

The use of biological treatment processes depends upon an understanding of the kinetics of the processes and the effects of the environmental factors on the culture. Various options and configurations can be considered based on what each stage might achieve. The configurations, in many cases, (Wood & O'Callaghan, 1974; Burton and Cumby, 1995) will affect the scope of the process as well as the operation.

The main common process types of biological treatment for livestock wastes are batch, semi-continuous and continuous used as an activated sludge process.

2.3.2. Batch process

The principle of the batch process is based on a sequence of three basic operations: fill, react and discharge. The reaction process is an unsteady state operation where composition/concentration of the reactor content changes with time. Batch aerobic treatment process is the simplest method for treating animal wastes. However, perhaps this is not the best process, because it has the major drawback of an unsteady microbial population, oxygen demand and heat output, hence the treatment is inconsistent. In a typical batch process, the microbial activity rises rapidly to the peak, then declines as the amount of nutrients decrease in the slurry (Hissett *et al.*, 1982). The advantage of the batch aeration process has better pathogen control compared with other methods. Oechsner & Ruprich (1989) found that thermophilic batch aeration is able to reduce the count of faecal streptococci from $10^5 g^{-1}$ to 10^0 in 4 days. Also Bohm (1984) observed that the numbers of pathogen falls rapidly in batch aeration. Munch *et al.* (1987) observed in a batch-aerated vessel that the number of specific bacteria falls exponentially in a time of 0.3 to 1.0 weeks.

Hissett *et al.* (1982) found a ten-fold variation in respiration rate over the first 24 hours in a laboratory batch aeration trials. From this point, it might be difficult to predict the size of aeration device for the farm scale system. An inadequate aeration system would cause an incomplete aeration.

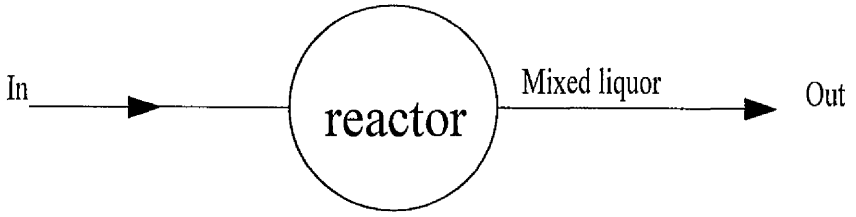


Figure 2.1 A straight through continuous treatment system

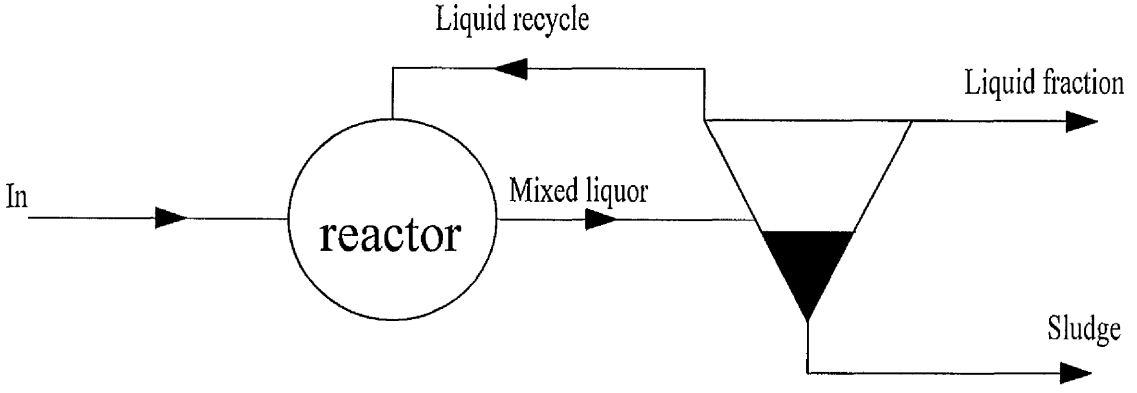


Figure 2.2 A continuous treatment system with separation and liquid recycle

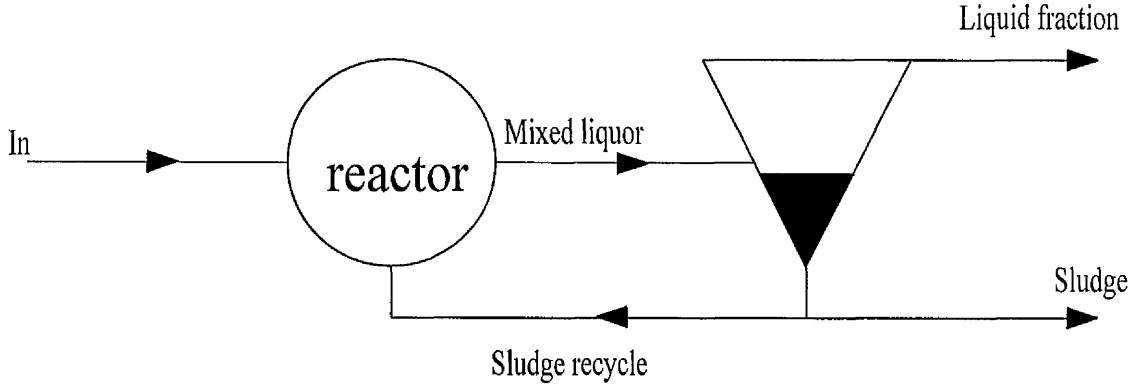


Figure 2.3 A continuous treatment system with separation and sludge (micro-organism) recycle

The generation of foaming may cause problems in batch aeration and generate a pressure head with the foam, this will reduce the air flow rate and mass transfer efficiency, resulting in a decrease in the aeration process as described by Nielsen *et al.* (1989).

2.3.3. Semi- continuous process

Semi-continuous or semi-batch (fed batch) process is characterised by the slurry either addition or removal from the reactor at a regular rate during the reaction period (Burton and Cumby, 1995). Semi-continuous process has a flexible control and is easier to set up, because the oxygen demand is steadier. Fed batch and sequencing batch reactor (SBR) system can be accounted as semi-continuous process. SBR has come into considerable attention since Irvine & Davis (1971) described its operation. Usually the SBR systems have five sequential steps as follows: (1) fill; (2) aeration (react); (3) sedimentation/clarification (settle); (4) draw (decant); and (5) idle; and the whole repeat cycle of operation lasts 4 to 24 hours.

Laboratory scale aerobic SBRs (Ng, 1987) were used to treat dilute and anaerobically digest piggery wastewater and this investigation showed that this process had a high treatment performance for BOD and ammonia removal. Wong *et al.* (1990) and Lo *et al.* (1991) reported that a very good quality effluent and both BOD_5 and suspended solids removal was obtained from a full scale SBR trial. Also SBR was successfully used to treat an agro-industrial (Ma *et al.*, 1986; Chin *et al.*, 1987) and municipal wastewater (Irvine *et al.*, 1985).

2.3.4 Continuous process

Continuous process involves a controlled addition of feed and removal of treated effluent at a constant flow rate, continuously, so that this process will achieve a controlled steady-state condition. Under such conditions, a consistent aeration, treatment and product of all slurry can be expected providing the system is well-mixed. Typical continuous aeration treatments were used with a Continuous Stirred Tank Reactor (CSTR). The configuration of this process can be varied, depending upon the treatment criterion or the individual farm waste management. The main common configurations for the continuous livestock wastes treatment were described by Woods & O'callaghan, (1974) and Burton & Cumby, (1995) and are illustrated in

Figures 2.1 - 2.3. Burton & Farrent, (1998) reported the use of a two-stage process as a better option than a single-stage, in term of organic matter removal in a pilot plant experiment trial.

Regular dosing and continuous aeration providing a system operates similarly to a chemostat which is likely to be cost-effective (Oleszkiewicz, 1985; Sneath, 1988; Williams *et al.*, 1989). Potential savings from the control and optimisation strategy will depend on the raw slurry characteristic. The power costs could be decreased by up to 90% with a controllable system in a continuous farm scale aeration plant (Burton & Sneath, 1995). The continuous culture process is more efficient than other processes because the population of micro-organism adapts to the physical and chemical environment within the reactor more readily, hence growth is maintained at a constant rate. The amount of nutrients is relatively low in the aeration vessel and microbial activity is limited. Thus this process is likely to be insensitive to the fluctuations of aeration level (Smith & Evans, 1982) and slurry temperature (Evans *et al.*, 1983; Cumby, 1987a).

Although the continuous process treatment is effective in controlling odour and carbonaceous material, it has to be less effective in controlling the amount of pathogens than in batch processes (Burton, 1992 & 1997b) due to the cross-contamination by the untreated slurry fed in.

2.3.5 Activated sludge process

Activated sludge process (ASP) is versatile and flexible, and in its simplest form it involves two stages: the first is aeration, usually by air, of effluent together with active biomass, and the second stage is the sedimentation which the solids (biomass) are separated from the liquid from the treated effluent. A fraction of this active biomass collected in the clarifier is recycled together with raw wastes to the aeration vessel or a lagoon (Metcalf & Eddy, 1991).

The application of the activated sludge process to the treatment of livestock slurries has been investigated by a number of researchers (Owens *et al.*, 1973; Baines *et al.*, 1973; Forster *et al.*, 1984; Johnestone, 1984; Hong, 1999; Chou *et al.*, 2000). However, activated sludge processes are rarely applied on livestock wastes due to a

required high dilution of influent, a high energy cost which is reflection of a high oxygen demand for wastes (high variable organic concentration) and skill and maintenance (Johnstone, 1984). Activated sludge process can be used for livestock slurries treatment if the system is modified such as contact stabilisation, extended aeration and the slurry is diluted to a certain strength (Loehr, 1984). Although the activated sludge process is not popular use with highly concentrated agriculture effluents, it has been used to treat the diluted livestock wastes recently (Gray *et al.*, 1991; Bicudo & Svoboda, 1995; Chou *et al.*, 2000; Osada, 2000), and is more widely used in other waste treatment industries, particularly in treatment of municipal sewage. Bicudo & Svoboda (1995) estimated that about 115 $kWh.d^{-1}$ of energy was consumed and total cost of US$2.50 per pig produced was required for running an activated sludge extended-aeration treatment plant for pig slurry.

2.4 Aeration treatment technology

This section reviews the available aerators used for the aerobic treatment of livestock wastes.

2.4.1 Introduction

The aeration method is dependent upon the process requirements and the slurry characteristics. If the aeration is inefficient, it can cause in some regions of the vessel deficiency of oxygen, and then it will make the treatment process worse. Additionally, poor mixing and the resultant foam can lead to an incomplete treatment of slurry. Therefore selection of the aeration devices is very important in a particular treatment system.

There are many aerators or aeration devices which were used for waste-water treatment industries, but not many are suitable for the treatment of livestock slurries. Gjervan (1982) discussed a number of aerators used in various processes for composting of livestock slurry. Cumby (1987c) also reviewed many slurry aeration devices in detail. The performance of the main types of aerators is shown in Table 2.5. Some aerators cannot be used for the slurry treatment without modification. The aeration devices can be catalogued into three main types:

(a) Mechanical aerators;
(b) Compressed air aerators;
(c) Combined compressed air and mechanical aerators.

Table 2.5. The performance of main types of aerators (Cumby, 1987c)

Type of aeration		Typical performance values		
		Efficiency, η ($kg\ O_2.kWh^{-1}$)	Capacity, γ ($kgO_2.h^{-1}$)	Intensity, I ($kgO_2.h^{-1}.m^{-3}$)
Mechanical:	surface	1.0 – 1.5	medium	high
	subsurface	0.5 – 1.5	medium	medium
	pumped liquid	0.5 – 2.0	low/medium	medium
Compressed air		2.0 – 5.0	variable	low
Combined air/mechanical		1.0 – 2.0	medium	high

For each type of aeration devices there are many different aerators, some of which were described by Admed (1974). Only the most popular and common aerators are discussed in this section.

Before selecting the aeration device, an understanding of oxygen transfer is particularly important in design and operation of biological system for livestock waste treatment. The theory and the factors affecting the oxygen transfer process are described below.

2.4.2 Oxygen transfer in biological system

The process of oxygen transfer in the biological system is behaved similar theory as mass transfer for chemical reaction (Coulson & Richardson, 1993).

The transfer of oxygen from the gaseous phase to the cell material (microbial culture) presented in the liquid is generally considered to take place in three stages as illustrated in Figure (2.4):-(1) Oxygen molecules are transferred from the bulk gas phase to the air/liquid interface, establishing a saturated oxygen layer at the interface; (2) Oxygen passes through interface by the relatively slow process of molecular diffusion; (3) Having passed through the interface, dissolved oxygen is then dispersed in the body of the liquid by further diffusion and by convective force, then oxygen is absorbed by micro-organisms. Each stage above presents a resistance to oxygen transfer to the cells as described by Richards (1961).

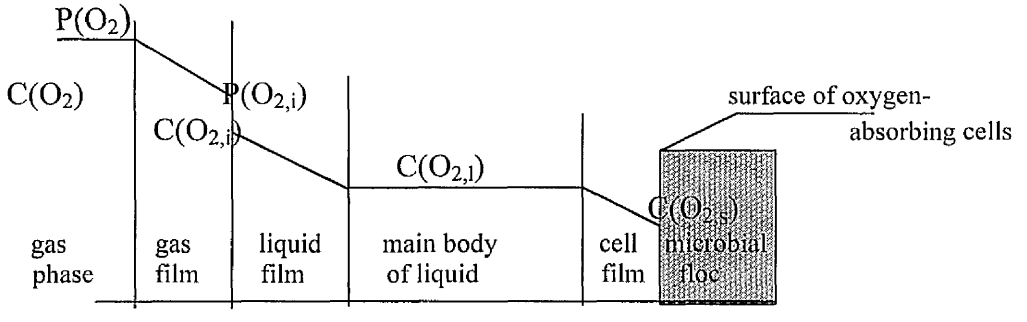


Figure 2.4 Schematic representation of a gas transfer to a liquid and oxygen absorption by microbial floc (Levenspiel, 1976. Chapter 13, Figure 7 modified).

Where

$P(O_2)$ is the gas pressure in the gas phase

$P(O_{2,i})$ is the gas pressure in the gas -liquid interface

$C(O_2)$ is the oxygen concentration

$C(O_{2,i})$ is the dissolved oxygen concentration in the gas-liquid interface

$C(O_{2,l})$ is the dissolved oxygen concentration in the liquid phase at equilibrium

$C(O_{2,s})$ is the dissolved oxygen was absorbed by microbial floc.

According to the two film theory, the rate of oxygen transfer in most practical aerobic treatment of slurries and wastewater can be estimated by a first order differential equation (Lewis & Whitman, 1924). Assuming the processes are under steady condition, resistance on the gas-film is negligible and only the oxygen transfer (OT) is controlled by diffusional resistance, then the equation is expressed:

$$dC/dt = K_L\, a\, (Cs - C_L) \qquad \text{Equation (2.17)}$$

Where dC/dt is the rate of change of dissolved oxygen concentration in liquid, $kg.m^{-3}.s^{-1}$

K_L is the overall liquid phase coefficient, $m.s^{-1}$

a is specific interfacial area, is the ratio of interfacial area per unit volume of liquid, $m^2.m^{-3}$

Cs is the saturation oxygen concentration in liquid at atmospheric pressure, $kg.m^{-3}$

C_L is the local dissolved oxygen concentration in liquid, $kg.m^{-3}$.

2.4.2.1 Factors affecting the oxygen transfer

However, the amount of oxygen is also continuously required for the microbial activity in the biological treatment system. Then the term of the microbial respiration rate (r) is added into equation 2.17 and becomes (Loehr, 1984):

$$dC/dt = K_La\ (Cs - C_L) - r \qquad \text{Equation (2.18)}$$

From the equations 2.17 and 2.18, the overall oxygen transfer rate shown is dependent on:-(a) K_La, is available interfacial area for the diffusion of oxygen, which is affected by the bubbles' size, the diffusivity of oxygen in the liquid. (b) Cs-C, is a driving force of the process, Cs is affected by temperature, dissolved material and pressure of air introduced to liquid, etc; (c) the microbial respiration rate (r), which is affected by the temperature, nutrients, and the population of active micro-organisms.

The rate of oxygen transfer that can be achieved in an aeration system is expressed in terms of oxygenation capacity (Heduit & Racault, 1983). It is a direct measurement of the system performance, by a specific aeration equipment under given operating conditions. Usually the unit of the oxygenation capacity is kilogram O_2 per hour ($kgO_2.hr^{-1}$) or milligram O_2 per second ($mgO_2.sec^{-1}$). The rate of oxygen transfer into the liquid or mixed liquor is expressed per unit energy by aeration equipment. It is generally referred to as aeration or oxygenation efficiency ($kg.O_2.kWh^{-1}$). It is another indication of aeration system performance that can be produced by a specific aerator.

The oxygenation capacity or efficiency of aeration equipment in the specific system that can be determined in water or slurry is described in Methods and materials (Chapter 3.17). The test is often expressed as standard oxygen transfer rate (SOTR) or efficiency (SOTE). However, the oxygenation capacity can vary for the same aerator under the variable process conditions in slurries. Therefore the equation (2.17) of oxygen transfer (OT) must be modified in order to obtained the actual oxygenation capacity. In fact, the modifications relate to the conditions of K_La, Cs and temperature. Thus the modification factors, α, β and θ were developed by (Stenstrom & Gilbert, 1981). Then the actual field oxygenation capacity can be calculated correctly by using these factors in order to adjust the different K_La, Cs and temperature. These factors, often called correction factors, are expressed as follows:

$$\alpha = \frac{(K_{La})s}{(K_La)w} \qquad \text{Equation (2.19)}$$

$$\beta = \frac{(Cs)s}{(Cs)w} \qquad \text{Equation (2.20)}$$

$$K_La_{(T)} = K_La_{(20)}\,\theta^{(T-20)} \qquad \text{Equation (2.21)}$$

Where

α = the ratio of the K_La in the slurry (K_L a)s to the (K_L a) in the clean water (K_L a)w at the same conditions of temperature, pressure, mixing characteristic, and vessel geometry. The typical value of α is between 0.3 to 1.2 for wastewater (Metcalf & Eddy, 1991). An average value of α in slurries of 0.5 was suggested by Vasseur & Laigneau (1975).

β is the ratio of the oxygen saturation concentration in the slurry (Cs)s at temperature T and normal atmospheric pressure to the oxygen saturation concentration in clean water at 20 C (Cs)w and atmospheric pressure. Usually the value of β is less than 1.0, as so many characteristics of slurries can decrease the oxygen saturation concentration. Eckenfelder & Barnhart (1961) reported that β factor is dependent on the composition of slurries such as solids concentration, surface active material, salts, etc. The typical value of β is 0.9 for wastewater (Metcalf & Eddy, 1991). θ is the temperature correction factor. It is exponential to the ratio of the oxygen transfer coefficient at local temperature T ($K_La)_T$ to the oxygen transfer coefficient at 20°C ($K_La)_{20}$. The commonly used value of θ is 1.024 in wastewater.

Much research has been done to investigate these correction factors in wastewater, but very little in livestock slurries. The data for the slurries are thus limited. However, the oxygen transfer is dependent on many other factors in slurries similarly to the wastewater, which mainly are physical, biochemical characteristics such as fatty acid concentration, soluble BOD, COD, viscosity, nature of solids etc. as investigated by a number of researchers (Scheltinga & Polelma, 1970; Baker, 1973;

Robinson, 1974; Evans *et al.*, 1979; Ellis & Stanbury, 1980; Hester, 1987). Besides, the types of aeration equipment significantly affect the oxygen transfer. For example, different aeration equipment were investigated on continuous treatment of pig slurry by Allen (1996) and Bloxham (1996); and the aeration efficiency and the percentage of oxygen transfer were shown on Table 2.6.

Table 2.6. Performance of aerators (Allen, 1996; Bloxham, 1996).

	Aerators type			
	Venturi	Surface	perforated pipe	Fine bubble
Aeration efficiency ($kgO_2\,kWh^{-1}$)	1.0	3.49	1.83	2.15
% O_2 transferred	34.6	NA	NA	32.3

Note: NA = No value available

Therefore, it is important to know the SOTR or SOTE before designing an aeration equipment, because the oxygenation capacity will provide a guideline to determine the size and the number of aerators that will be required for the treatment. Also aeration efficiency will govern the size of a compressor or motor and the rate of energy consumption required to achieve a given rate of oxygen transfer. It thus provides an estimate of capital and operating costs. Aeration efficiencies vary with different aeration devices. A range of aerators are described in the following section.

2.4.3 Energy consumption

Aeration is usually the major energy consuming process in a waste treatment system, so it is always an important issue related to the operation cost. This is due to the energy which is continuously required to transfer the required oxygen to meet the treatment criterion. Different aeration systems would require varying amounts of energy for supplying air. For instance, the energy used by the venturi system in a treatment plant was mainly required for the aeration pump and the blower while the minor ones were for foam breaker, separator, feed and discharge pumps. For example, Sneath *et al.*, (1990) estimated that about 90 % of electrical power was for slurry aeration pumps and the blower supplying compressed air to the venturi.

Higher power use of the shorter residence time is mostly a reflection of longer running time of the blower, and Sneath *et al.* (1990) also found that energy fell with

the shorter treatment to 30, 17 and 9 kWh.ton^{-1} of slurry for 4, 2, and 1 d runs respectively. Burton & Sneath (1995) found that between 50 to 90 % of the power costs can be saved in a controlled system compared with the uncontrolled system in which equipment runs continuously. The cost of energy can be reduced by improving the design and operation of aeration system (i.e. selecting more efficient machinery and minimising equipment use or improve the oxygen transfer). Cumby (1987c) reviewed the performance of a wide range of aeration equipment which were used for livestock wastes treatment. Typically, an aerator supplies 1 kg of oxygen per kWh power consumed. The efficiency of aerator (η) is normally calculated from the difference in COD (i.e CODin – CODout) over the power consumed by the compressor or blower. The equation normally used is as follows:

$$\text{Efficiency of aerator, } \eta = \frac{[COD]start - [COD]end}{Q} \qquad \text{Equation (2.22)}$$

Total power consumption:

$$Q = \text{power of blower} \times \text{Total aeration time} \qquad \text{Equation (2.23)}$$

where η, kg COD.kWh^{-1}
COD start, kg
COD end, kg
Power of blower, kW
Total aeration time, hr
Q, kWh

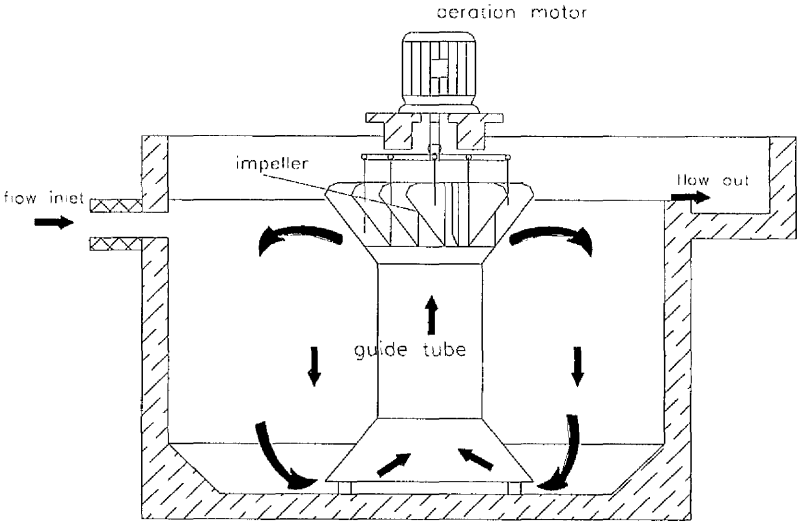


Figure 2.5. " Simplex" Vertical shaft surface aerator with guide tube

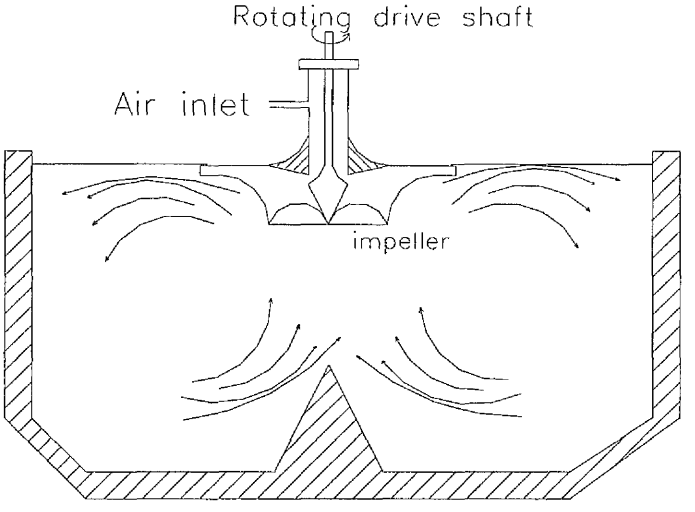


Figure 2.6. BSK turbine surface aerator

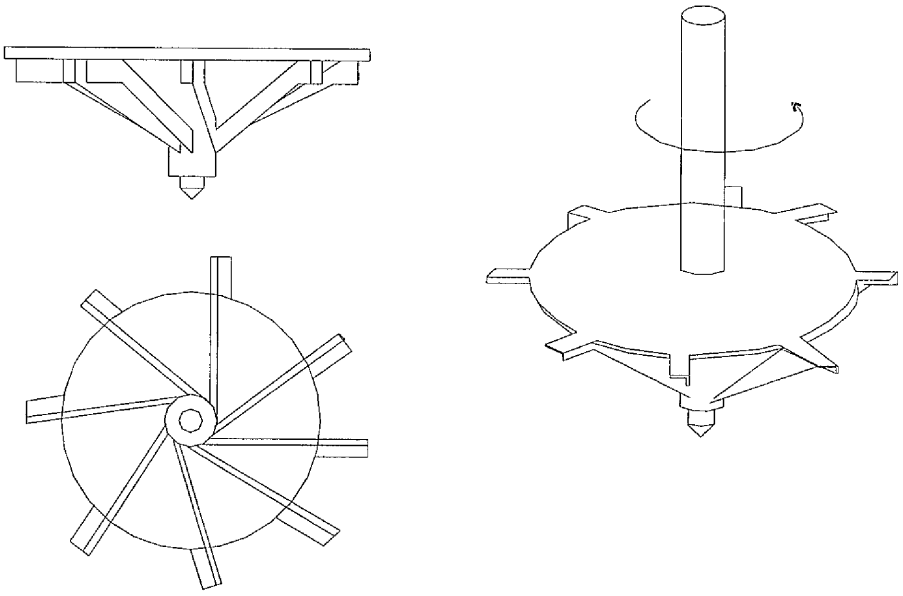


Figure 2.7. "Simcar" cone surface aerator

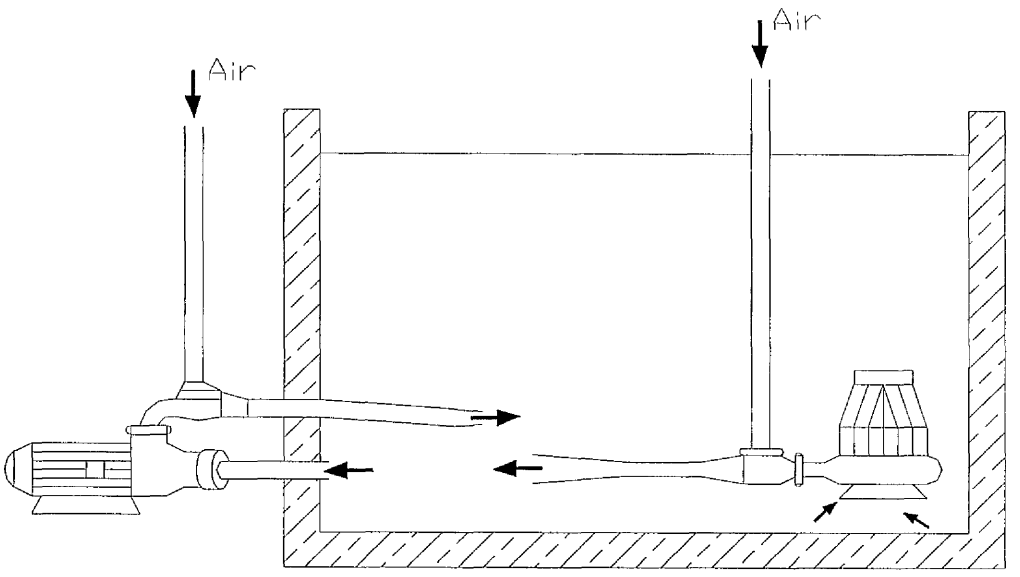


Figure 2.8. Venturi jet aerators (mounted and submersible pump version)

2.4.4 Mechanical aeration

Major mechanical aerators are commonly divided into three groups: *surface, subsurface and pumping liquid aerators*. They are based on major design principles and features of operation to meet the treatment requirement. For example, the arrangement of these aerators can be in the form of a vertical or a horizontal axis (WEF, 1996). In either case, oxygen normally is entrained from the atmosphere air or pure oxygen is introduced into the mixed liquor vigorously, generating the air-liquid interfacial area and may disperse liquid in form of droplets, of which contact with the ambient air through a thin film (Eckenfelder & Ford, 1968). However, the action of pumping or agitating by the aerator helps the mixing process but can lead to unwanted aerosols that increase the odour emission (Zlokarnik, 1983).

Common mechanical aerators are Simplex Hi-Cone aerator (Figure 2.5) (Hobson & Robertson, 1977), Simcar cone aerator (Figure 2.6) (Zlokarnik, 1983), BSK turbine aerator (Figure 2.7) (van der Emde, 1968), Brush aerator (Heduit & Racault, 1983), suction aerator, Fuchs aerator, plunging jet aerator (Admed, 1972; Sneath, 1978) and Venturi ejection aerator (Figure 2.8) (Morgan & Littlewood, 1979). Various commonly used mechanical aerators are briefly described below.

2.4.4.1 Surface aerator

This type of vertical axis aerator, is designed to induce either updraft or downdraft flow motion through the pumping action, by the submerged or partially submerged impellers attached to motors mounted on floats or on fixed structures. The aerator may also be classified into two categories with: low speed (60 to 120 $rev.min^{-1}$) and high speed (900 to 1400 $rev.min^{-1}$) type of impellers (Vasseur & Laigneau, 1975). "Low" and "high" refer the centrifugal and axial aerator respectively (Heduit & Racault, 1983). The medium speed will be referred to as "radial-axial". In low speed aerators, the impeller is driven through a reduction gear box by an electric motor. This arrangement, although more costly than a direct drive, gives an excellent mixing characteristic. The motor and gearbox are usually mounted on a supported platform. In high speed aerators, the impeller is coupled directly to the rotating shaft of the electric motor (Heduit & Racault, 1983; Ellis & Stanbury, 1980).

Surface aerators have been widely used in treatment of livestock slurries. Cumby (1987c) suggested that the dry matter content of slurry should be low (i.e. 1% dry matter) for optimum performance. The surface turbine aerators which were tried on pig slurry had aeration efficiency between 1.5 to 1.8 kg $O_2.kWh^{-1}$ and 1.86 kg $O_2.kWh^{-1}$ (Humenik *et al.* (1975) and Evans *et al.* (1979) respectively. Simplex Hi-cone surface aerator (Figure 2.5) was used to treat pig slurry with 1% of dry matter (Scheltinga & Poelma, 1970) and the aeration efficiency was found 1.5 kg $O_2.kWh^{-1}$. The advantage of surface aerators is in an easy installation in existing, shallow vessels or in lagoons using floats. They also provide a good aeration efficiency.

Subsurface aerators operate similarly as surface aerators. They provide an aeration of deeper layers, usually to about 2.5m (Cumby, 1987c). Aeration efficiency of subsurface aerators are in average, about 1.5 kg $O_2.kWh^{-1}$ as indicated by treatment of piggery slurry (Robertson *et al.*, 1974). Kessener brush aerators (Day *et al.*, 1975) and Fuchs aerators are popular types of subsurface aerators with relatively high efficiency. Brush aerators had been successfully used for odour control with pig, poultry and cattle slurry (Robinson *et al.*, 1971; Martin & Loehr, 1975; Martin *et al.*, 1980). Riemann (1974) found the aeration efficiency of Fuchs aerator to be 1 to 3.5 kg $O_2.kWh^{-1}$ in pig slurry with 6 - 8% of dry matter. The subsurface aerator is

another option for smaller aeration applications. Their performance is average, but they provide effective foam control (Riemann, 1974).

2.4.4.2 Plunging jet aerator

A plunging jet aerator is a type of the pumped liquid aerator (Burgess & Molloy, 1973). It involves a common feature of a pump that draws liquid from the aeration vessel and delivers it under pressure to an aerating device. In this system, the liquid or slurry is pumped from a pump through an elevated barrel via a nozzle into the surface of the bulk of liquid, producing aeration by air entrainment at the surface of liquid. Ahmed (1974) and Sneath (1978) proved that the jet system provides a good mixing effect, because the pumping system recirculates liquid continuously in the aeration vessel. The aeration efficiency is dependent on the nozzle size and the efficiency of the pump. Foaming problems usually significant, occur in this system.

The plunging jet can be developed into various designs. For example, the Jet-Aero-Mix (Simons *et al.,* 1974) used a multiple nozzle. Sneath (1978) reported the high rates of COD, BOD and odour removal at short retention period by plunging jet aerator in treatment of pig slurry. He commented that the aerobic treatment by plunging jet aerator is low on both capital and running costs. Thus this system could be an option for the livestock waste treatment.

2.4.4.3. Venturi ejection aerator

The venturi aerator system (Figure 2.8) is another form of pumped liquid aerator, with a different configuration of jet system. Venturi aerator provides mixing, filling, emptying as well as aeration itself. The venturi device is employed to create a suction force that entrains air into the mixed liquor (Figure 2.9).

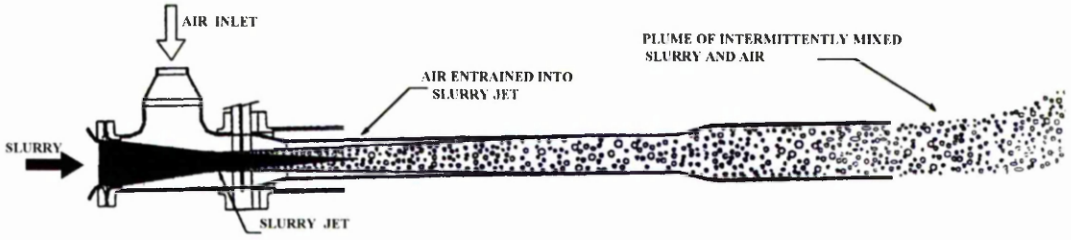


Figure 2.9. Venturi aerator

The air bubbles are broken down into smaller diameter ones by the shear force which is generated when the flow accelerates through the venturi nozzle (Huang & Mandt, 1972). Thus venturi jet creates high speed of flow and provides a good mixing effect. This system is usually submerged into the mixed liquor, or mounted outside the tank with its outlet passing through the tank wall to the venturi. Zlokarnik (1983) reported various types of design such as vertical, horizontal and radial discharge. Cumby (1987c) reviewed the optimum depth for a jet nozzle of Venturi. It varies for different aerators, and depends on the air suction which is necessary to overcome the hydrostatic pressure of the liquor. Therefore the position of the venturi in the reactor is important for the design. Air is usually supplied using a compressor or blower when the venturi jet outlet is situated in the liquid depth greater than 2.5 m.

However, the venturi system is very popular and commonly used in either wastewater treatment industries or livestock wastes treatment. For example, SmithKline Beecham Pharmaceutical (1999), Irvine is successfully using this system for their wastewater treatment. Venturi aerator treatment of piggery slurry in a farm aeration system has been investigated and shown to have high treatment performance of BOD, COD and odour control removal, and also a high oxygen transfer efficiency of 35% (Allen, 1996). Bloxham (1996) concluded that the venturi aerator is a very reliable system when applied to aerobic treatment of livestock slurries. However, this aerator can be blocked by solid materials easily in the nozzle.

2.4.5 **Compressed air aeration**

Compressed air aeration is a kind of a diffused air system, where the compressed air is forced into the mixed liquor through porous diffusers (i.e. spargers, holes in a pipe,

disc). The air is usually supplied from the atmosphere via a blower or compressor device. The mechanism of the aeration unit is such that the rising bubbles create turbulence and mixing and hence oxygen transfers into the liquid phase of slurry. The aeration efficiency is dependent on the interfacial area of air-liquid, retention time of bubbles, size of bubbles, degree of mixing and turbulence are also significant factors affecting the efficiency of oxygen transfer. Diffusers with smaller openings have problems of clogging by the solid materials, and the bacteria development, resulting in reduction of oxygen transfer efficiency (Boyle and Redmon, 1983). The depth of the bubble discharge point is important, because longer retention time (hold up) of air bubbles will increase the oxygen transfer rate. Imhoff (1969) had suggested 3 metres is the minimum depth for reasonable oxygen transfer. Sittig (1982) & Zlokarnik (1983) reported that in a deep aeration system such as ICI Deep Shaft system, can achieve a high utilisation of oxygen.

The diffused compressed air system is widely used in sewage treatment and water industries. It is not so popular in treatment of agricultural wastes with the high solid concentration. Although compressed air aerators represent the most efficient aerators available, they have a major drawback in the low aeration intensity. This type of aerators thus only suitable for dilute slurries and effluents or for long treatment (>10 day) time (Hanhe, 1996).

There are various compressed air fine bubble diffusers, coarse bubble diffusers, Danjes system, Inka system etc. Only aerators used for livestock wastes treatment are briefly described below:

2.4.5.1 **Fine air bubble diffuser**

The principle of this type diffuser is described above. The basic mechanism is that bubbles are produced when the compressed air emerges at the pores of a diffuser in form of bubbles which grow and then detach when the buoyancy forces of the bubbles exceed the surface tension forces holding the bubbles at the pores. Fine bubbles are produced when smaller surface tension forces are encountered by the smaller size of pores. The porous size of the fine bubble diffusers are typically less than 1 mm diameter (Eckenfelder & Moore, 1955) in order to generate fine bubbles (typical bubbles diameters are between 2 to 2.5 mm). Fine bubble diffusers provide

great interfacial area and hence have high oxygen transfer rates. The rate of oxygen transfer is inversely proportional to the bubble size. Also an experiment (Lister and Boon, 1973) showed that the efficiency of fine bubble diffused air system can be reduced more than 50% by surface active materials. Newbry (1998) demonstrated that the efficiency of fine bubble diffuser increased as bubble size decreased, he also commented that the efficiency can be affected by the energy input, configuration and type of bubble aerators.

The common commercial aerators are plates, tubes or disc constructed of silicon dioxide, aluminium dioxide or ceramic materials. Moreover, fine bubble diffusers are rarely used in treatment of livestock slurries. Gjervan (1982) observed that the fine bubble diffusers give poor mixing and high rates of bubble coalescence, leading to low aeration efficiencies once applied in livestock slurries. However, the membrane tube diffusers are recently developed by Monsal, Envicon Ltd and other manufacturers. The advantage of membrane diffusers is that, once the compressed air is switched off, the membrane will fasten tightly on the air distribution rods, forcing out the liquid and solid materials as well as bacteria. That reduces the fouling and clogging when used for the treatment of livestock slurries. Farrell (1996) carried out a pilot scale treatment using membrane diffusers which performed successfully in treating cattle slurry. Allen (1996) found that the aeration efficiency was 1.88 kgO_2 kWh^{-1} in the semi-continuous treatment of pig slurry with membrane diffuser system resulting in a high treatment performance, in term of BOD (85%) and COD (40%) removal. VFA also was reduced below 0.23$kg.m^{-3}$ within the first 2 weeks.

2.4.5.2 **Coarse air bubble aerator**

This unit operates as same as the fine bubble diffuser except for a bigger size of the pores in the diffusers. According to Van Der Emde (1968), the coarse bubbles are obtained from openings of the size of 5mm diameter. Coarse bubble aerator provides different option other than fine bubble diffuser, they will have less blockage problems than the fine bubble diffusers. The performance of coarse bubble diffusers can be improved by modified design. For example, suitable baffles above the outlet of air outlets, increase the retention times of bubbles. Hence systems such as that of Danjes (Van der Emde, 1968) and Inka (Wheatland & Borne, 1970) were developed.

Sparger aerator (non-porous aerator)

This system is one type of coarse bubble diffuser, which is different from the porous devices, because they use the larger diameter of orifice or opening that do not clog easily. A sparger is constructed of moulded plastic and saddle mounted below the air header located along the side of the wallet spacing of 0.3 to 0.6 m (Wheatland & Borne, 1970). It usually contains four horizontal orifices with 5 to 8 mm diameter (WEF, 1996), with air inlet and releases air through these orifices at high velocity. A low density air-liquid turbulent interface created by a row of spargers. The perforated piping is an another similar type of fixed orifice non-porous diffuser.

The design sparger diffusers have been modified in shape and material, in an attempt to improve the performance. The other types of non-porous diffuser such as slotted tube, static tube, and valved orifice diffuser.

2.4.6 Combined aeration

Principle of combined aeration

Combined aeration is a combination of compressed air and mechanical aeration. Various commonly used combined aeration units are usually a combination of a diffuser or a sparger with submerged turbine impeller. In this system, the diffuser supplies air and the turbine supplies the mixing. Air is delivered from the nozzles or the sparger rings below the submerged turbine or impeller, into the mixed liquor. As the air bubbles disperse through the turbine, the size of the bubbles is reduced due to the shear effect (Solomon *et al.,* 1981; Mann, 1983), creating a large air-liquid interfacial area. The turbine also generates considerable turbulence and mixing to aid oxygen transfer from the air bubbles. Bruxelmane (1981) reported the detail design considerations of combined aeration. The three main factors in the design were: specific power of compressor or blower, the speed of turbine and the average pumping time.

However, combined aeration system requires two separate power inputs for the submerged turbine's motor and a compressor. Such a system inherently has high capital and running costs. Cumby's (1987c) review indicated an aeration efficiency

in poultry wastes (1-6% D.M) of 2 to 2.3 kg $O_2.kWh^{-1}$ with submerged turbine aeration system.

PART B: LABORATORY EXPERIMENTAL WORK

3. ANALYTICAL METHODS AND MATERIALS

3.1 Total solids and total volatile solids

Total solids (TS) were determined using a drying method. 30 ml of well mixed sample were pipetted into a crucible of know weight and weighed. The sample was dried in an oven at 105°C for about 24 hours. The crucible was withdrawn from the oven and was weighed after it cooled down in the desiccator. Sample was then placed in a muffle furnace and combusted at 550°C for 2 hours, and was weighed after it was cooled down in the desiccator. Determination of volatile solids (VS) was calculated as the difference between the dry weight and the weight of the ash.

3.2 Total suspended and volatile suspended solids

To determine the total suspended solids, 30 ml of sample was filtered through a weighed 90 mm diameter glass fibre filter (Whatman type GF/A, BDH) using a low power vacuum pump. The filter with filtered solids was then placed and dried in the oven at 105 °C for 24 hours, cooled in the desiccator and weighed to obtain the total suspended solids (TSS) as described by Standard Methods (APHA, 1992). The filter with dried solids was then placed in the muffle furnace and was combusted at 550 °C for two hours. Then the filter was weighed after it had cooled down in the desicator. The volatile suspended solids (VSS) were calculated by the difference of TSS and ash on the filter.

3.3 Biochemical oxygen demand (BOD)

The Biochemical oxygen demand was determined by a modification of a dilution method as described in Standard Methods (APHA, 1992). The dilution water was prepared from deionised water (Millipore R/Q water purifier) at 20 °C. An appropriate amount of deionised water was aerated with air by using a sinter stone for about 2 hours in order to reach the saturated level, then the water was left unaerated for at least 30 minutes before use to avoid super-saturation. During the aeration, the water was seeded with an inoculum of a bacterial population, which was prepared from cattle slurry. About 30 ml of aerobic culture of cattle slurry was withdrawn from a 3 litre continuously stirred reactor, then the culture was diluted to 100 ml with deionised water and well shaken in a measuring cylinder. The solid particles in the

mixed liquor were allowed to settle for 5 - 20 minutes, so that the supernatant of this liquid portion could be used as inoculum. 2 ml of the inoculum and 1 ml of each three mineral salts solution (Mg, K, Fe) was added to each litre of aerated deionised water as described in Standard Methods (APHA, 1992).

The analysed slurry sample was diluted to a suitable concentration with seeded dilution water, in order to achieve about 30 - 50% use of the dissolved oxygen after incubation at 20 ^{o}C. Each sample was prepared in duplicates in 250 ml glass bottles. All the sample bottles were placed in an ultrasonic bath at 20 ^{o}C for one minute to expel all air bubbles from the bottles before closure with a ground glass stopper. The stoppered bottles were placed into a basket and submerged in deionised water to prevent air being drawn into the bottles during incubation for 5 days at 20 ^{o}C. Duplicate blank samples contained the same seeded water as the normal samples and were prepared along with those samples.

After five days, the amount of dissolved oxygen (DO) content was measured by using a dissolved oxygen probe (Orion, model 97-08-99) and a digital pH/mV and temperature meter (Kent, Electric instruments Limited, model 7065) with magnetic stirrer (Gallenkamp). The O_2 probe was calibrated in moist air at 20 ^{o}C at atmospheric pressure before measurement. The dissolved oxygen in 100 % saturated water was 9.08 $mgO_2.l^{-1}$ at standard atmospheric pressure. The DO at atmospheric pressure P was calculated as:

$$DO = 9.08 \times P/760 \quad (mg\ O_2.l^{-1}) \qquad \text{Equation (3.1)}$$

where
P was the atmospheric pressure at the time of measurement.

Therefore the BOD_5 ($mg.O_2.l^{-1}$) can be expressed as :

$$BOD_5 = (\text{blank DO} - \text{sample DO}) \times \text{Dilution factor} \qquad \text{Equation (3.2)}$$

3.4 Chemical oxygen demand (COD)

Chemical oxygen demand was determined by the digestion (oxidation) method described in Standard Methods (1992). 20 ml of a suitable diluted sample was mixed with 10 ml of concentrated sulphuric acid with silver sulphide catalyst and 10 ml of 0.25 N potassium dichromate solution (12.259 g of $K_2Cr_2O_7$ + 0.12 g of Sulphuric acid per litre) in a COD flask to which 3-4 glass beads had been added. The content was boiled for 2 hours under a reflux condenser. After cooling, about 70 ml of deionised water and ferroin indicator were added, then titrated with 0.1 N ferrous ammonium sulphate solution (78.4g FAS + 40 ml concentrated H_2SO_4 per litre) to a brown end-point.

3.5 Ammoniacal nitrogen

Ammoniacal nitrogen (NH_4^+-N) was determined by steam distillation with some modification of the version in Standard Methods (1992). An appropriately diluted 40 ml sample was added to a flask, which contained a spatula measure of muffled magnesium oxide before distillation. Ammonia was distilled into 20 ml of indicating boric acid (20 $g.l^{-1}$) which was then titrated with 0.01 Molar sulphuric acid as described in Standard Methods (1992).

3.6 Kjeldahl nitrogen

The determination of Kjeldahl nitrogen (Kj-N) was performed as described by Glowa (1973). A 15 ml of diluted sample was digested with zirconium dioxide and copper sulphate catalyst, then distilled by steam into 20 ml indicating boric acid (20 $g.l^{-1}$). The indicating boric acid was then titrated with 0.01 Molar sulphuric acid as described in Standard Methods (1992).

3.7 Nitrite and nitrate nitrogen

Nitrite and nitrate nitrogen were determined semi-quantitively using " Merckoquant" indicator strips (BHD Ltd) by matching the colour on the strips to the colour on the scale.

3.8 Stripped ammonia

The determination of ammonia gas released from the reactor was carried out during the aeration of livestock slurry. The ammonia gas evolved from the reactor was bubbled through 100 ml of 20 $g.l^{-1}$ indicating boric acid in a 250 ml measuring cylinder for one hour. Then the boric acid was titrated with standard 0.01 Molar sulphuric acid to a grey end-point. A 100 ml portion of indicating boric acid was used as a blank sample, which has not been exposed to ammonia gas, and was then similarly titrated with sulphuric acid.

The amount of stripped ammonia gas (mg $NH_3.l^{-1}.h^{-1}$) was calculated using the following equation:

NH_3-N = (sample titrated - blank sample) × 0.28 Equation (3.3)

3.9 Total volatile fatty acids (VFA)

VFAs were analysed with Gas chromatograph (GC) equipped with a flame ionisation detector (FID). The VFA samples were prepared with 10 ml of appropriately diluted supernatant into a Universal vial, then 1 ml of internal standard solution (1g pivalic acid and 20.8 g oxalic acid made to 500 ml with distilled water) was added. All samples were left for 24 hours for protein precipitation before analysis using a GC.

The VFA were analysed in a GC (AMS, model 93) with a 2.13 metres long, 2 mm internal diameter column packed with 80/120 Carbopack B-DA/4% Carbowax 20M, and nitrogen was used as carrier gas. The oven temperature was maintained at constant 175 °C. The pressures of air and hydrogen were at 15 and 5 psi respectively. The injector and detector block temperatures were at 200 °C. Each analysis was run for 40 minutes.

The six VFA analysed by GC were: Acetic, Propionic, Iso-Butyric, N-Butyric, I-Valeric and N-Valeric acid.

3.10 Total indoles and phenols (TIP)

TIP were separated in Gas Chromatograph machine (Chrompack Instruments Model 103), which used a 25m long, 0.25mm diameter, 0.2 micron coated capillary column. The oven operation conditions were 40 °C for 1 min, to 140 °C at 50 °C /min, to 200 °C at 4 °C/min, to 220 °C at 20 °C/min, 220 °C for 5 min. The detector and injector temperatures were at 300 and 270 °C respectively. Helium was used as a carrier gas. Each analysis was run for 40 minutes.

TIP before analysing on GC were firstly extracted from the samples by mixing 40 ml of slurry supernatant with 20 ml of extraction mixture of methylene chloride containing o-(2) ethyl phenol as an internal standard, and shaking for 10 minutes in tightly closed 250 ml glass bottles on a vortex mixer. Then the emulsified mixture was centrifuged at 2000 rpm and 5 °C for 20 minutes, the solvent with TIP was pipetted from the bottom of the tube into an Universal vial and about 1 gram of anhydrous calcium sulphate was added to dry the solvent. Then, about 0.5 ml of solvent with TIP was pipetted into a crimp cap vial and stored pending analysis. For each analysis 0.5 microlitres of sample was used.

The five indole and phenol components analysed by the GC were: Phenol, P-Cresol, O-ethyl-Phenol, Indole and Skatole.

3.11 Total organic acids (TOA)

Total organic acids were determined in the supernatant sample by the colorimetric method which was used for sewage sludge liquors, Montgomery *et al.* (1962). 0.5 ml of diluted sample of supernatant was reacted with three different reagents in turn. 1.7 ml of reagent R1 (a mixture of 30 ml of ethanediol and 4 ml of 50 % concentrated sulphuric acid) were added to the sample, then mixed well and boiled for 3 minutes before cooling in cold water. Next, 2.5 ml of reagent R2 (a mixture of 40 ml of 4.5 N NaOH and 10 ml of 100 $g.l^{-1}$ hydroxylammonium sulphate) were added to sample, mixed well and left to stand for 1 minute before adding 10 ml of reagent R3 (a mixture of 20g of ferric chloride hexahydrate and 20 of ml concentrated sulphuric acid per litre). The sample was then mixed and left to stand for at least 10 minutes

before measuring the optical density at 500 nm in a 10mm cell using a spectrophotometer (Hydrocheck,WPA).

Standard solutions of zinc acetate were made at concentrations of 0.5, 1, 1.5, 2 and 2.5 $g.l^{-1}$ and deionised water was used as a reagent blank. The standards were treated similarly to the samples and the corresponding absorbances were measured. These absorbances were used to obtain a calibration factor (i.e. slope of the line).

Additionally, each sample needed a sample blank to account for the inherent background colour due to the sample. For this sample blank, reagent R2 was replaced with a similar volume of deionised water. Then the corrected absorbance of each sample was calculated by subtracting its sample blank from the absorbance of the coloured sample. The final TOA concentration was then calculated by multiplying the corrected absorbance by the calibration factor, taking into account any dilution factor used.

3.12 Respiration rate

Respiration rates of aerobic fresh slurries were determined using a Rank Oxygen Electrode. The electrode was set up before the experiment. Initially, the base of the incubation vessel was detached by unscrewing the perspex locking nut, then a sufficient amount of saturated KCl solution was added to wet the silver and platinum electrodes. A 1 cm square of lens tissue was cut, and a 1 mm diameter hole was made in it. The tissue was placed over the platinum electrode so that the hole was directly over the electrode. A 1cm square piece of Teflon membrane was then cut and placed over the lens tissue, and was locked in place by putting the incubation vessel in place and screwing down the locking nut to ensure that no air bubbles were trapped. Finally the electrode was set and the incubation vessel was placed on the magnetic stirrer, ready for operation.

To prepare for the analysis, the Ag-AgCl electrode was connected to the positive side of the potential divider and the platinum electrode to the negative. The electrode was calibrated with aerated water at 20 ^{o}C for half an hour in the incubation vessel, and the sensitivity control was adjusted to give a suitable deflection (9.06 $mg.l^{-1}$) on the

recorder. Then 2 ml of sample were poured into the incubation vessel where a small magnetic stirrer continuously kept the sample in a homogeneous state. The vessel was sealed with a perspex plunger, which had a 1mm diameter hole in the centre to release any retained air bubbles from the sample chamber. Each sample was well shaken to ensure that it was initially fully aerated before introducing it to the incubation vessel. The decline in the concentration of dissolved oxygen versus time was recorded on a chart recorder, and the respiration rate of the sample was calculated from the slope of the DO against time graph. The respiration rates (r) were determined in duplicate, and the results were expressed in $mgO_2.l^{-1}.hr^{-1}$.

For the next sample, the perspex plunger was removed and the vessel was washed out with deionised water, with the sample being sucked out with a syringe.

3.13 pH value

The pH value was determined by a combination pH electrode and a pH meter (E.I.L model). The pH electrode was calibrated at each session of use with buffer solution at the values of 7 and 9.20 scale at 20 °C before measuring the sample.

3.14 Redox potential

Redox potential was measured using a Hg/HgCl-Pt electrode which was filled with saturated KCl solution in order to complete the salt bridge and connected to a pH meter (91B EIL Ltd). The readings were also continuously recorded on the chart recorder.

The Redox electrode was calibrated with slurry and Zobell's solution (Jacob, 1970) for the low and upper part of the scale at 20 °C respectively .
The composition of Zobell's solution consisted of:

Potassium ferrocyanide	$K_4Fe(CN)_6.3H_2O$	0.704g
Potassium ferricyanide	$K_3Fe(CN)_6$	0.549g
Potassium chloride	KCl	3.728g

and was made up to 500 ml with denionised water. The normal value is given by a clean electrode immersed in Zobell's solution was +200 mVE_{cal} and about -300 to -400 mVE_{cal} when in the raw slurry. If these observed values varied more than ± 5 mVE_{cal}, then the electrode was cleaned with chromic acid or replaced by a new one.

3.15 Dissolved oxygen (DO)

The Dissolved Oxygen concentration of mixed liquor in the reactor was measured with a wall mounted microprocessor-based analytical transmitter and associated sensors, which were continuously monitoring the level of dissolved oxygen (model 4555 ABB Kent-Taylor Ltd). The electrode sensor was calibrated, at the start and in weekly intervals of the experiment, with aerated water (100% saturation) and 5 % sodium sulphite solution (0% DO concentration) at the experiment temperature before set to use. The results of DO were also recorded on the chart continuously.

3.16 Oxygenation capacity (OC)

Water

The oxygen transfer efficiency of the venturi aeration system was tested with tap water. Initially, the reactor vessel was filled with tap water to the desired level. Then the tap water was de-oxygenated with sodium sulphite, which had been dissolved in warm water. 16 g of sodium sulphite crystals were allowed for each gram of oxygen dissolved in the water, and an excess of approximately 15 % of sulphite was added to overcome the amount of oxygen transferred to the water by the aerator during the deoxygenation (WPC, 1987). Cobalt chloride was used as a catalyst.

A dissolved oxygen meter (YSI Incorporated, Model 95/25 FT CE) was calibrated at zero, and at 100% of saturation in order to cover the full range of DO values. The test was carried out at ambient temperature and at atmospheric pressure. The water was mixed well to ensure the DO concentration was uniform throughout the whole vessel. Once the DO concentration was reduced to near or at zero in the water, then this water was re-aerated, so that the DO concentration started to increase. The concentration of dissolved oxygen (C) was then noted and recorded after equal time intervals. The values of oxygen deficit (Cs - C) were then calculated from the recorded data. These calculated values were used to plot a graph of oxygen deficit

against time on Log-Linear graph paper and the best fit straight line was drawn through the points. The time required for a 90% reduction of oxygen deficit values was read from the graph, and K_{La} was calculated by the following expression:

$$K_La = \frac{2.303}{t_{(90\%)}} \qquad (hr^{-1}) \qquad \text{Equation (3.6)}$$

From the value of K_{La} above, the oxygenation capacity (OC) was then calculated using following equation:

$$OC = K_La\,(t) \times V \times Cs(t) \times 10^{-3} \qquad (kg.h^{-1}) \qquad \text{Equation (3.7)}$$

where :

Cs(t) = oxygen saturation concentration ($kg.m^{-3}$) in clean water at the test temperature (water) when the atmospheric pressure is 760 mm mercury.

V = aeration tank volume occupied by the water (m^3)

Slurry

The determination of the oxygen transfer efficiency in slurry was performed similarly to the determination in water. Initially, the reactor vessel was filled with slurry which was then aerated until the system reached a steady state condition. The respiration rate of the slurry was then determined. Approximately 500 ml of slurry was withdrawn from the reaction vessel, then poured into a 250 ml bottle carefully to minimise the incorporation of air bubbles, then the slurry DO concentration decrease was measured with a DO probe fitted inside the bottle, with measurements being made at equal time intervals.

The respiration rate of the sample was calculated from the slope of the DO vs time graph as described in Section 3.12 respiration rate. After the determination of the respiration rate, the slurry in the reactor was re-aerated. The DO concentration was measured and recorded with a DO probe at equal time intervals and then the oxygen

transfer coefficient K_La was calculated using the same method as for water. Finally the *OC per unit volume* slurry was calculated by the following expression.

$$OC = K_{La}(t) \times Cs(t) \times 10^{-3} - \text{Respiration rate (r)} \quad (kg.l.^{-1}.h^{-1}) \quad \text{Equation (3.8)}$$

4. ANAEROBIC STORAGE OF CATTLE AND PIG SLURRY

4.1 Introduction

After the literature review, the first step into the design of the suitability of the Continuous Aerobic Treatment Reactor was to investigate the effect of storage on the changes of slurry characteristic. The changes of cattle and pig slurry characteristics during laboratory storage experiments were investigated in this study. This preliminary investigation assessed the changes of concentration of various parameters in liquid phase of slurries, particularly odorous compounds, during storage period and temperature. The results would provide a guide for the optimal storage time interval and the treatment temperature to minimise the pollutants contents (i.e. COD, BOD, NH_4^+-N, etc.) and offensive odour in slurries.

During the storage, which is anaerobic for the bulk of slurry, anaerobic decomposition of slurry takes place (Williams & Evans, 1981; Williams *et al.*, 1991). There is a production of a number of compound gases, normally carbon dioxide, methane and ammonia and organic compounds in the liquid phase. Thus two different experiments were designed with the liquid phase was analysed.

4.2 Experimental design and methods

4.2.1 Slurry collection and preparation

Fresh slurry from cattle, fed on a diet of silage and concentrate, was collected from the channel floor of a cattle unit. The slurry, consisting of faeces and urine, was, for more accurate handling and analysis accuracy, slightly diluted with tap water and then large solids were separated using a 5mm sieve.

Slurry from pigs, fed on a barley diet with ad lib. water, was collected from the reception pit of a commercial piggery. This slurry was also processed similar to the cattle slurry before being used for the laboratory experiments.

The same cattle and pig slurries were used for storage experiments. Total solids (TS) concentration of cattle and pig slurry was 74.5 and 84.1g.l^{-1} respectively. This and other characteristics of both slurries are given in Table 4.1.

Table 4.1. Initial characteristics of cattle and pig slurry in anaerobic storage

Parameter		Cattle		Pig	
		Value	% TS(w/w)	Value	% TS (w/w)
TS	g.l^{-1}	74.5	100.0	84.1	100.0
ASH	g.l^{-1}	22.3	29.9	22.3	26.5
VS	g.l^{-1}	52.4	70.3	61.8	73.5
TKN	g.l^{-1}	4.97	6.7	5.81	6.9
NH_4^+-N	g.l^{-1}	3	4.0	2.65	3.2
Organic-N	g.l^{-1}	1.97	2.6	3.16	3.8
BOD(w)	g.l^{-1}	13	17.4	23.5	27.9
BOD(s)	g.l^{-1}	6	8.1	5.7	6.8
COD(w)	g.l^{-1}	92	123.5	117	139.1
COD(s)	g.l^{-1}	34.3	46.0	19	22.6
VFA	g.l^{-1}	3.9	5.2	8.1	9.6
TIP	g.l^{-1}	0.21	0.3	0.1	0.1
pH	-	8.8	-	7.2	-

4.2.2 Slurry storage

Liquid phase

Both slurries were well mixed before each being dispensed into 30 of 250 ml white plastic (polythene) bottles with gas tight caps. Bottles were then incubated at 5, 10 and 15 °C respectively for 30 weeks. Temperature in the incubators was checked every two days. Gases, generated by anaerobic activity in slurry, were released 3 times a week by a slight unscrewing and then re-tightening of bottle caps.

Samples of cattle and pig slurry stored at all three temperatures were analysed every three weeks throughout the storage period. The initial sample, week 0, was frozen and analysed together with the final sample at the last week of the storage period. Each sample was well mixed before analysis. Analysis was done on whole slurry and a slurry supernatant, which was obtained by centrifugation at 10,000g for 20 minutes at 5°C.

Chemical analysis of Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total solids (TS), Volatile solids (VS), Total suspended solids (TSS), pH, NH_4^+-N, Kj-N, nitrate and nitrite, VFA, TIP and TOA in all slurry samples were analysed by Standard Methods (APHA, 1992) as described in Chapter 3.

4.3 Results and discussion

After storage, the biggest chemical changes in the cattle and pig slurry were to the VFA, TOA and TIP concentrations. They were found to increase with an increase in the temperature and the length of the storage period. Williams (1981) found that the odour offensiveness increased as the concentrations of VFA, phenol, p-cresol and skatole increased, which suggests that they may have potential as odour indicator compounds. The final characteristics of cattle and pig slurry characteristics after storage are shown in Table 4.2. The general changes in the cattle and pig slurry after storage appears to arise from two main processes:-a) maceration and subsequent degradation of solid materials and microbial cell debris into soluble end products; b) limited methanogenesis. All the analytical data for the anaerobic storage study are shown in Appendix B (Tables B1-B14), and the specific chemical changes in cattle and pig slurry are described below.

Table 4.2. Final characteristics of cattle and pig slurry after storage at 5, 10 and 15 ^{o}C.

Parameter		Cattle slurry			Pig slurry		
		5°C	10°C	15°C	5°C	10°C	15°C
TS	$g.l^{-1}$	71.0	74	70.3	76.3	68.4	73
ASH	$g.l^{-1}$	18.6	21.5	19.5	21.5	20.5	23
VS	$g.l^{-1}$	52.4	52.5	50.8	54.8	48	50
Kj-N	$g.l^{-1}$	6.0	5.4	5.62	5.6	5.4	5.8
NH_4^+-N	$g.l^{-1}$	3.6	3.6	4.03	3.1	2.9	3.7
Organic-N	$g.l^{-1}$	2.4	1.8	1.59	2.52	2.45	2.2
BOD_5w	$g.l^{-1}$	18.3	15.2	15.9	23	23	23
BOD_5s	$g.l^{-1}$	11.5	11.5	11.5	11.5	11.5	11.5
CODw	$g.l^{-1}$	117	110	110	128	114	132
CODs	$g.l^{-1}$	41.5	40	37	31	28	36
VFA	$g.l^{-1}$	7.1	8.3	8.9	16.3	16.4	18.1
TIP	$g.l^{-1}$	0.3	0.3	0.3	0.13	0.13	0.14
TOA	$g.l^{-1}$	7.0	7.7	6.3	9	9	12
pH	-	8.5	8.4	8.3	6.8	7.4	6.9

4.3.1 Cattle slurry

Volatile Fatty Acids (VFA)

The changes of VFA concentration in cattle slurry were clearly attributed to the storage time and storage temperature of slurry (Figure 4.1). As expected, the highest increase of VFA was observed at 15 °C. It occurred during the first 12 weeks of storage when the concentration of VFA more than doubled from 3.93 $g.l^{-1}$ to the maximum VFA level, reaching 9.4 $g.l^{-1}$. Concentration then slightly decreased and fluctuated around 8 ±1.0 $g.l^{-1}$ (Figure 4.1) for the rest of the storage period.

Similar changes in the VFA concentration were observed at 10 and 5°C. There was a relatively rapid increase in the first 9 weeks then a little change until the last ten weeks of storage when a further increase of concentration was measured. Final concentrations of VFA at all temperatures were within 20% of each other, in regard to the total concentrations, which increased from a starting value of 3.93 $g.l^{-1}$ by 3.15, 4.34 and 5.01 $g.l^{-1}$ in cattle slurry stored at 5, 10 and 15 °C respectively.

The effect of storage temperature on the rate of VFA evolution was only significant at the beginning of storage. At 15°C, the rate of increase of 500 $mg.week^{-1}$ started immediately and lasted for 12 weeks, whilst at temperatures of 5 and 10°C there was a lag of 3 weeks before the similar rate of VFA evolution of approximately 520 $mg.week^{-1}$ was initiated, and lasted for 6 weeks (Figure 4.1).

The continuous increase of VFA in cattle slurry implies that the offensive odour, of which VFA are a good indicator (Williams, 1984), will also increase with the storage. The tendency curves show that, except for the 15 °C storage where a maximum concentration of VFA was reached in 12th week of storage, an increase of slurry storage time, required by PEPFAA Code (SOAEFD, 1997) although necessitated for water pollution prevention, may not improve the slurry odour.

The composition of VFA (Table 4.3) was similar in slurry stored at all three temperatures with the highest contribution by acetic acid increasing from 80 % to an average of 83% of total VFA. The other VFA components were: 7% to 10% of

Figure 4.1 Total volatile fatty acids (VFA) of cattle slurry at different temperatures

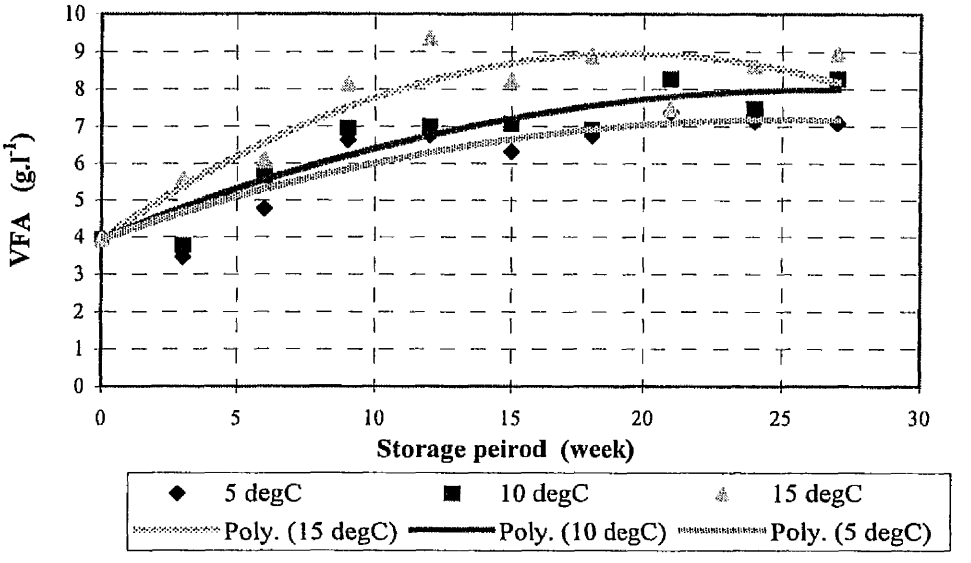
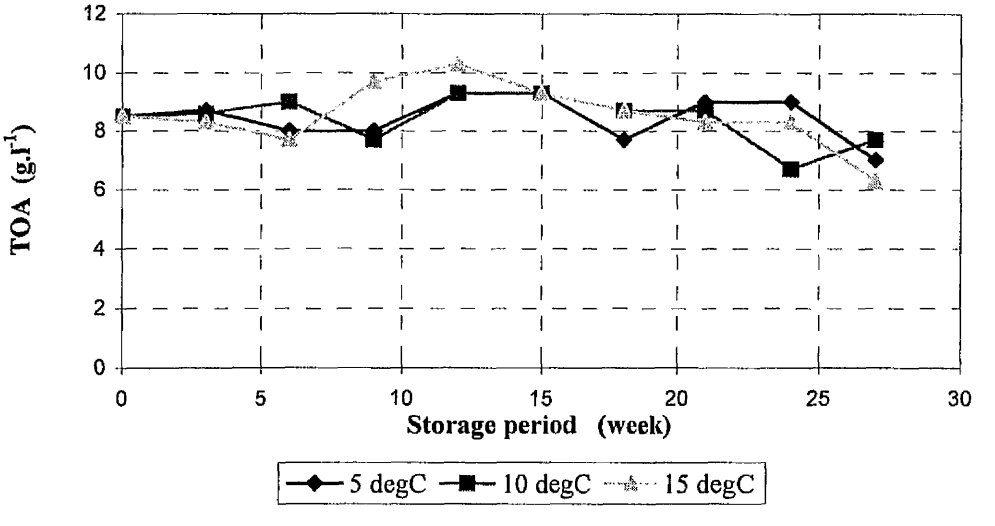


Figure 4.2 Total organic acid (TOA) of cattle slurry at different temperatures



Note : Poly. = Polynomial trendline

Table 4.3. Individual volatile fatty acid (VFA) of cattle slurry stored at 5, 10 and 15 °C.

5 °C						
Week	**Acetic** $mg.l^{-1}$	**Propionic** $mg.l^{-1}$	**I-Butyric** $mg.l^{-1}$	**N-Butyric** $mg.l^{-1}$	**I-Valeric** $mg.l^{-1}$	**N-Valeric** $mg.l^{-1}$
0	3149	388	51	237	59	43
3	3019	207	63	99	54	18
6	4094	366	81	136	60	25
9	5433	615	121	311	104	51
12	7532	814	137	303	102	34
15	5210	613	122	258	84	33
18	5586	654	108	272	89	31
21	5958	793	128	336	111	44
24	5968	683	115	241	90	31
27	5915	687	114	246	94	28

10 °C						
Week	**Acetic** $mg.l^{-1}$	**Propionic** $mg.l^{-1}$	**I-Butyric** $mg.l^{-1}$	**N-Butyric** $mg.l^{-1}$	**I-Valeric** $mg.l^{-1}$	**N-Valeric** $mg.l^{-1}$
0	3149	388	51	237	59	43
3	3273	269	69	90	57	15
6	4918	422	83	135	66	17
9	5773	645	119	281	96	39
12	5799	654	124	295	102	31
15	5879	643	134	294	89	32
18	5669	680	111	319	89	40
21	6789	825	127	385	106	34
24	3308	471	91	205	62	22
27	6888	798	121	332	99	34

15 °C						
Week	**Acetic** $mg.l^{-1}$	**Propionic** $mg.l^{-1}$	**I-Butyric** $mg.l^{-1}$	**N-Butyric** $mg.l^{-1}$	**I-Valeric** $mg.l^{-1}$	**N-Valeric** $mg.l^{-1}$
0	3149	388	51	237	59	43
3	4868	400	108	129	59	17
6	4348	447	87	146	75	18
9	6754	778	124	340	97	47
12	7612	954	152	470	114	62
15	6874	812	120	342	93	31
18	7373	910	126	339	96	50
21	6344	878	126	354	105	38
24	4905	484	137	308	120	41
27	7411	916	127	338	106	37

propionic acid; 2% to 6% of N-butyric acid, 2% of Iso-butyric acid, and 1% of Iso-valeric and N-valeric acid. These results show that the only significant changes (mainly increase) occurred in the concentration of acetic, propionic and N-butyric acid. The concentrations of other three acids remained fairly constant.

Total organic acids (TOA)

The TOA concentration for all three storage temperatures, varied by ±25% of the starting value during the storage time (Figure 4.2) achieving the highest values after first 12 weeks of storage while after 25 weeks the levels were the lowest. The ratio of VFA/TOA concentration of 0.4 was the lowest at the start of storage experiment while the highest of 0.8 was at the end, this being the result of more than doubling of VFA concentration while the TOA remained the same or slightly decreased. This change of the VFA/TOA ratio indicates that, for stored slurry, there is not a constant relationship between these two analytes as had been described by Williams (1981) and Thacker & Evans (1986). Although his equation was deduced for raw and aerobically treated pig slurry, it will be seen in the (Chapter 4.3.2. on the storage of pig slurry), that the VFA/TOA ratio for stored pig slurry was even more variable than for cattle slurry. There is a proposition that the higher the concentration of TOA or VFA of stored slurry the more offensive the slurry becomes, but the relationship between odour offensiveness and the TOA/VFA concentration appear quite different from that described by Williams (1981).

Total indoles and phenols (TIP)

During the first three weeks of storage the concentration of TIP in stored slurry increased from 207.6 $mg.l^{-1}$ by between 23% and 32% (5 and 15 °C) (Figure 4.3). For the remainder of the storage the TIP concentration remained relatively unchanged except for the last three weeks when it decreased by approximately 18% to $250mg.l^{-1}$. These changes were particularly due to the decrease of p-Cresol, which contributed by about 80 % to TIP at 5°C and 77% at 10 and 15°C (Table 4.4). The increase of phenol concentration was the fastest at 15°C, reaching its highest level within three weeks while at 5 °C full 12 weeks was required. The effect of storage temperature was most evident on indol and skatole concentration (Table 4.4). Indole

Table 4.4. Individual indoles and phenols of cattle slurry stored at 5, 10 and 15 °C.

5° C					
Week	**Phenol** $mg.l^{-1}$	**P-cresol** $mg.l^{-1}$	**O-ethyl-phenol** $mg.l^{-1}$	**Indole** $mg.l^{-1}$	**Skatole** $mg.l^{-1}$
0	11	192	4	1	0
3	32	233	5	3	0
6	34	237	5	3	0
9	51	228	5	3	0
12	63	217	5	3	0
15	62	204	5	3	0
18	64	233	5	2	1
21	64	232	5	2	0
24	67	227	5	3	0
27	55	189	4	2	0

10° C					
Week	**Phenol** $mg.l^{-1}$	**P-cresol** $mg.l^{-1}$	**O-ethyl-phenol** $mg.l^{-1}$	**Indole** $mg.l^{-1}$	**Skatole** $mg.l^{-1}$
0	11	192	4	1	0
3	40	234	5	3	0
6	61	231	5	3	0
9	64	232	5	3	0
12	55	224	5	1	1
15	64	201	5	1	0
18	60	232	5	1	1
21	65	233	5	1	4
24	104	198	5	1	4
27	54	194	4	1	3

15° C					
Week	**Phenol** $mg.l^{-1}$	**P-cresol** $mg.l^{-1}$	**O-ethyl-phenol** $mg.l^{-1}$	**Indole** $mg.l^{-1}$	**Skatole** $mg.l^{-1}$
0	11	192	4	1	0
3	62	232	5	3	0
6	63	234	5	1	0
9	66	232	5	1	3
12	67	219	5	1	2
15	67	200	5	1	1
18	70	240	5	0	4
21	66	229	5	0	0
24	80	225	5	0	1
27	53	190	4	0	2

Figure 4.3 Total indoles and phenols (TIP) concentration of cattle slurry at different temperatures

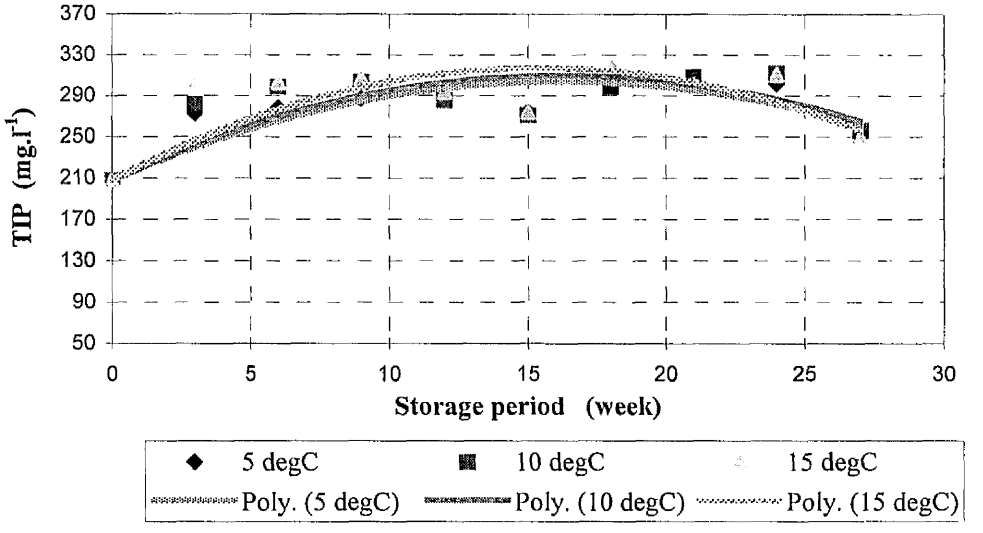
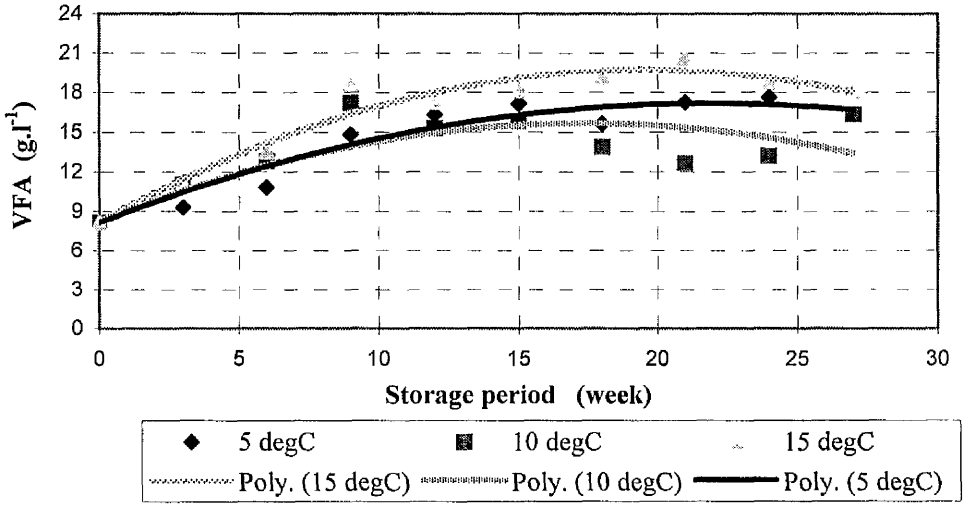


Figure 4.4 Total volatile fatty acids (VFA) of pig slurry at different temperatures



Note : Poly. = Polynomial trendline

concentration increased in the first three weeks to its maximum of about 3 $mg.l^{-1}$ but it was then transformed/biodegraded to a non detectable level in 15 weeks at 15 °C, to <1 $mg.l^{-1}$ and 1.5 $mg.l^{-1}$ in 24 weeks at 10 and 5 °C respectively. Skatole was not observed at 5°C except at 17th week, while at 10 °C its concentration fluctuated between 0 and 1 $mg.l^{-1}$ increasing to >3.5 $mg.l^{-1}$ after 20 weeks of storage. At 15 °C, although it was not detectable during the first 6 weeks, it increased to relatively high values, up to 3.6 $mg.l^{-1}$, and fluctuating concentrations were observed during the rest of the storage time (Table 4.4).

Although the total concentration of TIP did not vary considerably during the storage, the most odorous compound from these analytes, skatole, was generated, particularly at higher temperature after the first 6 weeks and remained at a relatively high concentration. This would once more indicate that the storage of cattle slurry does not contribute to the decrease of the offensive odour but rather otherwise.

pH and ammoniacal nitrogen

The pH value of slurries stored at 5, 10 and 15 °C decreased during the storage from 8.8 to 8.5, 8.2 and 8.0 respectively. The content of ammoniacal nitrogen increased from 3 to 3.6 $g.l^{-1}$ within the first 5 to 7 weeks of storage, then decreased to its original value in week 15 when it started to increase once more reaching the maximum values (Table 4.5) in the final 25th week.

Since the ammoniacal nitrogen concentration of slurry changed only minimal, the pH value was affected only by generation of organic acids and CO_2, thus pH decreased.

Supernatant chemical oxygen demand (CODs)

Supernatant COD increased from its original value of 34.3 $g.l^{-1}$ and fluctuated around 37.5 $g.l^{-1}$ ending with the final values of 42, 40 and 37 $g.l^{-1}$ for temperatures 5, 10 and 15°C respectively (Table 4.5). This was expected since the anaerobic degradation produces smaller water soluble molecules from the slurry solids and perhaps increases the susceptibility of smaller molecules to chemical oxidation.

Table 4.5. Ammoniacal nitrogen, whole COD, Supernatant COD and pH of cattle slurry stored at 5, 10 and 15 °C.

Week	NH_4^+-N , $mg.L^{-1}$			COD Whole $g.L^{-1}$			COD Supernatant $g.L^{-1}$			pH		
	5 °C	10 °C	15 °C	5 °C	10 °C	15 °C	5 °C	10 °C	15 °C	5 °C	10 °C	15 °C
0	3003	3003	3003	92	92	92	34	34	34	8.8	8.8	8.8
3	3010	3080	3570	83	87	91	39	39	38	8.8	8.7	8.5
6	3650	3430	3460	94	87	81	35	33	33	8.7	8.6	8.4
9	3220	3514	3619	94	99	96	37	39	36	8.6	8.4	8.3
12	3510	3110	3440	98	102	101	40	41	37	8.6	8.4	8.3
15	3020	3000	3280	88	98	94	42	39	39	8.5	8.3	8.1
18	3050	3200	3340	90	93	93	39	40	38	8.5	8.3	8.0
21	3730	3200	3490	98	105	101	40	39	36	8.5	8.2	8.0
24	3402	3080	3950	99	90	105	40	36	35	8.5	8.3	8.0
27	3600	3550	4020	117	110	110	42	40	37	8.5	8.4	8.2

4.3.2 Pig slurry

Chemical changes occurring in pig slurry were more apparent than in cattle slurry during the anaerobic storage. Pig slurry is less stable than cattle slurry, which undergone more intensive digestion in the animal gut, thus the anaerobic decomposition can produce higher concentration of metabolites, which are predominantly highly odorous.

Volatile fatty acids (VFA)

Increase of VFA concentration in the first 9 weeks was rapid with at approximately 1g VFA per week (Figure 4.4). After this period the concentration remained relatively constant, except for the storage temperature of 10 °C, when it decreased and remained under the levels observed at temperatures 5 and 15°C. The polynomial tendency curves indicate (Figure 4.4) that the maximum VFA concentration was reached between 15 and 22-th weeks of the storage period. It then tended to decreased until the end of the storage period. Acetic acid contributed by the highest percentage to the VFA content (averaging 55%), propionic and N-butyric acid by about 35% while the remaining fatty acids concentrations hardly changed and were about 10% of the total VFA content (Table 4.6). These concentrations of VFA show more than 90% similarity with the results of Williams (1981).

Similarly, as for cattle slurry, the nearly three times increase of VFA concentration during the pig slurry storage, particularly at higher temperature, would increase the offensive odour of slurry. Although some decrease of VFA concentration was observed after the 20th week of storage its value was still double of that at the start of storage.

Total organic acids (TOA)

The rate of TOA concentration increase was fastest in the first 9 weeks of storage period at three temperatures, as for VFA. The highest value (approximately 26 $g.l^{-1}$) was achieved in the 18th week and maintained at the level for 4 weeks of storage period. TOA content was then continually decreasing and at the 27th week it reached

Table 4.6. Individual volatile fatty acid (VFA) of pig slurry stored at 5, 10 and 15 °C.

5 °C						
Week	**Acetic** $mg.l^{-1}$	**Propionic** $mg.l^{-1}$	**I-Butyric** $mg.l^{-1}$	**N-Butyric** $mg.l^{-1}$	**I-Valeric** $mg.l^{-1}$	**N-Valeric** $mg.l^{-1}$
3	5753	1952	262	936	251	140
6	6532	2476	274	1074	295	149
9	8859	3394	398	1566	354	232
12	10268	4653	650	2199	482	286
15	9907	4245	445	1868	420	236
18	8811	3975	413	1801	407	228
21	9580	4442	469	2048	467	235
24	9622	4612	469	2184	479	250
27	9377	4063	405	1856	420	218

10 °C						
Week	**Acetic** $mg.l^{-1}$	**Propionic** $mg.l^{-1}$	**I-Butyric** $mg.l^{-1}$	**N-Butyric** $mg.l^{-1}$	**I-Valeric** $mg.l^{-1}$	**N-Valeric** $mg.l^{-1}$
0	5273	1652	214	873	252	146
3	6383	2579	289	1321	313	176
6	7470	3156	322	1354	326	184
9	9150	4581	502	2200	480	286
12	8575	3825	408	1861	379	234
15	10785	5516	735	3050	558	267
18	7524	3393	530	1783	408	233
21	4900	2357	341	1322	321	150
24	4517	2215	255	1045	236	135
27	8967	3830	520	2227	523	277

15 °C						
Week	**Acetic** $mg.l^{-1}$	**Propionic** $mg.l^{-1}$	**I-Butyric** $mg.l^{-1}$	**N-Butyric** $mg.l^{-1}$	**I-Valeric** $mg.l^{-1}$	**N-Valeric** $mg.l^{-1}$
0	5273	1652	214	873	252	146
3	6313	2764	297	1251	312	173
6	8252	3182	340	1324	305	150
9	9447	5088	606	2691	543	281
12	9151	4398	629	2380	469	243
15	7083	3354	426	1827	374	232
18	10183	4963	650	2591	502	252
21	10714	5484	674	2893	565	265
24	10313	4780	543	2434	487	255
27	9747	4464	582	2495	565	275

Figure 4.5 Total organic acid (TOA) of pig slurry at different temperatures

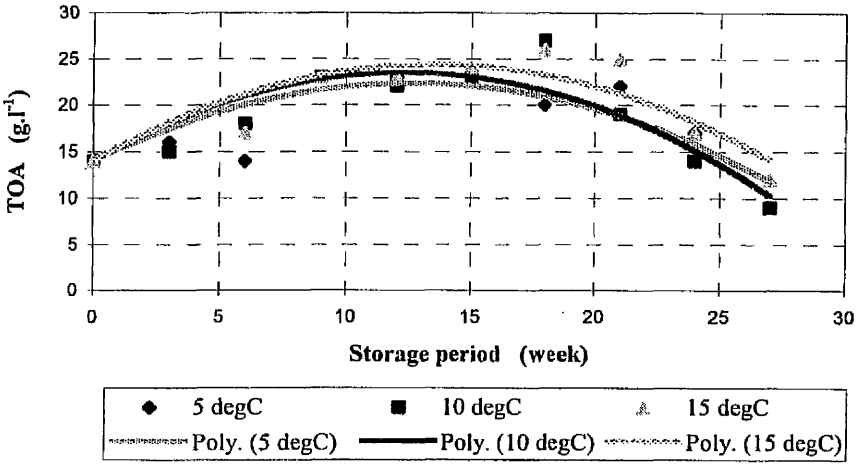
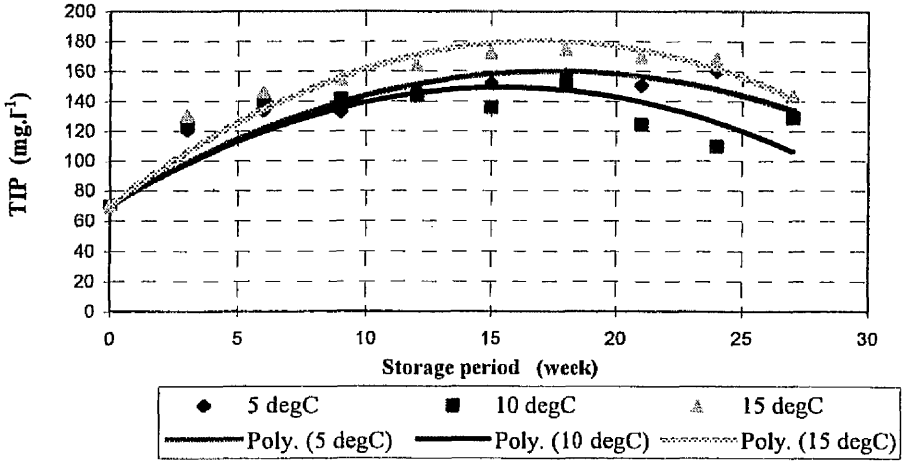


Figure 4.6 Total indoles and phenols (TIP) concentration of pig slurry at different temperatures



Note : Poly. = Polynomial trendline

levels lower than those measured at the beginning of storage (Figure 4.5). The ratio VFA/TOA during storage showed once again that it was changing with storage time. While it remained relatively constant during the first 18 weeks between 0.6 and 0.75, then with a rapid decrease of TOA, the ratio increased up to 1.5 for the storage temperature of 15°C. This rapid decrease of TOA while VFA remained high, this could possible the long chain of organic fatty acids (i.e. C_{16}-C_{28}) were broken down into the smaller ones, which have not been detected, therefore the TOA would be decreased whilst the VFA increased.

Total indoles and phenols (TIP)

The rapid increase of TIP content in the first 3 weeks (Figure 4.6), nearly doubling the starting concentration, was followed by a steady growth till week 18 when the concentration began to decrease, finishing at the 27th week of storage with approximately twice the starting concentration. The highest production of TIP occurred at 15°C, reflecting the highest (for all storage temperatures) rate of production of p-cresol component which contributed by 75% to TIP while only by 65% at the lower temperatures (Table 4.7).

Although the concentration of the rest of individual components, except phenol, remained relatively low, some of them, particularly skatole would have a large effect on the offensiveness of odour. The skatole concentration change, had a similar trend to that of TIP, rapidly increasing for all three temperatures during the first 10 weeks (Figure 4.7), when it had contributed to TIP by about 2%. Even though the skatole only increased by a small quantity, it may has contributed to a large extent to the offensive odour.

pH and ammoniacal nitrogen

The content of ammoniacal nitrogen was not significantly affected neither by the temperature nor by the storage time, and fluctuated around 2900 (± 200) $mg.l^{-1}$ (Table 4.8). Any variations of the pH values were therefore dependent on the organic acids' content and dissolved carbon dioxide concentration. At 15 and 5°C, the pH values decreased as VFAs (mainly acetic acid) content increased. However, at 10°C,

Table 4.7. Individual indoles and phenols of pig slurry stored at 5, 10 and 15 °C.

5° C					
Week	**Phenol** $mg.l^{-1}$	**P-cresol** $mg.l^{-1}$	**O-ethyl-phenol** $mg.l^{-1}$	**Indole** $mg.l^{-1}$	**Skatole** $mg.l^{-1}$
0	17.4	47.3	3.6	1.0	0.8
3	34.5	76.9	5.0	2.2	2.3
6	39.3	84.4	5.2	1.3	3.7
9	42.8	79.7	5.1	1.1	4.2
12	44.0	91.2	5.3	1.3	4.8
15	45.7	94.3	5.4	1.4	5.1
18	49.4	96.2	5.3	1.6	5.1
21	45.5	94.4	4.9	1.6	4.4
24	48.2	99.7	5.4	1.6	5.2
27	42.1	79.8	4.4	1.3	3.7

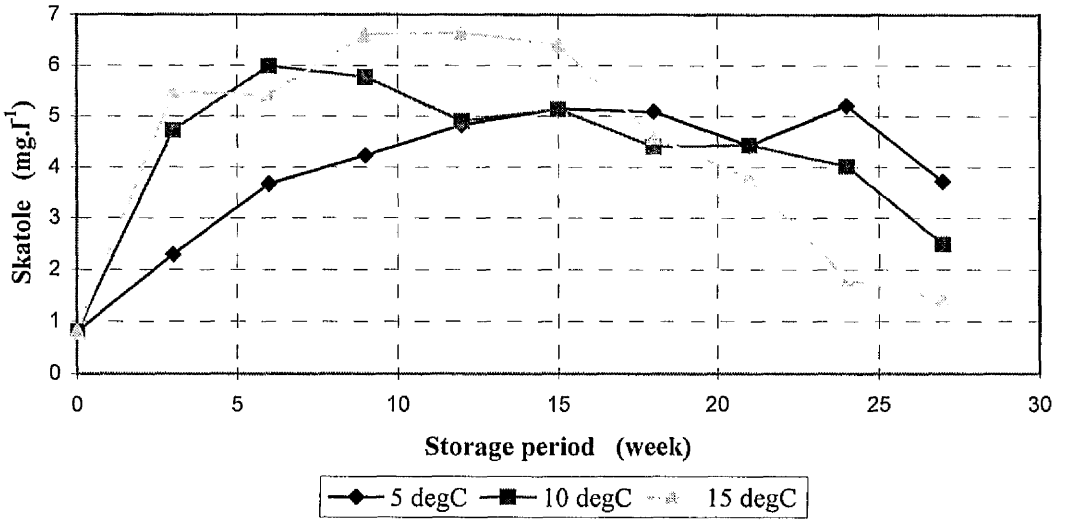
10° C					
Week	**Phenol** $mg.l^{-1}$	**P-cresol** $mg.l^{-1}$	**O-ethyl-phenol** $mg.l^{-1}$	**Indole** $mg.l^{-1}$	**Skatole** $mg.l^{-1}$
0	17.4	47.3	3.6	1.0	0.8
3	30.5	82.0	5.2	0	4.7
6	31.8	95.1	5.5	0	6.0
9	31.7	98.2	5.3	0.6	5.8
12	33.0	99.9	5.0	0.7	4.9
15	40.9	84.2	5.0	0.6	5.1
18	55.1	86.7	5.3	0	4.4
21	35.7	79.5	4.5	0	4.4
24	29.9	71.5	4.0	0	4.0
27	46.8	75.5	4.2	0	2.5

15° C					
Week	**Phenol** $mg.l^{-1}$	**P-cresol** $mg.l^{-1}$	**O-ethyl-phenol** $mg.l^{-1}$	**Indole** $mg.l^{-1}$	**Skatole** $mg.l^{-1}$
0	17.4	47.3	3.6	1.0	0.8
3	29.2	90.9	5.3	0	5.5
6	29.5	105.7	5.6	0	5.4
9	29.3	113.3	5.5	0	6.6
12	29.3	122.6	5.4	0	6.6
15	29.7	130.9	5.8	0	6.4
18	29.9	135.1	5.6	0	4.6
21	29.1	132.0	5.3	0	3.8
24	30.3	131.4	5.4	0	1.8
27	23.6	114.2	4.3	0	1.4

Table 4.8. Ammoniacal nitrogen, whole COD, Supernatant COD and pH of pig slurry stored at 5, 10 and 15 °C.

Week	NH_4^+-N mg.l^{-1}			COD Whole g.l^{-1}			COD Supernatant g.l^{-1}			pH		
	5 °C	10 °C	15 °C	5 °C	10 °C	15 °C	5 °C	10 °C	15 °C	5 °C	10 °C	15 °C
0	2650	2650	2650	117	117	117	19	19	19	6.8	6.8	6.8
3	2520	2730	2800	118	116	107	23	25	28	6.8	6.7	6.6
6	3220	2880	2880	110	108	105	23	24	25	6.7	6.6	6.6
9	2786	2709	2828	107	107	115	25	26	33	6.7	6.6	6.5
12	2940	3070	3190	113	112	114	28	31	34	6.7	6.8	6.7
15	2810	2720	3070	118	113	116	29	31	35	6.6	6.9	6.5
18	2910	2500	2700	120	107	117	28	32	34	6.6	7.0	6.5
21	2670	2850	3170	118	106	120	26	30	34	6.6	7.0	6.5
24	2912	2760	3045	119	106	116	25	32	34	6.6	7.3	6.5
27	3080	2930	3560	128	114	132	28	31	36	6.8	7.4	6.9

Figure 4.7 Skatole concentration of pig slurry at different temperatures



the pH value increased gradually from acidic to an alkaline level probably because of the acid content decrease.

Supernatant chemical oxygen demand (CODs)

The COD of supernatant increased steadily and by the 15th week reached its maximum levels, approximately 45% higher than the starting level, which were, with minor fluctuation, maintained till the end of the storage period. This increase was expected, and as for cattle slurry was caused by the anaerobic degradation and solubilisation of solids.

5. LABORATORY SCALE REACTOR TREATMENT: STUDY 1

5.1 Introduction

This chapter draws upon the literature review of aeration methods for livestock slurry treatment in order to design a laboratory treatment system. A laboratory scale reactor was thus constructed for the preliminary study for a continuous "steady state" aerobic treatment process. This preliminary study deals with a series of laboratory experiments designed to investigate the effect of minimal aeration, with short residence time, on biological and chemical aspects of livestock slurry, particularly odour offensiveness removal. The oxygen mass balance, in term of COD removal, was also analysed, calculated and related to the solids concentration. The total oxygen requirement for the treatment, necessary for odour removal, was compared with models described by Evans *et al.* (1983), and Sneath *et al.* (1992). The findings were used to provide a reliable basis for the design of a full-scale system.

5.2 Experimental design and methods

Two experiments were carried out in this study:

Experiment 1: cattle slurry,

Experiment 2: pig slurry.

Both experiments were designed to treat 45 litres of slurry for two passes in a single stage reactor, each with a 1 day residence time (i.e. two cycles, "2" day residence time) (Chapter 5.2.2.3). Therefore the total duration of continued treatment and storage required was 90 days.

This treatment period simulated an average storage period on farm. The slurry should be therefore continuously maintained at a "faintly offensive" odour condition during the storage before spreading.

Fresh raw slurry was added into the feed storage reservoir weekly. The feed raw slurry was treated in the reactor vessel, then the treated mixed liquor (ML) was stored until the first run was completed. Afterwards, the stored aerobically treated slurry was used as feed slurry for the second run, after which it was stored once more. Therefore the slurry was treated twice. The summaries of the treatment conditions are shown in Table 5.1.

The details of the experimental method, materials and conditions are described in following Chapters 5.2.1 and 5.2.2.

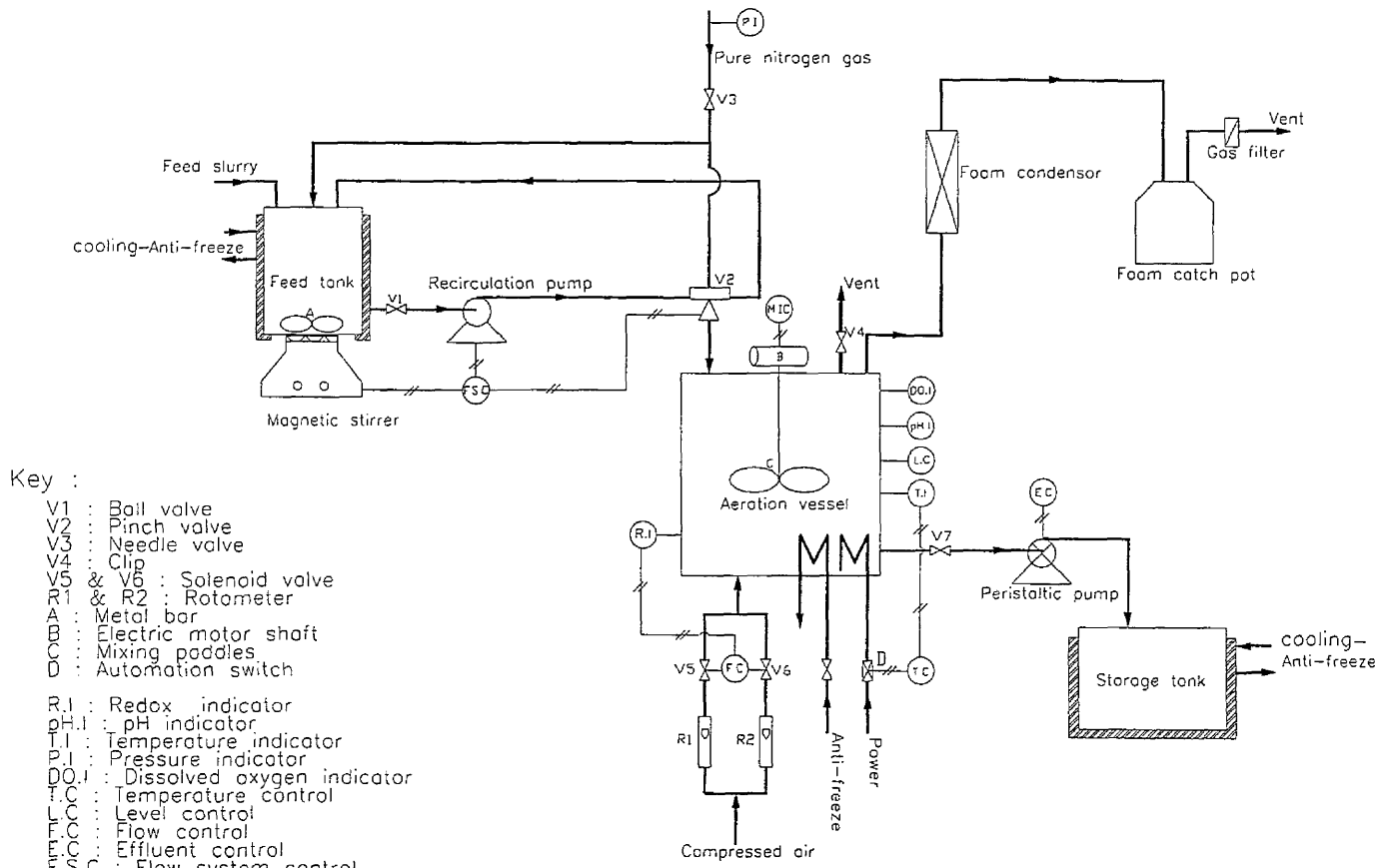
Table 5.1 Treatment conditions of Experiments 1 and 2 (Study 1)

Condition	Experiment	
	1 (cattle slurry)	2 (pig slurry)
Nominal residence time, *d*	2	2
Actual residence time, *d*	1.8	1.8
Treatment period, (each cycle) *d*	45	45
Total treatment period, *d*	90	90
Redox potential, mV_{Ecal}	-150	-150
Temperature, ^{o}C		
Feed	10	10
Reactor vessel	15	15
Store	10	10

5.2.1 Process and apparatus description

The complete treatment system used in Experiments 1 and 2 is illustrated in Figure 5.1. The process configuration was based on a single stage treatment (Figure 5.2). The reactor working volume was maintained by an automatic control of regular feeding and treated mixed liquor removal. The conditions thus closely approached those found in a chemostat, and hence, the reactor could be referred to as being a continuous culture treatment system. The culture was continuously mixed in the reactor vessel (Chapter 5.2.2.5). The slurry was fed into the reactor regularly (Chapter 5.2.2.3) from a slurry feed reservoir, and the treated mixed liquor was discharged intermittently from the reactor. The discharged volume was measured and collected in a measuring cylinder before transferring into the storage tank, which was used to store the treated mixed liquor until the first run was completed.

Figure 5.1
Laboratory Scale Aeration System



Key :

V1 : Ball valve
V2 : Pinch valve
V3 : Needle valve
V4 : Clip
V5 & V6 : Solenoid valve
R1 & R2 : Rotometer
A : Metal bar
B : Electric motor shaft
C : Mixing paddles
D : Automation switch

R.I : Redox indicator
pH.I : pH indicator
T.I : Temperature indicator
P.I : Pressure indicator
DO.I : Dissolved oxygen indicator
T.C : Temperature control
L.C : Level control
F.C : Flow control
E.C : Effluent control
F.S.C : Flow system control
M.I.C : Motor indicator and control

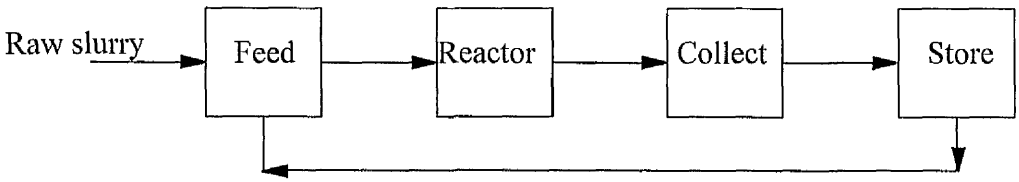


Figure 5.2 Flow diagram of laboratory Study 1

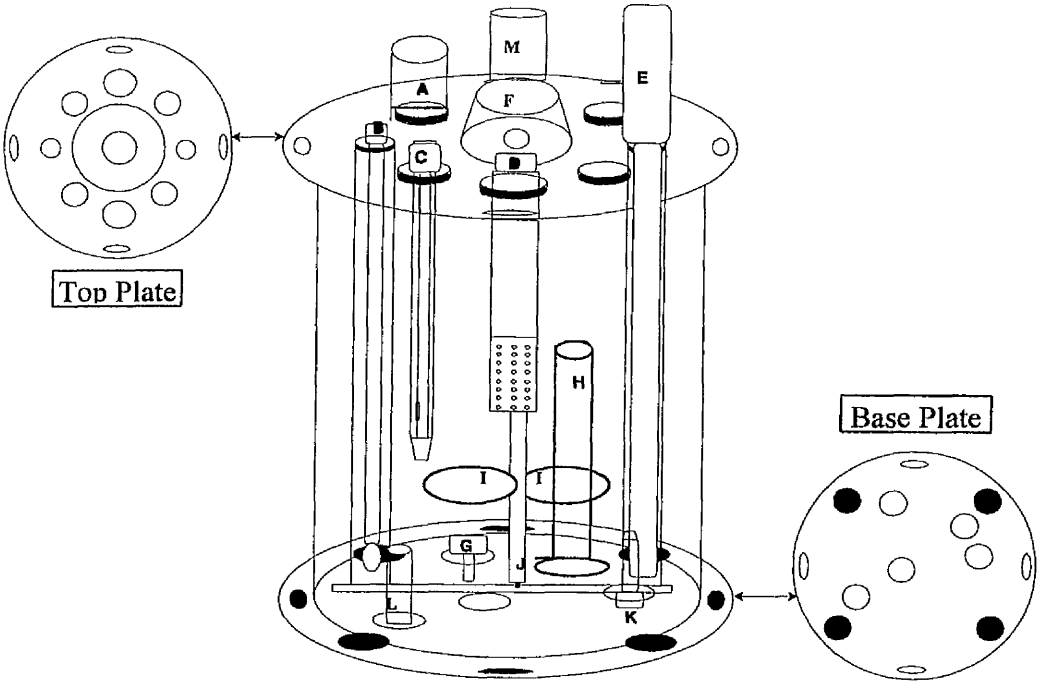
5.2.1.1 Aerobic reactor and auxiliary apparatus

An aeration vessel with 1.4 litre nominal volume (Biotec Ltd) was used as a laboratory scale reactor (Figure 5.3). It was made from a glass cylinder of 150mm length and internal diameter of 110 mm enclosed with a stainless steel lid and a base, supported by 4 stainless-steel stand-rods. The reactor vessel was gas tight and the glass wall of reactor was sealed by rubber gasket. It was possible to avoid any leaking or ingress of atmospheric air. Through the base of vessel was projected a stainless steel cooling finger. A stainless steel stirrer was positioned at the centre of the vessel. An 15 mm internal diameter PVC overflow tube protruding from the bottom of reactor vessel, and was used to maintained the working volume of 0.9 litre.

A 40 litres plastic storage tank was located below the reactor vessel. This container was surrounded with cooling copper coil and insulated with polystyrene. It was also covered by a polystyrene lid, which floated on the surface of the mixed liquor (ML), thus minimising the air diffusion into the ML.

A 15 litres glass jar was used as a slurry feed tank. It was placed on a magnetic stirrer (Voss S/MAG/30). This feed tank was surrounded with cooling copper tubing connected to a chiller circulator (Grant LC 10), and insulated with polythene bubble wrap.

Figure 5.3. 1 litre laboratory aerobic reactor.



Key:
A = Foam overflow outlet.
B = Temperature sensor.
C = Redox probe.
D = Dissolved oxygen probe.
E = Heating element.
F = Magnetic drive for mixing paddle.
G = Sintered glass air sparger.
H = Desludging outlet.
I = Mixing paddle.
J = Tungsten-carbide bearing.
K = Temperature control thermister.
L = Cooling finger.
M = Slurry dosing point.

5.2.2 Process control and monitoring parameters

The operation parameters such as air supply, redox potential, dissolved oxygen level, residence time, temperature and mixing in this process were controlled automatically, so that consistent conditions could be achieved at their pre-set desired levels.

5.2.2.1 Air supply and DO level

Compressed air was used as the oxygen source. It was passed through a moisture trap (Norgren, England) in order to remove any residual water and oil contamination. Air was then introduced into the reactor at approximately 800-900 kPa, through a fine sintered glass sparger (BDH). The amount of air supplied was measured using two Gap rotameters; one with a maximum flowrate of 1.2 $l.min^{-1}$ to indicate the low flow, and another one with a maximum flowrate of 2 $l.min^{-1}$ to indicate the high flow. The actual flow rates were regulated using flowstats and needle valves (G.A. Platon Ltd). On/off switching of high and low air flow was controlled by redox potential feed back using a pH/ORP meter.

5.2.2.1.1 Redox potential

Redox potential was measured and used to control the low levels of dissolved oxygen in the mixed liquor in this experiment. The redox electrode (Pt/Calomel) was calibrated before use, and the detail of electrode and calibration method was described in section 3.14. Redox was chosen because its control could offer greater reliability and higher accuracy than dissolved oxygen measurement when measuring lower levels of DO (Hewitt, 1950). Redox control has also been found to be effective in the laboratory scale systems (Williams *et al.*, 1989).

The reactor was fitted with a Redox electrode (Russell pH. CMPTR/CAL/120/SA) which was connected to an EIL 91B industrial pH/ millivolt meter/controller. The redox potential output from the meter was transmitted as an electrical current signal (0 - 10mA) which was connected across a multiturn potentiometer. The potentiometer converted the current signal into a voltage which activated the potentiometric chart recorder to be operated on 0 - 1mV scale, thus allowing redox values to be recorded visually and monitored. The reactor was operated with the redox potential controlled between predetermined set points (Table 5.1) using two solenoid valves via a trip amplifier which was built into the meter. These solenoid

valves were activated automatically such that, between the two set points, a low air flow was supplied to the reactor vessel, and if the redox values fell below the lower set point, a high air flow was supplied in addition to this. Above the higher set point, all the air supply was switched off. As a result, the redox potential was maintained at an average of -150 mV E_{cal} (± 30 mV E_{cal}), and hence, the dissolved oxygen level was close to 0% of saturation resulting in a minimal DO concentration in the ML.

5.2.2.1.2 Dissolved oxygen (DO) concentration

DO measurement was also used to monitor the dissolved oxygen level, other than the redox potential, in the mixed liquor. This was to ensure and further confirm that the minimal aeration was reached and maintained, thus avoiding excessive use of air.

A dissolved oxygen probe was immersed in the mixed liquor from the top of reactor and connected to the digital display of a DO meter (ABB Ltd), and hence the DO value was monitored in % of saturation and recorded. The detail of DO measurement was described in Chapter 3.16.

5.2.2.2 Residence time (RT) and dosing control strategy

The residence time at a constant treatment temperature is one of the main parameters controlling the characteristic of treated slurry. In this work, odour offensiveness control was a main concern. Thacker & Evans (1986) suggested that short term aeration (i.e. < 2 day) would be sufficient to remove the odour offensiveness. Therefore two treatments of a nominal residence time of 1 day (i.e. 2 day residence time in total) were used in these experiments (Table 5.1). The time period for the overall treatment and storage of slurry was designed to be 90 days (Chapter 5.2 Experimental design & methods). Thus the volume of slurry to be treated was in excess of 45 litres (including samples for the analysis).

The 15L feed slurry container was manually filled every week with fresh, well-mixed, slurry (approximately 10 litres). Feeding into the reactor and the discharge were controlled by a process timer described by Owens *et al.* (1973). Firstly, the feed slurry was well mixed for 2 minutes in the feed tank with a magnetic stirrer. Then the feed centrifugal pump was switched on and circulated the slurry through the dosing

apparatus (Owens & Evans, 1972) and a small portion of slurry was trapped in a pipe above a pinch valve. The positive pressure of nitrogen (1 psi) was required to force the dosing volume into the reactor after the pinch valve was opened. The reactor was fed every 10-11 minutes and the mean dosing volume was calibrated to be approximately 7 cm^3.

The mixed liquor (ML) was removed hourly by a reversible peristaltic pump. The discharge portion of ML was pumped through a silicon rubber tubing (Sterilin Ltd) with 12 mm outside diameter via an overflow PVC tube in the reactor. Initially, the pump was operated in reverse, pumping the overflow ML into the reactor, and mixed with the ML inside the reactor. Then the required volume of ML was pumped out into measuring cylinder and finally the tube was cleared out by reversing the pump again. The completed discharge sequence, *initiated every half an hour,* lasted approximately 1-2 minutes.

5.2.2.3 Treatment Temperature

The temperature of the reactor was controlled and maintained at 15°C (± 0.5°C). This temperature was chosen to simulate the average slurry storage temperature in UK. A thermistor probe was used to detect the temperature in the reactor. This probe was inserted into ML through the bottom plate of the reactor and was connected to a temperature meter/controller set to control the temperature at 15°C. The controller activated the heating system cartridge heater.

A separate temperature sensor was also inserted in the reactor. This sensor was connected to a DO/Temperature meter digital display (ABB Ltd), which was used to monitor the temperature of the reactor vessel, this temperature was recorded and noted daily.

The raw and discharge ML were stored at 10°C (± 2°C) and this temperature was maintained using a coolant at approximately 0°C. The coolant was pumped through the cooling coil wound around the feed and storage tank.

5.2.2.4 Mixing

The reactor was stirred by stainless steel paddles which was attached to a central shaft. The shaft was rotated by an electric motor through a flexible drive shaft and magnetic coupling at approximately 200 rpm. This speed ensured an adequate mixing of the contents without inhibiting floc formation, also it helped to provide a good oxygen transfer efficiency at low aeration intensities.

5.2.2.5 Foam control

Foaming is always a problem in the aeration systems either in laboratory or a full scale reactor. In these experiments, the foam was controlled by using a 50 cm long and 10mm I.D PVC pipe, which was connected to the top of the reactor vessel via a silicon tubing. Foam, carried by exhaust gases was trapped in the tube and then the foam reformed into the liquid phase and flow back to the reactor by gravity. When the foam was excessively generated, a small amount of antifoam agent (Polypropylene Glycol 2025) was added manually into the pipe.

5.2.3. Slurry sampling and preparation

Samples of raw (feed), treated (ML) and anaerobically stored slurry were taken twice a week for biochemical analysis throughout the monitoring period. Slurry sample was well mixed before sampling. Analyses for TS, VS, TSS, VSS, COD, BOD_5, Kj-N, NH_4^+-N, pH, VFA, TOA and TIP were performed according to APHA (1992) as described in Chapter 3.

5.2.3.1 Experiment 1: Cattle Slurry

Fresh cattle slurry was collected from the floor channel of a cattle unit in Gibbsyard SAC Auchincruive farm. Cattle were fed on a silage diet supplemented with concentrated yeast. The excreta consisted of faeces and urine. As it was too thick, it was diluted to a slurry with tap water. Solid/liquid separation was conducted before using in this experiment. Mechanical separation was manual and a 5 mm sieve was used.

Before the slurry was used as a feed to the reactor, the slurry was further diluted with tap water to a Chemical Oxygen Demand (CODw) concentration of 38 $g.l^{-1}$. The diluted slurry was then poured into four identical 25L containers. The resulting

mixture was stored at 5°C. The mean composition of raw cattle slurry is shown on Table 5.2.

5.2.3.2 Experiment 2: Pig slurry

Pig slurry was collected from the reception pit of a commercial piggery farm (SAC, Aberdeen). Pigs were fed on a barley diet. The slurry was also treated to similar dilution and separation processes as the cattle slurry before being used in the experiment. The mean composition of the raw slurry used for this study was shown on Table 5.3.

Table 5.2. Initial characteristics of the feed cattle slurry in Treatments 1 and 2 (Study 1)

Cattle slurry				
Parameter	Treatment 1		Treatment 2	
	$g.l^{-1}$	ratio/TS (w/w)	$g.l^{-1}$	ratio/TS (w/w)
TS	24.3	1.0	21.2	1.0
TS(s)	11.7	0.5	10.2	0.5
TSS	10.7	0.4	9.2	0.4
VS	17.5	0.7	15.2	0.7
VS(s)	6.2	0.3	5.5	0.3
VSS	10.3	0.4	9.1	0.4
CODw	38	1.6	27.7	1.3
CODs	13.8	0.6	11	0.5
BOD_5w	9.1	0.4	2.6	0.1
BOD_5s	5.1	0.2	1.4	0.1
Kj-N	1.7	0.1	1.5	0.1
NH_4^+-N	0.94	0.0	0.8	0.0
VFA	2	0.1	1.2	0.1
TIP	0.05	0.0	0.01	0.0
TOA	4.4	0.2	2.7	0.1
pH	8	-	8	-

Individual volatile fatty acid (VFA)				
Component	Treatment 1		Treatment 2	
	$mg.l^{-1}$	% of VFA	$mg.l^{-1}$	% of total VFA
Acetic	1350	69	703	58
Propionic	290	15	268	22
I-Butyric	60	3	60	5
N-Butyric	160	8	93	8
I-Valeric	65	3	69	6
N-Valeric	25	1	15	1
Total VFA	1950	100	1208	100

Individual Indoles and Phenols				
Component	Treatment 1		Treatment 2	
	$mg.l^{-1}$	% of TIP	$mg.l^{-1}$	% of TIP
Phenol	19.6	40	4.2	33
P-cresol	26.5	55	7.5	60
O-etyl-phenol	1.5	3	0	0
Indole	1	2	0.9	7
Skatole	0	0	0	0
TIP	48.6	100	12.6	100

Table 5.3. Initial characteristics of the feed Pig slurry in Treatments 1 and 2 (Study 1)

Pig slurry				
Parameter	Treatment 1		Treatment 2	
	$g.l^{-1}$	ratio/TS (w/w)	$g.l^{-1}$	ratio/TS (w/w)
TS	30.5	1.0	26.6	1.0
TS(s)	7.3	0.2	6.8	0.3
TSS	17.2	0.6	14.1	0.5
VS	24.3	0.8	18.8	0.7
VS(s)	3.4	0.1	2.7	0.1
VSS	14.8	0.5	14.4	0.5
CODw	38.0	1.2	33	1.2
CODs	8.3	0.3	6.4	0.2
BOD_5w	9.5	0.3	4.7	0.2
BOD_5s	4.2	0.1	1.5	0.1
Kj-N	2.9	0.1	2.6	0.1
NH_4^+-N	2.0	0.1	1.4	0.1
VFA	3.0	0.1	0.8	0.0
TIP	0.0	0.0	0.01	0.0
TOA	6.6	0.2	4	0.2
pH	8.5	-	8.9	-
Individual volatile fatty acid (VFA)				
Component	Treatment 1		Treatment 2	
	$mg.l^{-1}$	% of VFA	$mg.l^{-1}$	% of VFA
Acetic	2155	73	546	67
Propionic	480	16	168	21
I-Butyric	90	3	36	4
N-Butyric	110	4	27	3
I-Valeric	95	3	38	5
N-Valeric	31	1	2	0
Total VFA	2961	100	817	100
Individual Indoles and Phenols				
Component	Treatment 1		Treatment 2	
	$mg.l^{-1}$	% of TIP	$mg.l^{-1}$	% of TIP
Phenol	5.8	20	4.9	49
P-cresol	22	74	5	51
O-ethyl-phenol	1.9	6	0	0
Indole	0	0	0	0
Skatole	0	0	0	0
TIP	29.7	100	9.9	100

5.3 Results and discussion

5.3.1 Experiment 1: Cattle slurry

The treatment conditions were measured and recorded throughout the treatment period. The mean values of treatment parameters were calculated after steady state and are shown in Table 5.4. The steady state condition was reached after 4 days of starting the reactor.

Table 5.4. Mean values of operation conditions of Experiment 1 of cattle slurry in Treatments 1 and 2.

Parameters	Treatment 1			Treatment 2		
	Mean	S.D.	n	Mean	S.D.	n
Redox value, $mV\ E_{cal}$						
min	-141.5	4.3	30	-143.3	24.8	32
max	-168.0	10.6	30	-155.7	27.7	32
average	-153.8	5.6	30	-150.8	9.2	32
Temperature, ^oC						
reactor	15.0	0.1	30	15.0	0.2	32
store	10.3	1.1	30	10.4	1.3	32
Working volume, *litre*						
reactor	0.9	0.0	30	0.9	0.0	32
discharge-ML	0.84	0.1	30	0.92	0.2	32

The monitoring period of this experiment started on 24/4/1998 and finished on 19/6/1998. During the monitoring period, the chemical and biochemical characteristics of feed, treated (ML) and stored cattle slurry were analysed (Appendix C Tables C1 – C18). The results of Treatment 1 and 2 are presented separately.

The characteristics of feed cattle slurry and treated mixed liquor (ML) throughout the treatment were expressed as mean values with standard deviations and are shown in Table 5.5. The mean concentration of individual characteristics of feed cattle slurry after treatment were lower than in the raw initial stored slurry characteristics (Table 5.2), especially CODw and BODw during treatment. This suggested that there was either inadequate mixing or higher ambient temperatures promoting microbial activity in the feed slurry.

Change of slurry characteristic after Treatment 1

Total volatile fatty acids (VFA)

The mean values of feed slurry and ML (treated slurry) characteristics are shown in Table 5.5. The effect of continuous minimal aeration of cattle slurry was most evident on VFA concentration. There was significant difference ($p<=0.05$) in VFA concentration between feed and ML. This percentage destruction of VFA, which agreed with the finding by Svoboda & Sym (1997) was 95% from 1900 to 100 $mg.l^{-1}$. This final value was less than a half of the acceptable level (230 $mg.l^{-1}$) of odour offensiveness (Williams, 1984).

The mean values of individual VFA components in feed and ML are illustrated in Figure 5.4. The highest contribution by 68% and 61% to the total VFA in feed and ML respectively, was acetic acid. The lowest was N-valeric acid, which contributed only 1%. All the components were decreased significantly ($p<0.05$) after treatment.

The treatment was successful in controlling the odour of cattle slurry in terms of VFA concentration. During the first 15 days of storage after treatment, the VFA concentration (Figure 5.5) rapidly increased from 120 $mg.l^{-1}$ to reach approximately half of the mean VFA value (1.9 $g.l^{-1}$) of feed slurry. Then after 40 days, it increased slowly to 1200 $mg.l^{-1}$. During the storage period after Treatment 1, the fastest regeneration rate of individual VFA component, approximately 14 $mg.l^{-1}.d^{-1}$, was that of acetic acid as shown in Figure 5.6. Regeneration of propionic acid was high (approximately 5 $mg.l^{-1}.d^{-1}$ to maximum 270 $mg.l^{-1}$) and I-butyric, N-butyric , I-valeric and N-valeric acid increased only a little (<100 $mg.l^{-1}$).

Total organic acid (TOA)

The mean concentrations of TOA in feed slurry and ML are shown in Table 5.5. The variation of TOA concentration in feed slurry was greater than in the ML. Reduction of TOA concentration was significant ($p<0.05$), and 70% of TOA was removed by the treatment. Thacker and Evans (1986) found a highly significant correlation between

Table 5.5 Characteristics of the feed and ML of cattle slurry after the steady state periods during Treatment 1

Parameter		Feed				ML			
		Mean	S.D.	n	% of TS (w/w)	Mean	S.D.	n	% of TS (w/w)
TS	$g.l^{-1}$	22.5	1.7	6	100	21.7	2.1	11	100
TS(s)	$g.l^{-1}$	11.1	0.5	6	49	9.4	0.6	11	43
VS	$g.l^{-1}$	9.6	1.6	6	43	15.6	1.8	11	72
VS(s)	$g.l^{-1}$	6.2	0.4	6	28	5.1	0.5	11	23
TSS	$g.l^{-1}$	15.6	2.3	6	69	11.1	2.1	11	51
VSS	$g.l^{-1}$	9.1	1.3	6	41	10.3	1.6	11	48
CODw	$g.l^{-1}$	32.4	2.8	6	144	27.5	3.7	11	127
CODs	$g.l^{-1}$	13.2	0.6	6	59	8.6	1.3	11	40
BOD_5w	$g.l^{-1}$	5.4	0.7	6	24	2.8	0.6	11	13
BOD_5s	$g.l^{-1}$	4.0	0.7	6	18	0.7	0.3	11	3
Kj- N	$g.l^{-1}$	1.6	0.06	6	7	1.5	0.10	11	7
NH_4^+-N	$g.l^{-1}$	0.9	0.03	6	4	0.6	0.03	11	3
pH	-	8.6	0.2	6	-	9.0	0.1	11	-
TOA	$g.l^{-1}$	4.2	0.3	6	19	1.3	0.1	11	6
VFA	$g.l^{-1}$	1.9	0.2	6	8	0.1	0.02	11	0.4
TIP	$g.l^{-1}$	0.048	0.006	6	0.2	0.001	0.0	11	0.0

S.D. = standard deviation
n = number of sample analysis

Figure 5.4 Mean values of individual volatile fatty acid (VFA) concentration in the feed and in the ML of cattle slurry in Treatments 1 and 2

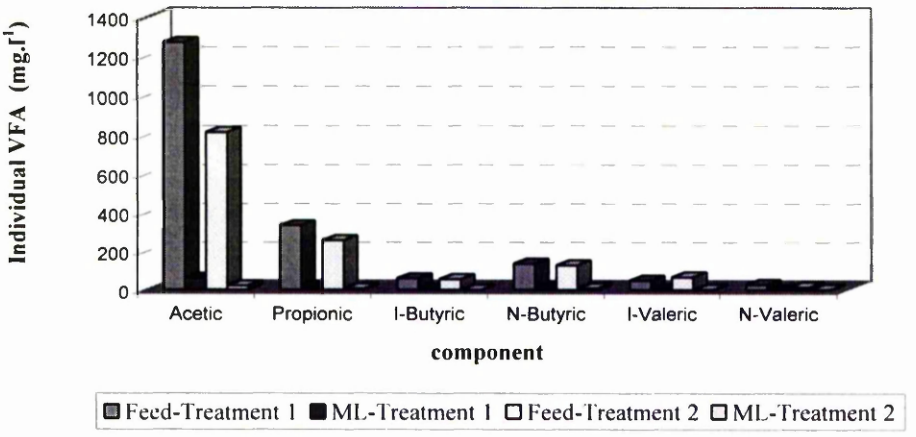


Figure 5.5 Total volatile fatty acids (VFA) concentration in the ML of cattle slurry during storage after Treatments 1 and 2 (Study 1)

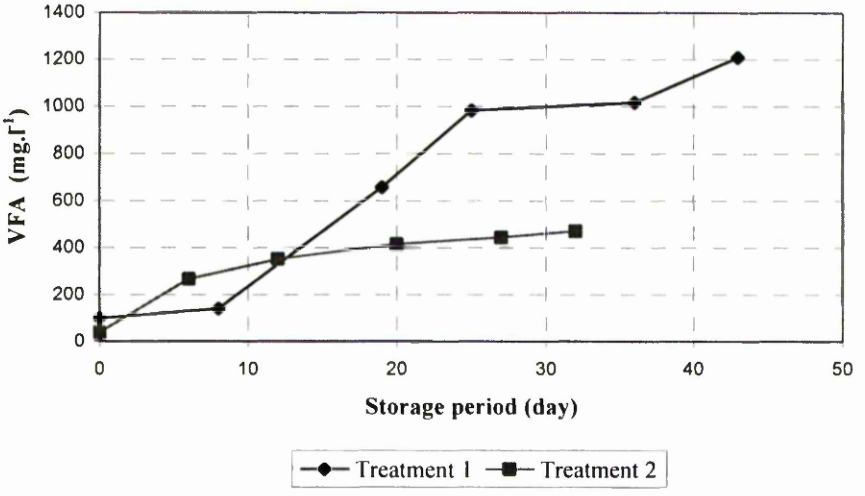


Figure 5.6 Individual volatile fatty acid (VFA) concentration in the ML of cattle slurry during storage after Treatment 1 (Study 1)

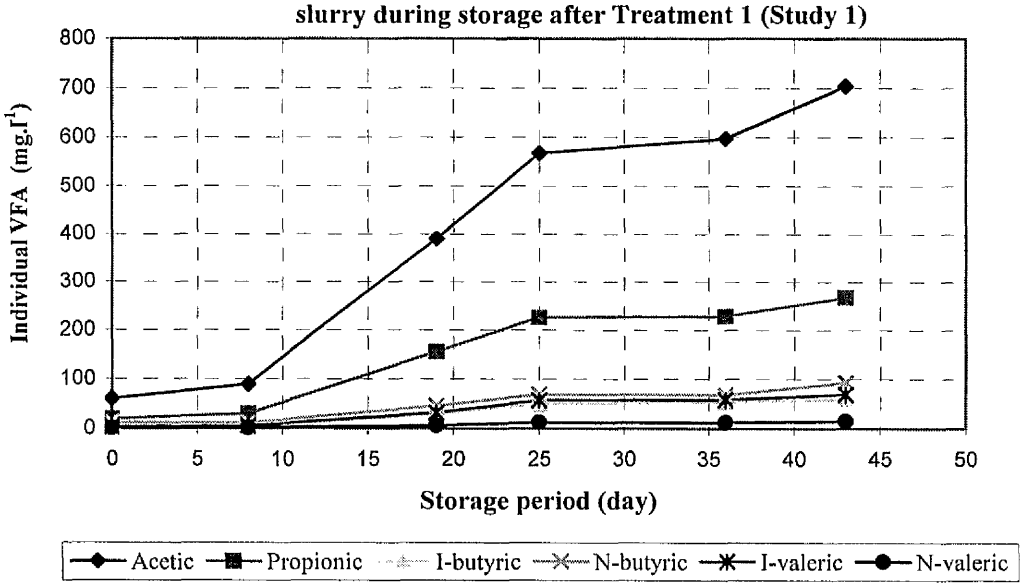
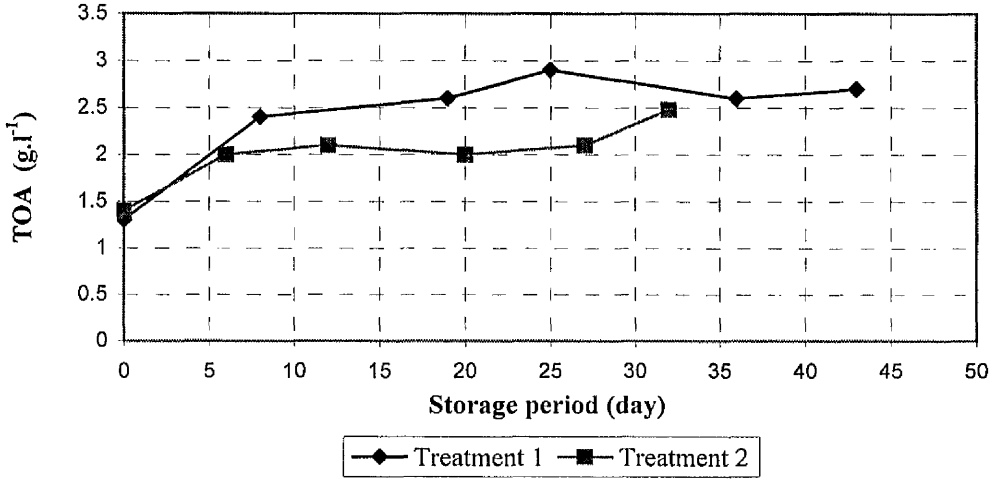


Figure 5.7 Total organic acid (TOA) concentration in the ML of cattle slurry during storage after Treatments 1 and 2 (Study 1)



the logarithm of the TOA concentration and the odour offensiveness of pig slurry using equation (5.1) below:

Odour offensiveness = 2.378 * log (TOA) + 2.327 Equation (5.1)

In this study, the concentration of TOA in feed slurry ranged from "definite offensive" odour rating 3.8 to "faintly offensive" odour rating 2.5 after the treatment, depending on treatment condition.

During anaerobic storage after Treatment 1, the change of TOA was low and is shown in Figure 5.7. The concentration of TOA increased from 1.3 to 2.9 $g.l^{-1}$, by 120%. The fastest regeneration rate of TOA was from 1.3 to 2.4 $g.l^{-1}$ during the first 8 days, then become relatively constant and fluctuated between 2.4 to 2.9 $g.l^{-1}$ thereafter This shows that there was only limited amount of organic material available for generation of the organic acids at the beginning of storage. Then the substrate became limited for further anaerobic degradation during storage.

Total Indoles and Phenols (TIP)

The mean concentration of TIP in the feed cattle slurry is shown in Table 5.5. TIP concentration was low at 48.5 $mg.l^{-1}$ and presented only 0.2% (w/w) of TS. The highest component of indoles and phenols (Figure 5.8) in the feed slurry was p-cresol (24 $mg.l^{-1}$), contributing 49% of TIP, whilst skatole was detected only in a few samples. However, TIP removal was the highest of all analysed parameters at 99% of TIP. Such high removal of TIP could be explained by that they were present in low concentrations and were soluble in the liquid, thus were being oxidised and eliminated faster than any other slurry components (Spoelstra, 1980; Williams, 1981). Most of the individual indoles and phenols were completely removed except phenol, which was detected in trace amounts in 4 out of 10 samples (Figure 5.8) during Treatment 1.

TIP increased approximately 25% (12.6 $mg.l^{-1}$) (Figure 5.9) of the mean value of feed slurry (48.5 $mg.l^{-1}$) after 36 days of anaerobic storage. Figure 5.10 illustrates the

Figure 5.8 Mean values of individual Indoles and Phenols concentration in the feed and in the ML of cattle slurry in Treatments 1 and 2 (Study 1)

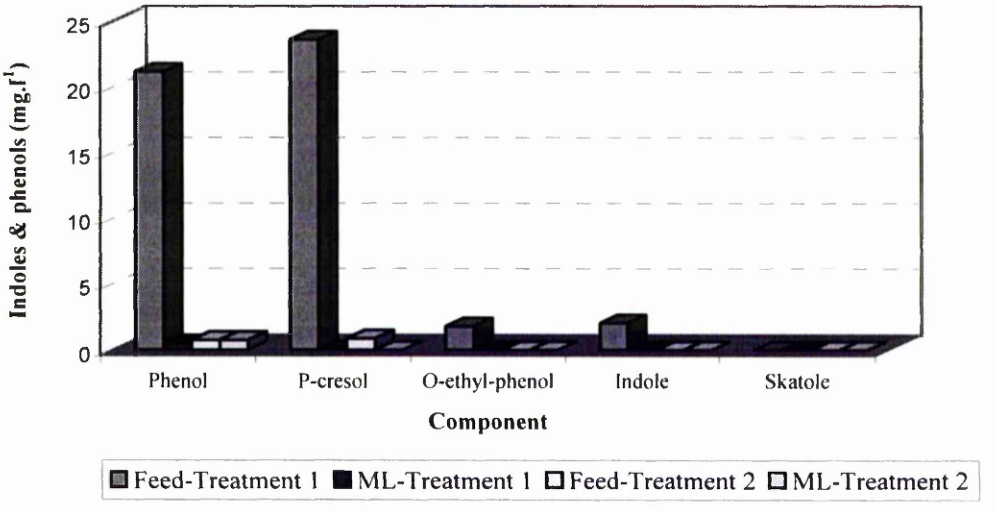
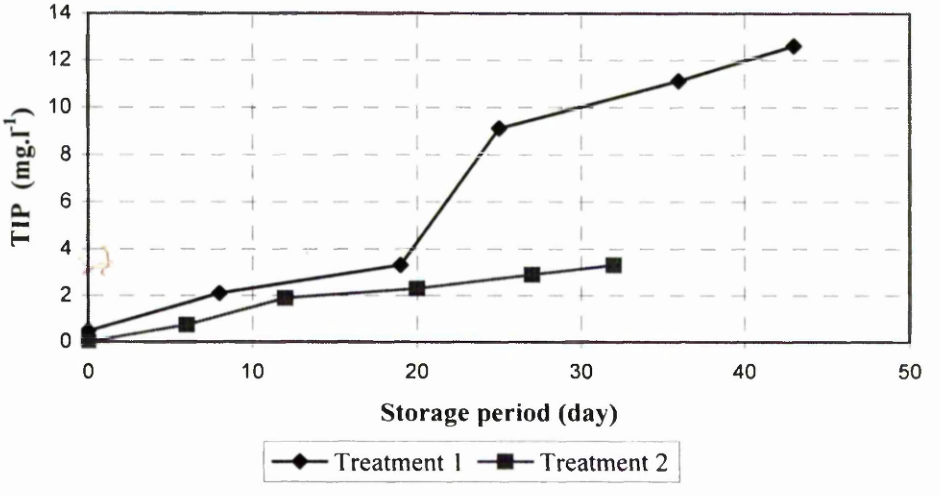


Figure 5.9 Total indoles and phenols (TIP) concentration in the ML of cattle slurry during storage after Treatments 1 and 2 (Study 1)



changes of individual TIP. Phenol, p-cresol and indole were increased, p-cresol increased the most, approximately 60% of TIP, whilst the O-ethyl-phenol and skatole were not detected during storage period.

Chemical oxygen demand (COD)

The CODw and CODs of feed slurry and ML varied (Table 5.5). These variations were due to the inadequate mixing in the feed and by additions of antifoam agent into the reactor. The total COD of anti-foam was found to be 1,150 $g.l^{-1}$ from the laboratory test. The decrease of CODw was only 15% from 32.4 to 27.5 $g.l^{-1}$ during treatment, indicating 4.9 g O_2 l^{-1} was consumed. Reduction in the CODs was greater than the CODw and approximately 78% of CODs was removed, because the soluble fraction was always removed faster than the CODw. CODw/TS ratio in the feed slurry and ML were similar, 1.4 and 1.3 respectively. These ratios were very similar to those of Evans *et al.* (1983).

During anaerobic storage, CODw and CODs did not change widely (Appendix C Table C7). CODw fluctuated at 27.2 $g.l^{-1}$, this value was same as the COD of ML. CODs was increased by 20% from 8.6 $g.l^{-1}$ to 10.8 $g.l^{-1}$. This increase of CODs was because of anaerobic degradation of solids materials as with VFA and TIP and BODs.

Comparison between predicted and actual observed values of COD

The treated COD value can be predicted using the mathematical model (equation 2.4) (Chapter 2.2.) derived by Evans *et al.* (1983). By knowing the value of feed slurry and residence time (0.9 day), the predictive value of treated CODw was calculated (Table 5.6). Although this model was used for calculating the pig slurry, there was only 1% difference between the calculated and observed values. The predicted CODw value was in good agreement with those actual observed value of cattle slurry.

Figure 5.10 Concentration of individual Indoles and Phenols in the ML of cattle slurry during storage after Treatment 1 (Study 1)

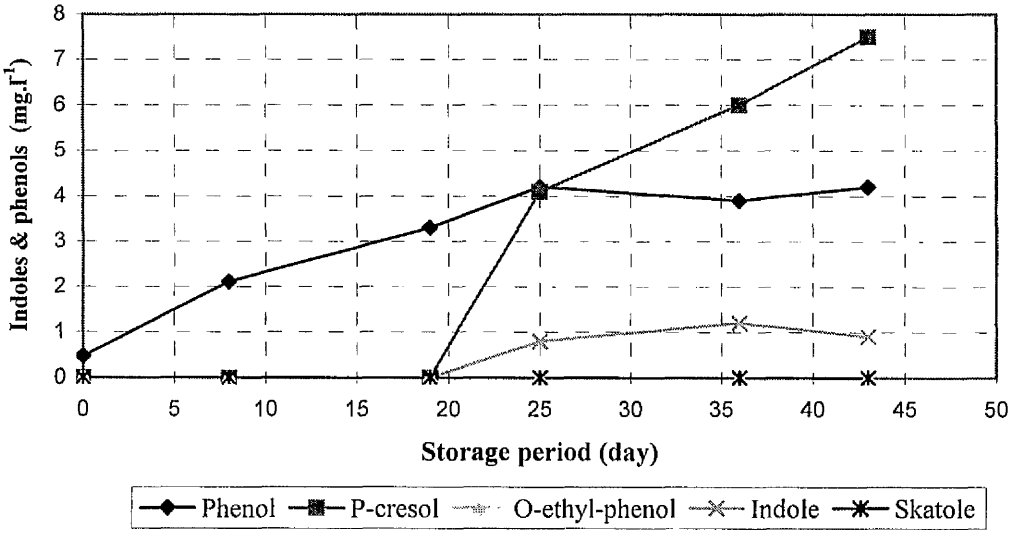


Figure 5.11 Supernatant COD and BOD_5 in the ML of cattle slurry during storage after Treatments 1 and 2 (Study 1)

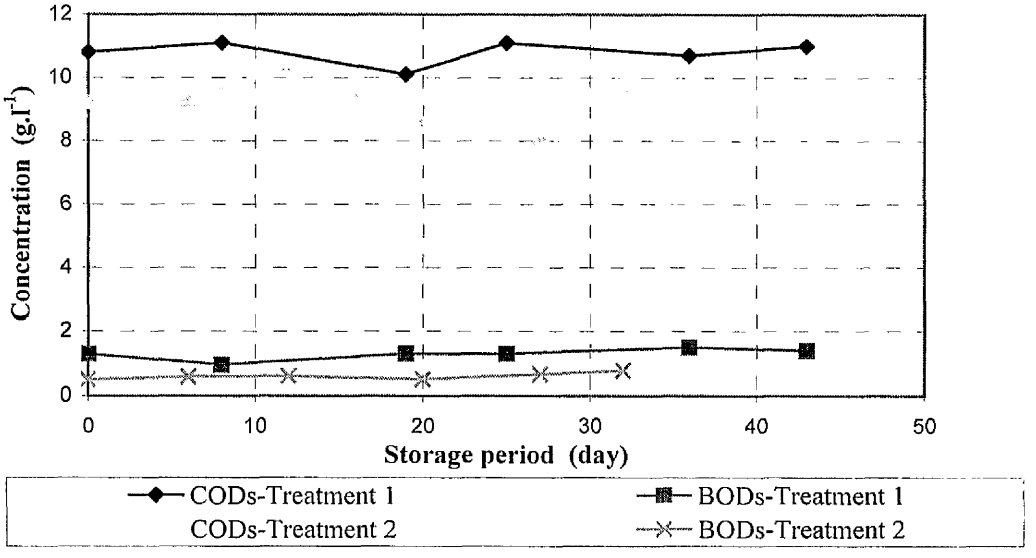


Table 5.6. Mean values of observed and predicted TS, TSS and CODw of cattle slurry in Treatment 1 and Treatment 2 (Study 1), using equations in Evans *et al.* (1983), and expressed in % difference = [(observed – predicted)/observed * 100].

	Treatment 1			Treatment 2		
	TS	TSS	CODw	TS	TSS	CODw
Observed, ($g.l^{-1}$)	21.7	11.1	27.5	21	10.4	25.5
Predicted, ($g.l^{-1}$)	22.2	9.6	27.8	20.6	11.8	24
% difference	-2	14	-1	2	-14	6

5-day biochemical oxygen demand (BOD_5)

The mean values of BOD_5w and BOD_5s are shown in Table 5.5. The decrease of BOD_5w and BOD_5s decreased by 50% and 80% respectively both values being significant ($p<0.05$). This shows that BODs was decreased by a rate similar to the organic odorants (VFA and TIP). Williams (1983) commented that these organic odorants and BODs have close relationship in pig slurry.

BOD_5w decreased little while BOD_5s in treated cattle slurry increased by approximately 45% (Figure 5.11) during anaerobic storage. Increase of BODs was because of the production of soluble end products from the anaerobic degradation of fibre and bacteria.

Nitrogen content

The mean values of total nitrogen (Kj-N) and ammoniacal nitrogen (NH_4^+-N) are shown in Table 5.5. Change in nitrogen level was low. The Kj-N was removed from 1600 to 1500 $mg.l^{-1}$ by 6% while the NH_4^+-N was reduced 30%, from 900 to 600 $mg.l^{-1}$. Hence the organic nitrogen (difference between Kj-N and NH_4^+-N), was increased approximately 25% from 700 $mg.l^{-1}$ to 900 $mg.l^{-1}$. This was due to the bacteria metabolising the macro-elements such as C, O, H, N, P, S into biomass from broken down protein components, thus increasing the organic nitrogen. Nitrate and nitrite were not detected, because nitrification and de-nitrification were not significant during a short residence treatment time associated with minimal aeration.

The Kj-N was increased slightly during anaerobic storage whilst the NH_4^+-N was increased approximately 20% from 600 to 760 $mg.l^{-1}$ during anaerobic storage. This could be due to decreases of the organic nitrogen by further degradation into amino acid/amino-organic compounds.

Solids concentration

All mean solids concentration of feed slurry and ML are shown in Table 5.5. They changed only a little during treatment. The highest solids contribution to the TS was TSS (70% w/w) in feed slurry and VS was (72% w/w) in ML. TS, TS(s), TSS and VS(s) were reduced by 4%, 15%, 29% and 18% respectively by the treatment. VS did not change whilst VSS increased by 13% reflecting increased biomass.

During anaerobic storage, the TS, VS, TSS VSS were fluctuating at average values of 20.9 $g.l^{-1}$ (S.D. 1), 15.2 $g.l^{-1}$ (S.D. 1.4), 9.4 $g.l^{-1}$ (S.D. 1.3) and 8.7 $g.l^{-1}$ (S.D. 0.8) respectively. All solids concentrations were further reduced during storage. The greatest degradation rate of solid concentration, 16% was for VSS. From all results of solid concentration, it seemed that suspended solids were affected the most by treatment and during storage.

Concentrations of treated TS and TSS can be predicted using equations 2.2 and 2.3 respectively (Evans *et al.*, 1983). These predicted values were compared with the actual observed values (Table 5.4). The predicted values of TS and TSS were only 2 % less than the actual values; this indicates that the models for TS and TSS prediction for the pig slurry were also fitted well for the cattle slurry.

pH value

The mean pH value (Table 5.5) increased by 5% from 8.6 to 9 during treatment, reflecting the nitrogen contents remaining at high concentration, and a high removal of organic acids. The pH decreased to 8.4 by 7% during anaerobic storage. This change was due to the rise of organic acids concentration (i.e. TOA and VFA) while the nitrogen concentration changed little.

Change of characteristics after Treatment 2

After completion of the anaerobic storage of aerobically treated slurry in Treatment 1, this slurry was then used as a feed slurry in Treatment 2. Thus the final characteristics of the stored slurry after Treatment 1 were the same as for the feed slurry in Treatment 2 (Table 5.2).

The mean values of feed and treated slurry (ML) after treatment in Treatment 2 are shown in Table 5.7. All the chemical and biochemical characteristics, except solids concentrations, were reduced further during Treatment 2. Decrease of organic odorants and BOD_5s was most evident by the treatment (as in Treatment 1). This indicated that the stability of cattle slurry in terms of odour offensiveness was further improved. The individual characteristics of the feed slurry, ML and subsequently anaerobic storage of ML (treated slurry) are described below:

Total volatile fatty acids (VFA) and Total organic acid (TOA)

The mean VFA values of feed slurry and ML are shown in Table 5.7. The mean value of VFA of feed slurry was approximately 8% greater than the final value of VFA of ML after Treatment 1. This was due to a continuous regeneration of VFA when the slurry was stored in the feed storage during treatment. Concentration of VFA was further reduced by 97% during treatment, to approximately 40 $mg.l^{-1}$, which was about 6 times lower than the lower limit of acceptable level (230 $mg.l^{-1}$) of odour offensiveness.

VFA concentration was increased to 470 $mg.l^{-1}$ after 33 days of storage after Treatment 2 (Figure 5.5). This value was below the upper limit of the acceptable offensiveness level of 520 $mg.l^{-1}$. This meant that slurry was still stable, in terms of odour offensiveness, after more than a month. The change of VFA (Figure 5.12) was mainly affected by the change of acetic acid, which contributed by approximately 60% to total VFA concentration. Similar to the VFA, concentration of TOA was further decreased from 3.4 to 1.4 $g.l^{-1}$ by 60% during Treatment 2, giving the ratio of

Table 5.7 Characteristics of the feed and ML of cattle slurry after the steady state periods during Treatment 2

Parameter		Feed				ML			
		Mean	S.D.	n	% of TS (w/w)	Mean	S.D.	n	% of TS (w/w)
TS	$g.l^{-1}$	20.9	2.4	5	100	21.0	1.4	10	100
TS(s)	$g.l^{-1}$	10.0	0.4	5	48	9.3	0.7	10	44
VS	$g.l^{-1}$	14.8	2.2	5	71	15.0	1.4	10	71
VS(s)	$g.l^{-1}$	5.3	0.4	5	25	5.0	0.7	10	24
TSS	$g.l^{-1}$	11.8	2.6	5	56	10.4	1.9	10	49
VSS	$g.l^{-1}$	11.4	2.2	5	55	8.8	3.6	10	42
CODw	$g.l^{-1}$	28.0	3.8	5	134	25.5	1.8	10	121
CODs	$g.l^{-1}$	10.7	0.3	5	51	8.9	1.2	10	42
BOD_5w	$g.l^{-1}$	2.4	0.2	5	12	1.6	0.3	10	7
BOD_5s	$g.l^{-1}$	1.6	0.2	5	8	0.4	0.1	10	2
Kj- N	$g.l^{-1}$	1.5	0.07	5	7	1.4	0.05	10	7
NH_4^+-N	$g.l^{-1}$	0.8	0.03	5	4	0.7	0.02	10	3
pH	-	8.5	0.2	5	-	9.0	0.0	10	-
TOA	$g.l^{-1}$	3.4	0.2	5	16	1.4	0.1	10	7
VFA	$g.l^{-1}$	1.3	0.1	5	6	0.04	0.02	10	0.2
TIP	$g.l^{-1}$	0.012	0.003	5	0.1	0.001	0.001	10	0.0

S.D. = standard deviation
n = number of sample analysis

Figure 5.12 Individual volatile fatty acid (VFA) concentration in the ML of cattle slurry during storage after Treatment 2 (Study 1)

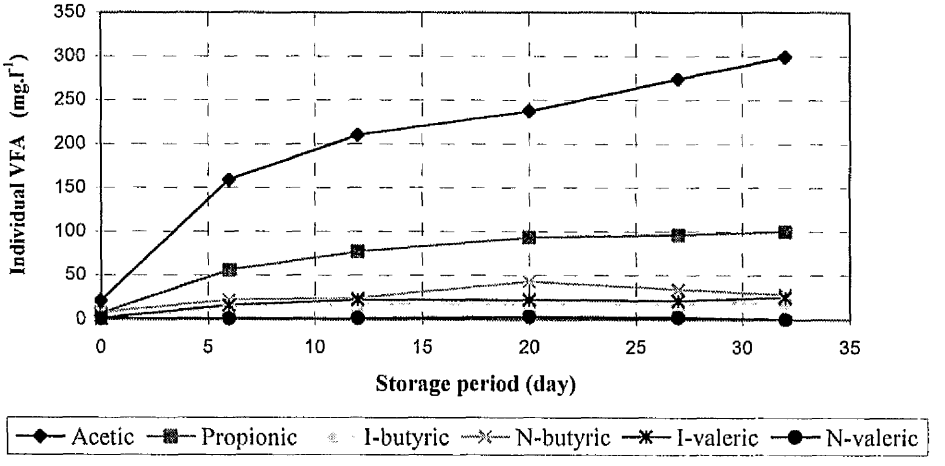
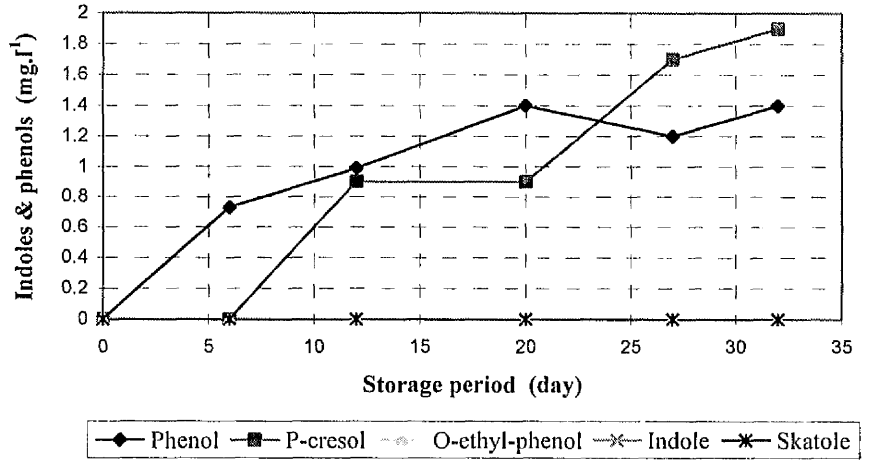


Figure 5.13 Concentration of individual Indoles and Phenols in the ML cattle slurry during storage after Treatment 2 (Study 1)



VFA/TOA of feed and ML between 0.38 and 0.03. But the regeneration of TOA has given an increase from 1.4 to 2.5 $g.l^{-1}$ (Figure 5.6) by 80% during the storage after Treatment 2.

Total Indoles and Phenols (TIP)

The mean TIP values of feed slurry and ML are shown in Table 5.7. Concentration of TIP was reduced by 94%, to a trace amount of 0.7 $mg.l^{-1}$ after Treatment 1. Only phenol was detected in 4 out of 10 measurements in treated slurry, and no other TIP components were detected.

At the end of the anaerobic storage, TIP (Figure 5.13) was increased by a small amount, approximately 3 $mg.l^{-1}$. Phenol and p-cresol were not detected until 7^{th} day of storage. The rate of regeneration of p-cresol (from 0 to 1.9 $mg.l^{-1}$) was faster than that of phenol (from 0 to 1.4 $mg.l^{-1}$).

5-day biochemical oxygen demand (BOD_5)

The mean values of BOD_5w and BOD_5s in feed slurry and ML are shown in Table 5.7. The reduction of BOD_5w and BOD_5s were 33 and 75% respectively after Treatment 2.

BOD_5s was increased from 590 to 780 $mg.l^{-1}$, by approximately 30%, during storage. The trend of BOD_5s was similar to those organic odorants (VFA and TIP) during anaerobic storage of ML. The rise of BOD_5s was probable due to anaerobic degradation of plant fibre and bacteria cells.

Chemical oxygen demand (COD)

The mean values of CODw and CODs in feed and treated slurry are shown in Table 5.7. The feed COD was not very stable with a standard deviation of 3.8 $mg.l^{-1}$. The reductions of CODw and CODs were 9% and 15% respectively. CODs was reduced in a greater extent than CODw, as similar to BOD_5s reflecting faster oxidation of COD of soluble fraction than the whole COD.

During anaerobic storage, CODw remained relatively constant while CODs was fluctuating within 8.1 to 10.4 $mg.l^{-1}$ as shown in Figure 5.11. The decrease of CODw was due to the carbonaceous materials being broken down into methane, carbon dioxide and water by anaerobic microbial activity.

As in Treatment 1, the predicted value of CODw agreed well with the actual observed value in treatment 2 (Table 5.6). Although the slurry had already been treated once during Treatment 1, the actual observed value of CODw after Treatment 2 was only 6% greater than the predicted values. This indicates that the predicted CODw would not be affected by the feed CODw, and the changes of feed CODw were directly reflected in the CODw of ML, although they were dissimilar in magnitude.

Nitrogen content

The mean values of Kj-N and NH_4^+-N after second treatment are shown in Table 5.7. The change of Kj-N and NH_4^+-N were not significant, fluctuating around average values of 1300 and 650 $mg.l^{-1}$ respectively, during storage after Treatment 2.

Solids concentration

The mean values of solids concentration (TS, TSS, VS, VSS, TS(s), VS(s)) after Treatment 2 are shown in Table 5.7. None of the solids concentrations was affected much by the Treatment 2. Both TS(s) and VS(s) were reduced a little, by approximately 6%. Similar to CODw, the predicted TS and TSS values of treated slurry were calculated and are shown in Table 5.6. The predicted mean value of TS was 2 % lower than the actual observed value, and the predicted TSS was 13 % greater than the observed one. This reflects the fact that the TS and TSS of cattle slurry after Treatment 2 also agreed well with those equations 2.2 and 2.3 (Chapter 2), although these equations were derived from pig slurry (Evans *et al.,* 1983).

Comparison of the predicted value of treated cattle slurry with the (one + one) day twice through reactor and 2 day residence time

In Treatment 1 and 2, the observed values of TS, TSS, CODw and BOD_5w were in a good agreement with the model prediction (Evans *et al.*, 1983) for 1 day residence time (Table 5.6).

By considering the process described in Chapter 5.2, the actual residence time of the overall treatment could be taken account at 2 day residence time, because the slurry was treated twice over with 1 day residence time. The predicted values of TS, TSS, CODw and BOD_5w were thus calculated, using 2 day residence time (Table 5.8). The percentage differences between the actual and the predicted values of TS, TSS, CODw and BOD_5w were -3%, 11%, -4% and -63% respectively. These predicted values agreed with the observed values.

Table 5.8. Observed and predicted mean TS, TSS, CODw and BODw values of cattle slurry with nominal (1+1) day and 2 day residence time, using equations in Evans *et al.*, (1983).

	TS	TSS	CODw	BODw
"1+ 1" day residence time				
Observed ($g.l^{-1}$)	21	10.4	25.5	1.6
Predicted (a) ($g.l^{-1}$)	20.6	11.8	24	3.8
% different	2	-13	6	-138
2 day residence time				
Observed ($g.l^{-1}$),	21	10.4	25.5	1.6
Predict (b) ($g.l^{-1}$)	21.6	9.2	26.4	3
% different	-3	11	-4	-63
(a-b)/a*100	-7	24	-8	21

Note: a = the predicted value using (1+1) day residence time
b = the predicted value using 2 day residence time
% difference = [(observed – predicted)/observed * 100]

The predicted BOD_5w was much greater than the actual observed value (similar to Treatment 2 with 1 day residence time). This could be explained if the predicted BOD_5w was mainly affected by the residence time in such a low concentration BOD of feed slurry, when applying the equation 2.5. Evans *et al.* (1979) found that observed BOD_5s was 147% greater than the theoretical predicted value at 1 day

residence time. Evans *et al.* (1979) and Evans *et al.* (1983) also found that there has no significant effect on the BOD_5 at residence time in excess of 1 day.

The TS, TSS, CODw and BOD_5w of treated slurry (ML) were well predicted using the same model as for (1+1) day residence time. The difference between the predicted values using 2 day RT and the predicted values using (1+1) day RT for TS, TSS, CODw and BOD_5w were 8, 24, 8 and 21% respectively. This demonstrated no great difference between process configurations (i.e. 2 day and "1+1" day residence time). The ML was only affected by the treatment residence time and not by the process.

5.3.2 Pig slurry experiment

Chemical analyses were not started until steady state condition was achieved within the mixed liquor at the end of the commissioning period. Evans *et al.* (1979) commented that approximately three mean residence times were usually required to establish steady state conditions.

The operating conditions during treatment are shown in Table 5.9. The mean feed values of the feed characteristics with standard deviations (Table 5.10) for pig slurry were calculated once steady state conditions through the aerobic treatment had been achieved.

Table 5.9. Operating conditions during Treatment 1 and 2 of pig slurry (Study 2)

	Treatment 1			Treatment 2		
	Mean	S.D.	n	Mean	S.D.	n
Redox value, mV E_{cal}						
min	-139.8	3.8	40	-145.3	10.8	25
max	-161.0	11.4	40	-159.7	9.7	25
average	-152.2	6.1	40	-151.2	7.2	25
Temperature, °C						
reactor	15.0	0.1	40	15.0	0.1	25
store	10.3	1.1	40	10.2	1.5	25
Working volume, litre						
reactor	0.9	0.0	40	0.9	0.0	25
ML	0.82	0.2	40	0.91	0.1	25

Note: ML was the discharge-treated effluent

Slurry characteristics change after treatment in Treatment 1

Similar to cattle slurry, the effect of aerobic treatment was most evident on soluble compounds, especially the odorous compounds VFA, TIP, TOA and BOD_5s. All the analytical data are given in Appendix C (Tables C19-C36). The individual chemical characteristics are described below.

Total volatile fatty acids (VFA)

The mean values, with their standard deviations, of total VFA in the feed slurry and ML are shown in Table 5.10. The total VFA was destructed by 98% after treatment to 70 $mg.l^{-1}$. This value was only 30% of that indicating the lower acceptable level (230 $mg.l^{-1}$) of odour offensiveness. This percentage destruction was very close to that

destruction found elsewhere at pilot scale (Williams *et al.*, 1989) and farm scale (Sneath *et al.*, 1992). Their operating conditions for the pig slurry treatment were similar to the present study. The treatment effect on total VFA levels in ML with respect to the feed slurry is illustrated in Figure 5.14.

The highest contribution to VFA was by acetic acid in ML of pig slurry with 65% of the total VFA (Figure 5.15). The lowest contribution was by N-valeric, only 3 $mg.l^{-1}$ was detected from 3 out of 14 measurements. Therefore, the mean concentration of N-valeric acid could be assumed to be negligible.

Change of slurry characteristics during storage

The ML of pig slurry was stored anaerobically from the beginning of treatment (i.e. after steady state condition). During storage, VFA concentration increased linearly with time (Figure 5.16) at the beginning of storage, at a constant rate of 18 $mg.l^{-1}.d^{-1}$ and reached 810 $mg.l^{-1}$ after 38 days. It then approached a constant value, at maximum 820 $mg.l^{-1}$. VFA reached the threshold limits of 230 and 520 $mg.l^{-1}$ after 8 and 21 days respectively.

The change of individual VFA during storage is shown in Figure 5.17. Acetic acid contributed approximately 70% of total VFA concentration of each sample during storage. Production of propionic acid was in considerably greater quantities than the other acids, even though it was only about one-third of the concentration of acetic acid. The concentration of N-valeric increased very little from its initial near zero value. This indicated the acetic acid was dominant in the total VFA production and thus the change of total VFA was mainly affected by acetic acid. This effect was agreed with the findings of Williams (1981).

Total organic acid (TOA)

The mean concentrations of TOA feed slurry and ML are shown in Table 5.10. Similar to cattle slurry, the reduction of TOA was significant ($p<0.05$), and 65% of

Table 5.10. Characteristics of the feed and the ML of pig slurry after the steady state periods during Treatment 1.

Parameter		Feed				ML			
		Mean	S.D.	n	% of TS (w/w)	Mean	S.D.	n	% of TS (w/w)
TS	$g.l^{-1}$	29.1	6.2	7	100	28.7	6.2	14	100
TS(s)	$g.l^{-1}$	6.1	0.5	7	21	6.6	0.5	14	23
VS	$g.l^{-1}$	21.5	5.0	7	74	20.8	5.2	14	72
VS(s)	$g.l^{-1}$	3.0	0.3	7	10	2.8	0.5	14	10
TSS	$g.l^{-1}$	16.2	4.3	7	56	16.2	3.6	14	56
VSS	$g.l^{-1}$	14.4	3.5	7	49	14.3	2.9	14	50
CODw	$g.l^{-1}$	37.8	3.7	7	130	31.8	7.1	14	111
CODs	$g.l^{-1}$	8.8	0.9	7	30	5.0	0.8	14	17
BOD_5w	$g.l^{-1}$	7.7	1.7	7	26	5.3	1.1	14	18
BOD_5s	$g.l^{-1}$	4.3	0.9	7	15	1.3	0.6	14	5
Kj- N	$g.l^{-1}$	2.6	0.2	7	9	2.4	0.2	14	8
NH_4^+-N	$g.l^{-1}$	1.9	0.1	7	7	1.3	0.1	14	4
pH	-	8.7	0.3	7	-	9.2	0.1	14	-
TOA	$g.l^{-1}$	6.8	0.2	7	23	2.4	0.2	14	8
VFA	$g.l^{-1}$	2.9	0.4	7	10	0.07	0.04	14	0
TIP	$mg.l^{-1}$	0.03	0.01	7	0	trace	0.0	14	0

S.D. = standard deviation
n = number of sample analysis

Figure 5.14 Total volatile fatty acids (VFA) concentration in the feed and in the ML of pig slurry during Treatments 1 and 2 (Study 1)

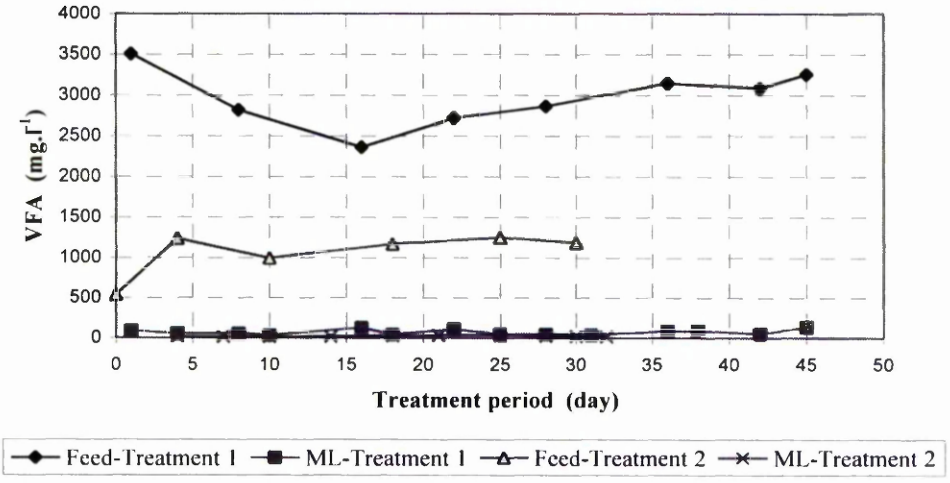
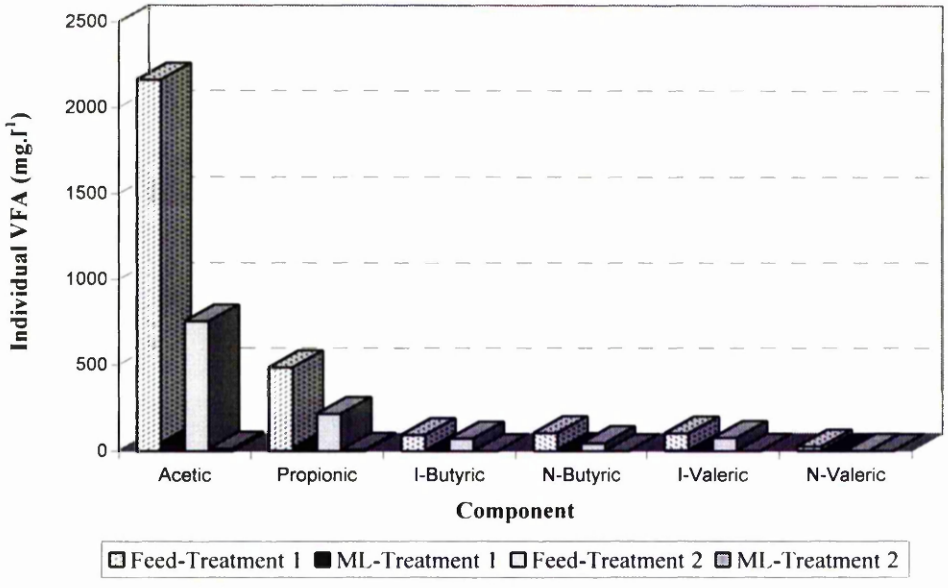


Figure 5.15 Mean values of individual volatile fatty acid (VFA) concentration in the feed and in the ML of pig slurry in Treatments 1 and 2 (Study 1)



TOA was reduced from the average value of 6.8 to 2.4 $g.l^{-1}$ by the treatment. This, representing the odour offensiveness, was from "strong" odour rating 4.3 to "definite" odour rating 3.2, using the equation (5.1) (Thacker and Evans, 1986). Ratio of VFA/TOA of the mean feed slurry and ML were 0.43 and 0.03, respectively. The lower ratio of VFA/TOA of ML reflected a greater reduction in VFA concentration than total organic acid (TOA). This indicates that the VFA is the single most important group of acids in the TOA, as reported by Williams (1983).

Similar to the VFA, the regeneration of TOA was significant and was increased from 2.8 to 4 $g.l^{-1}$ by 30% during anaerobic storage of ML after Treatment 1, as shown in Figure 5.18. This was due to the organic materials being broken down into the acids content by anaerobic microbial activity.

Total Indoles and Phenols (TIP)

The effect of aerobic treatment on TIP concentration was significant ($p<0.05$) (Figure 5.19). The mean value of TIP in feed slurry is shown in Table 5.10. The largest component of indoles and phenols was p-cresol (Figure 5.20), representing 66 % of the total TIP. Skatole, the strongest offensive component, contributed to TIP by only 3.4% of TIP content. The removal of TIP reached up to 100% (Table 5.10) after treatment. It was only detected in trace amounts, in 3 out of 15 analyses through the treatment. Phenol was only present in these 3 measurements, and the rest of the components of indoles and phenols were not detected. TIP compounds are therefore removed easily by the treatment, presumably because these compounds are soluble and they were only present in small quantity (approximately 0.1% of TS w/w) in feed slurry.

During storage of the ML of pig slurry after Treatment 1, TIP was regenerated (Figure 5.21) and increased to approximately (9.9 $mg.l^{-1}$) one-third of the feed mean TIP value. Both phenol and p-cresol started regenerating from 18th day of storage (Figure 5.22). Both increased to 4.9 and 5 $mg.l^{-1}$ respectively, by 50% of TIP after 45 days of storage . The other individual indole and phenol components were not detected during anaerobic storage. This indicates that the ML was stable for 18 days after

Figure 5.16 Total volatile fatty acids (VFA) concentration in the treated (ML) pig slurry during storage after Treatments 1 and 2 in Study 1

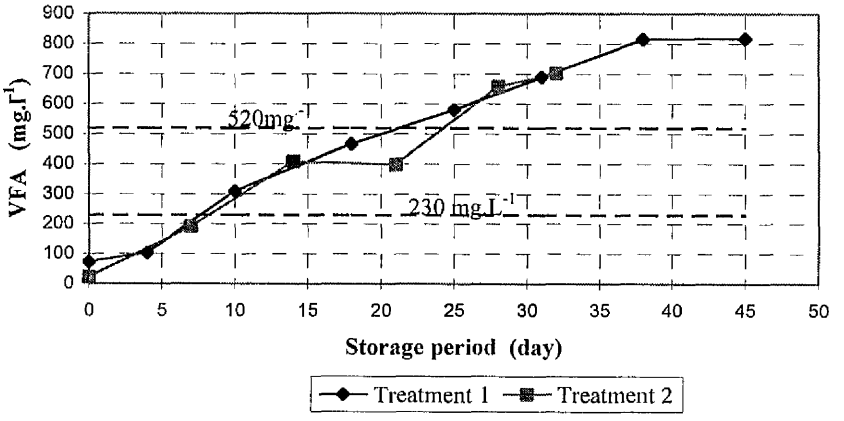


Figure 5.17 Concentration of individual volatile fatty acid (VFA) concentration in the ML of pig slurry during storage after Treatment 1 (Study 1)

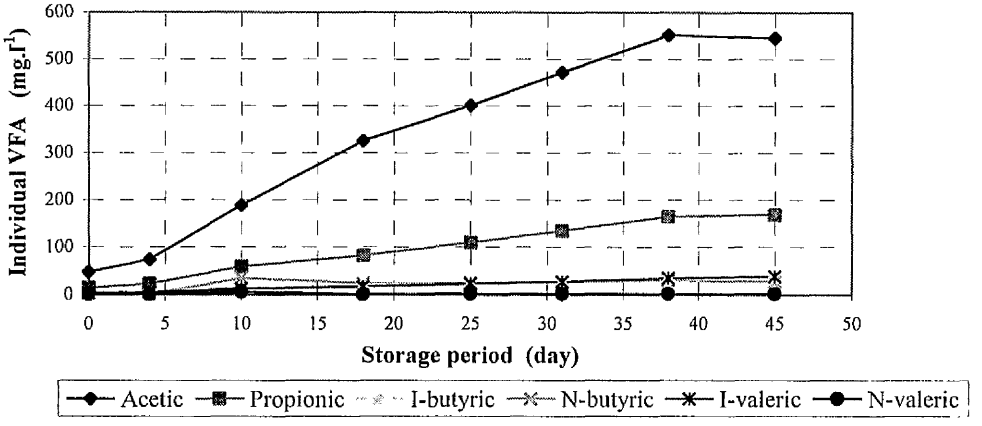


Figure 5.18 Total organic acid (TOA) concentration in the ML of pig slurry during storage Treatments 1 and 2 (Study 1)

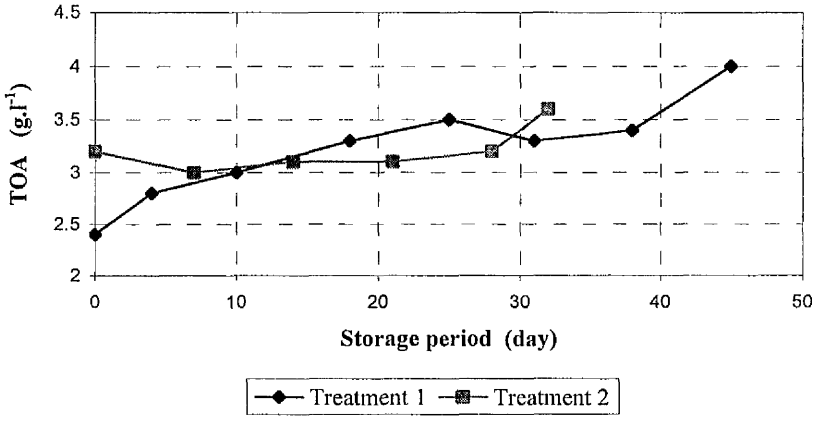


Figure 5.19 Total indoles and phenols (TIP) concentration in the feed and in the ML of pig slurry during Treatments 1 and 2 (Study 1)

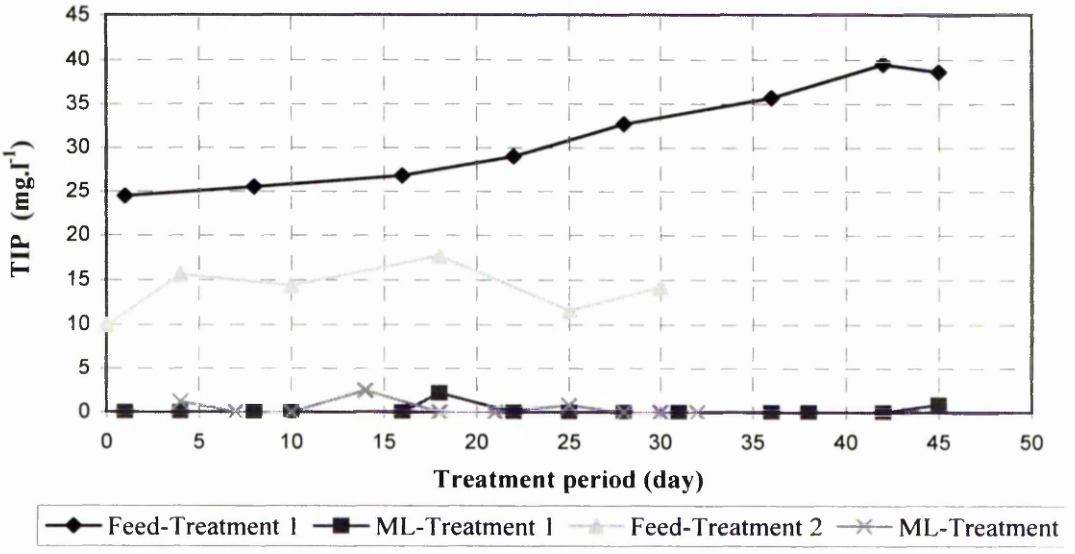


Figure 5.20 Mean values of individual Indoles and Phenols concentration in the feed and in the ML of pig slurry after Treatments 1 and 2 (Study 1)

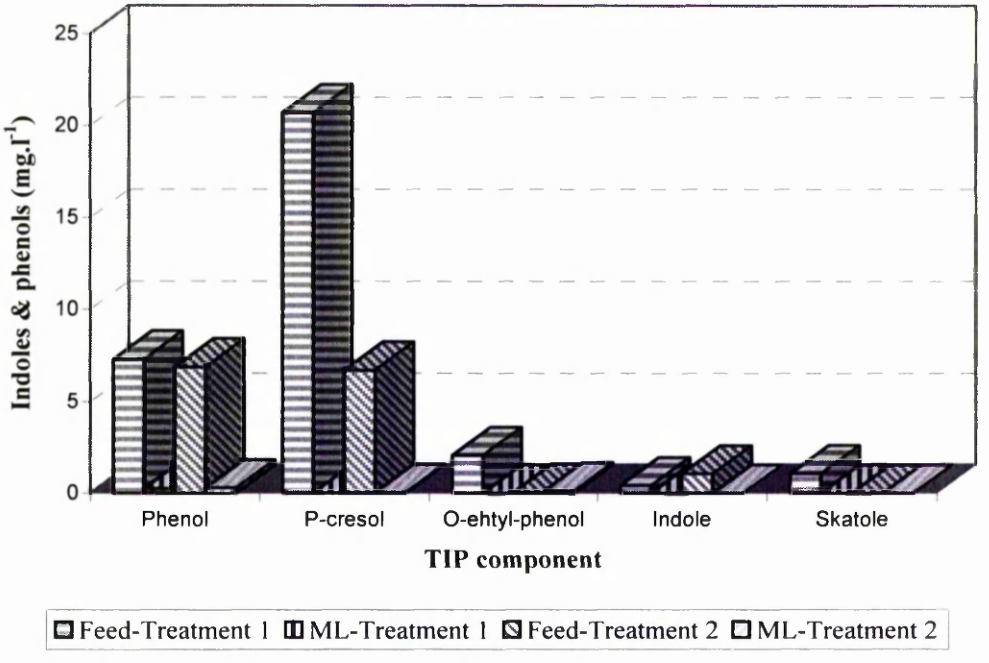


Figure 5.21 Total indoles and phenols (TIP) concentration in the ML of pig slurry during storage after Treatments 1 and 2 (Study 1)

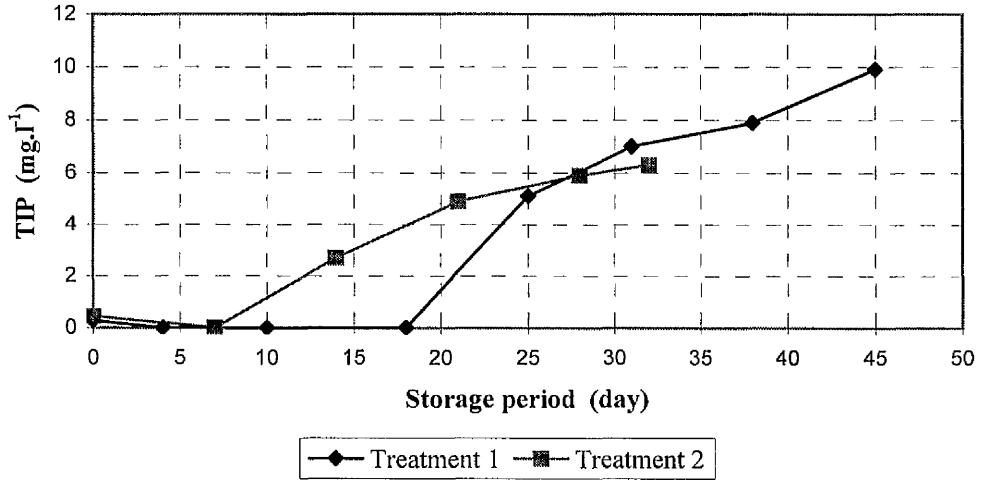
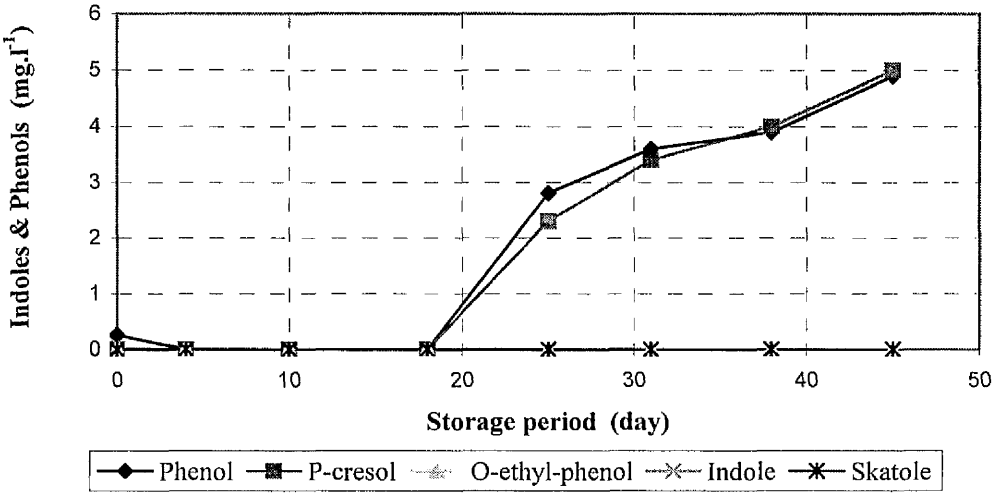


Figure 5.22 Concentration of individual Indoles and Phenols in the ML of pig slurry during storage after Treatment 1 (Study 1)



Treatment 1 and TIP were presented only in small amount, and were oxidised easily and hardly regenerated back to a significant level once they had been removed.

5-day Biochemical oxygen demand (BOD_5)

Reductions of BOD_5w and BOD_5s were significant ($p<0.05$) by treatment (Table 5.10). The percentage destruction of BOD_5s was more than twice greater than BOD_5w and were 31 and 70% respectively. Williams (1984) and Thacker & Evans (1986) found that BOD_5s was a good indicator of odour offensiveness, and it was more reliable than VFA and TIP when used as an odour indicator. The BOD_5s values of both feed slurry and ML varied widely, with standard deviation 0.9 and 0.6, respectively during Treatment 1 (Figure 5.23). BOD_5s was reduced from the mean value of 4.3 to 1.3 $g.l^{-1}$ by Treatment 1. When the mean value (1.3 $g.l^{-1}$) of ML BOD_5s was applied to the equation 5.2 (Williams, 1984) for offensiveness rating, it was shown that the treated (ML) slurry would still have definitely offensive odour of 3.2 rating scale.

$$\text{Odour Offensiveness} = (0.411 * \log_e BOD_5s) + 3.16 \qquad \text{Equation (5.2)}$$

One of the principal characteristics used to assess the effectiveness of the treatment was BOD_5s which behaves in a predictable manner during aerobic treatment (Evans *et al.*, 1979). As expected, BOD_5s concentration increased during storage while BOD_5w fluctuated between 3.5 and 5 $g.l^{-1}$ (Figure 5.24). BOD_5s increased to 1.5 $g.l^{-1}$, which 15 % over starting value (i.e. the mean value of ML) after 32 day of storage, reflecting that odour offensiveness had increased. This was due to the anaerobic microbial activity during storage.

Chemical oxygen demand (COD)

The reduction of COD by treatment was significant ($p<0.05$), as shown in Table 5.10. The variation of the mean feed COD concentration can be seen in Figure 5.25, together with the corresponding mean value of ML COD during Treatment 1. The whole COD and supernatant COD were removed by 16 and 43% respectively. Low removal of CODw was because of the short residence time (<2 day residence time)

Figure 5.23 Supernatant BOD concentration in the feed and in the ML of pig slurry during Treatments 1 and 2 (Study 1)

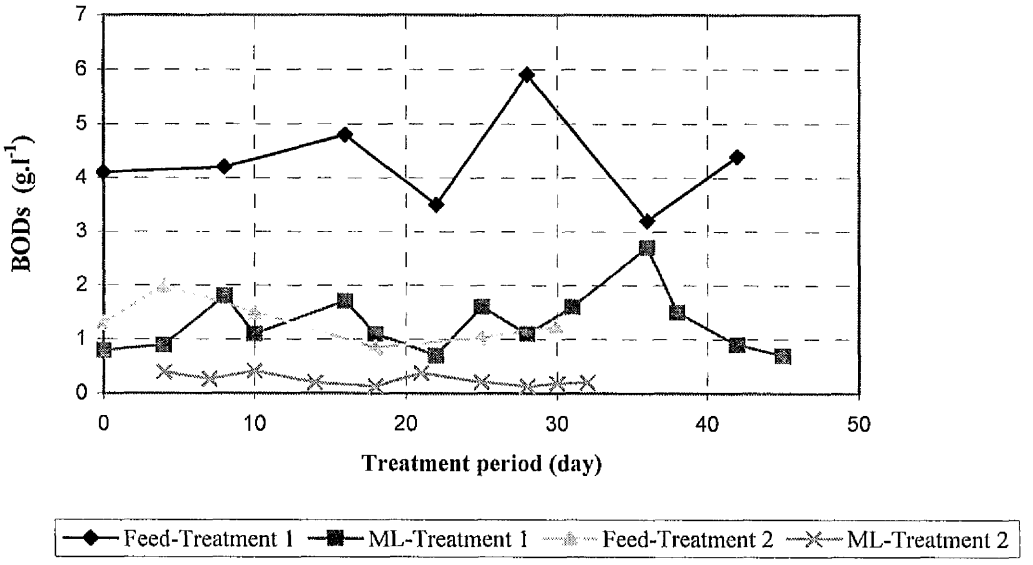


Figure 5.24 Whole and supernatant BOD concentration in the ML of pig slurry during storage after Treatments 1 and 2 (Study 1)

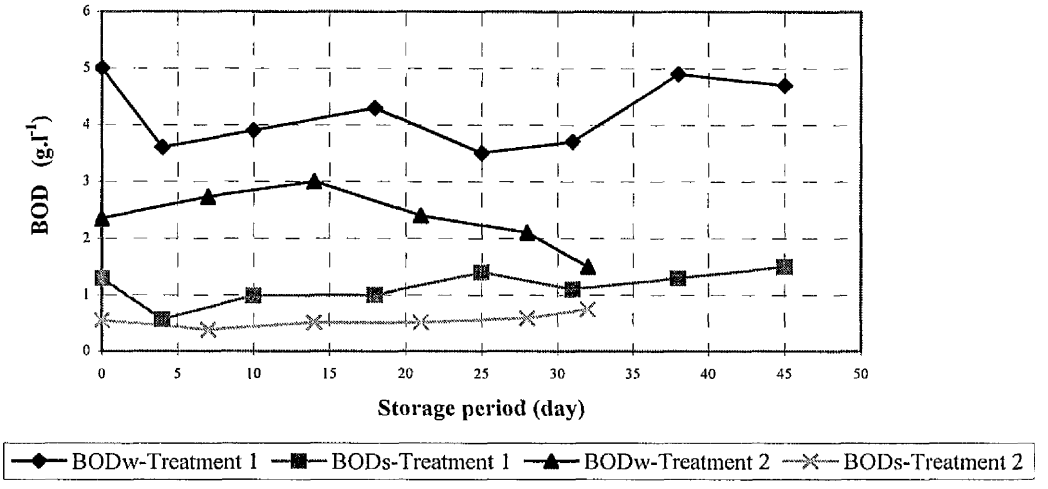


Figure 5.25 Whole and supernatant COD concentration in the feed and in the ML of pig slurry during Treatment 1 (Study 1)

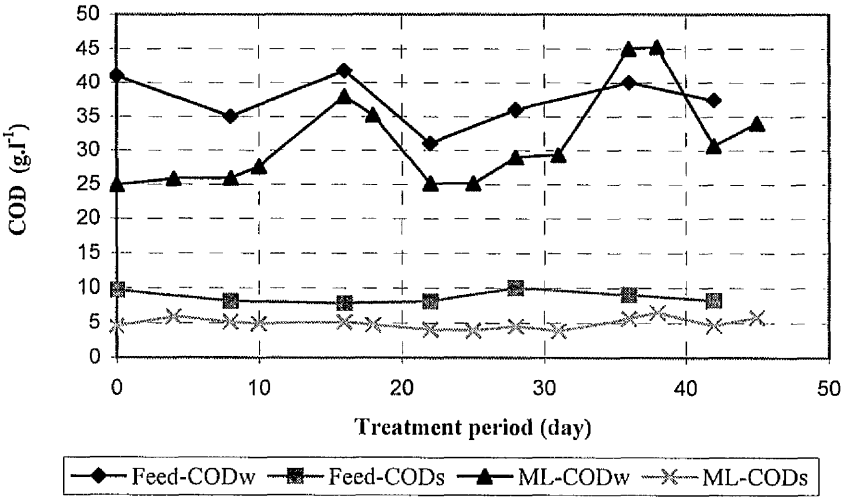
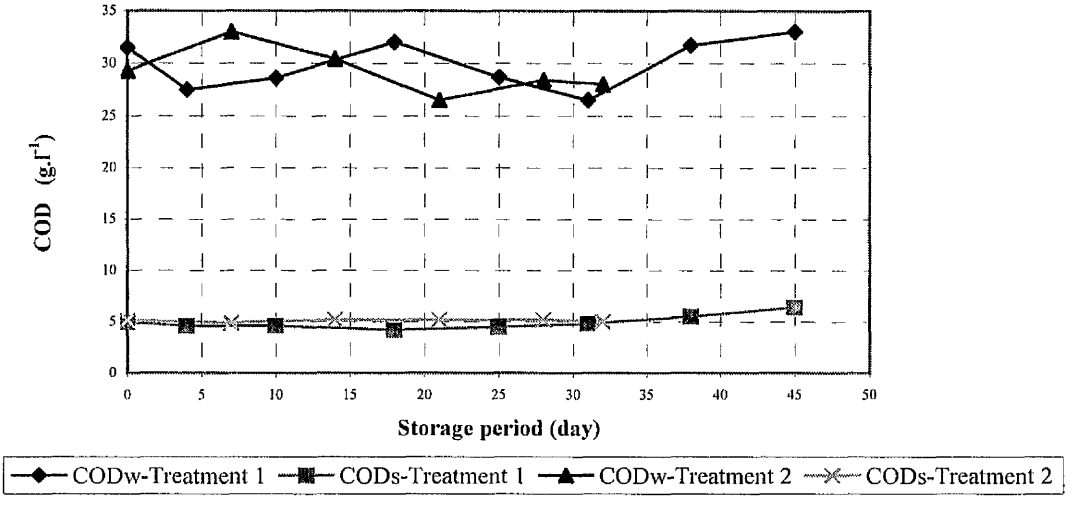


Figure 5.26 Whole and supernatant COD concentration in the ML of pig slurry during storage after Treatments 1 and 2 (Study 1)



and minimal aeration (Evans *et al.*, 1979; Smith & Evans, 1982). This percentage of CODw removal was similar to those findings by Evans *et al.* (1983); Evans *et al.* (1979) and Burton *et al.* (1998).

During anaerobic storage, CODw and CODs were not significantly changed (Figure 5.26) and fluctuated at average values of 30 and 5 $g.l^{-1}$ respectively.

Predictive CODw of treated pig slurry (Table 5.11) was calculated using equation (2.4) Evans *et al.* (1983), and proved satisfactory. These predicted values, were only 1% greater than observed value for treatment 1, and 4% lower than the observed value for treatment 2.

Table 5.11. Observed and predicted mean values of pig slurry in Treatments 1 and 2, using equations in Evans *et al.* (1983) (Study 1).

	Treatment 1			Treatment 2		
	TS	TSS	CODw	TS	TSS	CODw
Observed, ($g.l^{-1}$)	28.7	16.2	31.5	26.8	15.3	30.3
Predicted, ($g.l^{-1}$)	28.8	16.3	32.4	27	15.6	29.1
% difference	0	-1	-1	-1	-2	4

Note: % difference = [(observed – predicted)/observed * 100]

Nitrogen content

Mean concentrations of total (Kj-N) and ammoniacal nitrogen in feed slurry and ML are shown in Table 5.10. As in cattle slurry, the nitrate and nitrite were not significant, due to short residence time and low aeration level (Smith & Evans, 1982; Evans *et al.*, 1986). The loss of nitrogen content was significant ($p<0.05$), the percentage loss of Kj-N and NH_4^+-N being 8% and 32% respectively. However, the organic nitrogen (difference between Kj-N and NH_4^+-N) was increased by 40% after treatment to 1.1 $g.l^{-1}$. Stripping of ammonia was observed in trace amounts during aerobic treatment.

During anaerobic storage of ML, NH_4^+-N increased slowly to approximately 1.4 $g.l^{-1}$, by 8%. Organic nitrogen was increased by about 25% because bacteria metabolised macro-elements into biomass, resulting in an increase in organic nitrogen during storage.

Solids concentration

The mean values of all solids concentrations of feed slurry and ML are shown in Table 5.10. The ratio of mean values ML/feed slurry of TS, TSS, VS, VSS and supernatant of TS and VS were approximately 1. This indicates that the solids concentrations were not affected significantly in such a short residence time and low dissolved oxygen (DO) level as quoted by (Evans *et al.*, 1983; Smith & Evans, 1982). The predicted mean value of TS (Table 5.11) of treated (ML) slurry from the mean feed value showed no difference from the actual observed mean value, while TSS was only 1% greater than the observed value.

During anaerobic storage, the supernatant solids concentrations (TS(s) and (VS(s)) were increased slightly. This was due to the solids being broken down by the anaerobic microbial activity.

pH value

The mean pH value increased by 5% from 8.7 to 9.2 during treatment (Table 5.9). This change during treatment was caused by a decline of acids concentration while the loss of ammoniacal nitrogen content was very small, and thus resulted increase of pH value.

The change of pH value was not significant during storage, it fluctuated between 9.3 and 9.8 (Appendix C Table C25). This was because the nitrogen level did not change and although the acid concentration increased, it was only by a small amount.

Change of characteristics after Treatment 2

The stored ML of Treatment 1 was used as feed slurry for Treatment 2 (Chapter 5.2 experimental design and method). Characteristics of feed slurry thus were the same as the final characteristics of the stored ML (treated slurry) in Treatment 1. The mean characteristics of feed slurry and ML values in Treatment 2 are shown in Table 5.12.

The pattern of change for Treatment 2 was similar to Treatment 1 in chemical and biochemical characteristics of slurry. They were generally further reduced by the treatment. The most affected characteristics were odour indicators as VFA (Figure

5.14) and TIP (Figure 5.19). Concentration of VFA and TIP were further decreased approaching complete removal after Treatment 2. Reduction of BOD_5s was also considerably high (80%) in this treatment. A major change in slurry characteristics is described below.

Total volatile fatty acids (VFA) and total organic acid (TOA)

VFA was destroyed by 98% to 23 $mg.l^{-1}$, which indicates 10 times below acceptable level of odour offensiveness (230 $mg.l^{-1}$ of VFA). The total VFA mainly consisted of acetic acid, more than 60% of total VFA, in ML (Figure 5.15) while I-Butyric and N-Valeric were not detected throughout Treatment 2. However, all the components of VFA were regenerated during storage (Figure 5.27), and the rate of regeneration of VFA was similar to Treatment 1. It took approximately 10 days to return back to the acceptable level of 230 $mg.l^{-1}$ and odour offensiveness (500 $mg.l^{-1}$) reappeared about 25 days after the storage.

Similar to the VFA, concentration of TOA was further decreased from 3.9 to 1.8 $g.l^{-1}$, by 54% during Treatment 2, giving that the ratio of VFA/TOA of feed and ML were 0.31 to 0.01. But the regeneration of TOA was low (Figure 5.18) and fluctuated around the mean value of 3.2 $g.l^{-1}$ (S.D. 0.2) during storage after Treatment 2. The lower regeneration of TOA indicates that the maximal reduction of TOA occurred by Treatment 2, and most of the organic materials were broken down during treatment.

Total Indoles and Phenols (TIP)

TIP were only present in small amounts (14.7 $mg.l^{-1}$) in feed slurry after the first treatment, then they were reduced by 97% down to almost zero again (Figure 5.20) after Treatment 2. Phenol was only detected in 3 out of 10 samples.

During the storage, the individual indole and phenol components were regenerated again except skatole (Figure 5.28). TIP increased to a maximum of approximately 6 $mg.l^{-1}$ after 32 day of storage; it was about 40% of the mean value of feed slurry in

Figure 5.27 Individual volatile fatty acid (VFA) concentration in the ML of pig slurry during storage after Treatment 2 (Study 1)

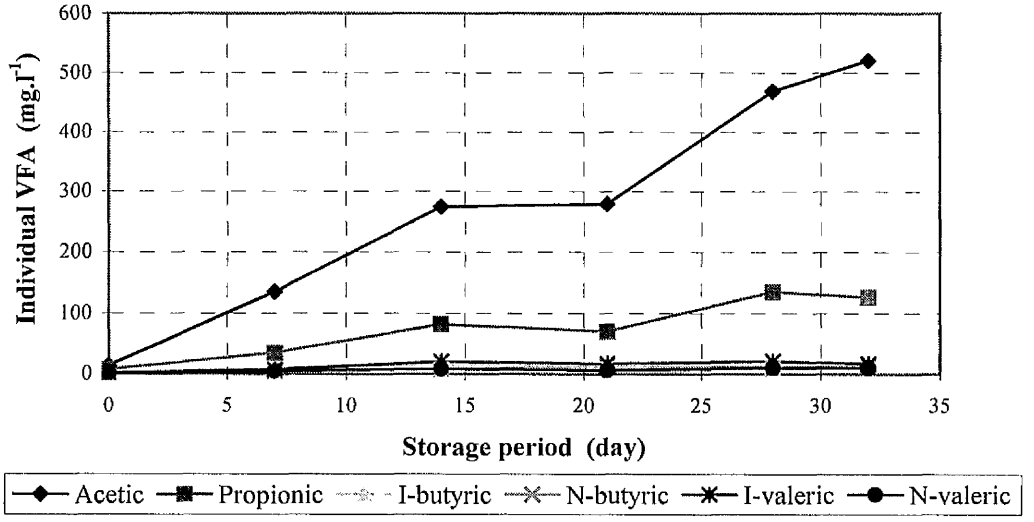
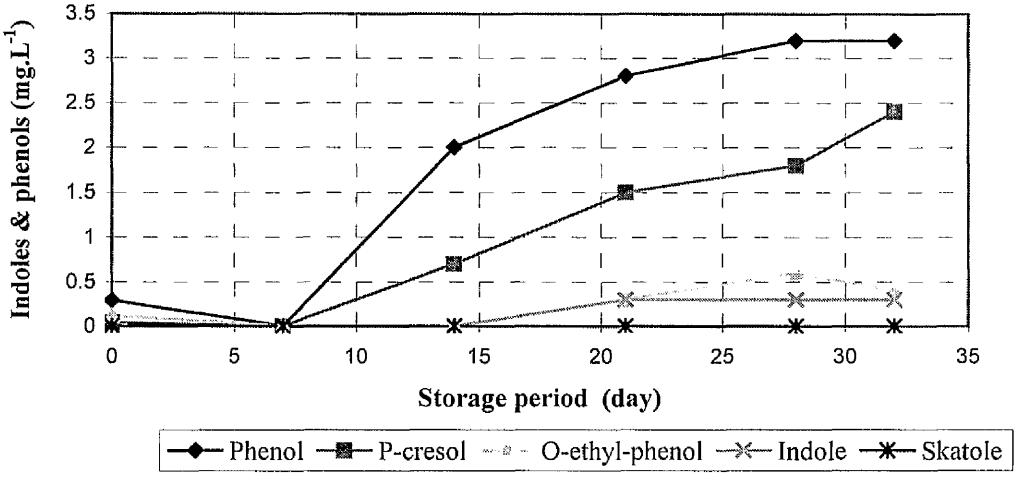


Figure 5.28 Concentration of individual indoles and phenols in the ML of pig slurry during storage after Treatment 2 (Study 1)



Treatment 2. This value indicates that the increase of TIP during storage was limited by the amount of substrate which was left after the first treatment.

5-day Biochemical oxygen demand (BOD_5)

Figure (5.23) shows that the BOD_5s concentration of ML after Treatment 2 has a similar changing manner to Treatment 1 (as with VFA and TIP). It was further reduced by 80% to 200 $mg.l^{-1}$, then returned to 50% of mean value of feed slurry during storage after Treatment 2 (Figure 5.24). This shows that the BOD_5s has close relationships with these organic odorants, and also indicates that the supernatant (soluble) fraction materials were faster and more easily oxidised than the insoluble fraction. It was because the short residence time and low aeration level, causing the time and oxygen to be restricted for further biodegradation any materials.

The predicted mean treated (ML) value of BODw was approximately 50% greater than the actual observed value (Table 5.13). This percentage different was much lower than the finding of Evans *et al.* (1979); they found that predicted BODw value was about 147% greater than the observed one; at similar conditions of treatment residence time and temperature to those of the present study.

Chemical oxygen demand (COD)

CODw and CODs were further decreased (Table 5.12) by 10 and 15 % respectively after Treatment 2, but there was not a significant change during storage (Figure 5.26). This small change was mainly due to the short residence time and minimal aeration. Prediction of treated (ML) CODw in Treatment 2, using the equation (2.4), agreed well with the observed mean value (Table 5.13).

Nitrogen content

The concentration of nitrogen content is shown in Table (5.12). Transformation of nitrogen contents (Kj-N, NH_4^+-N) were low during Treatment 2 while NH_4^+-N was decreased by 14%, mainly by stripping in form of NH_3 gas. This could be explained in that a short residence time with low aeration was used, so that nitrification and de-nitrification were not significant. During anaerobic storage, the change of nitrogen content was not significant (Appendix C TableC34).

Solids concentration

Changes of solids concentration (TS, TSS, VS and VSS) were low throughout the treatment (Table 5.12) and during storage (Appendix C5.34). They was because short residence time and minimal aeration was used, caused the growing biomass to be washed out very quickly (Burton, 1992; Greatorex, 1995). Therefore the degradation of solids materials were not significant. However, the predicted values of TS and TSS agreed well with the observed values (Table 5.12), using equations 2.1 and 2.2, at 1-day residence time of Treatment 2.

Table 5.12. Characteristics of the feed and the ML of pig slurry after the steady state periods during Treatment 2.

Parameter		Feed				ML			
		Mean	S.D.	n	% of TS (w/w)	Mean	S.D.	n	% of TS (w/w)
TS	$g.l^{-1}$	27.3	1.6	5	94	26.8	2.4	10	92
TS(s)	$g.l^{-1}$	6.9	0.2	5	24	6.8	0.4	10	23
VS	$g.l^{-1}$	19.8	1.3	5	68	19.1	2.0	10	65
VS(s)	$g.l^{-1}$	3.4	0.2	5	12	3.1	0.3	10	10
TSS	$g.l^{-1}$	15.5	1.5	5	53	15.3	1.9	10	53
VSS	$g.l^{-1}$	13.6	1.4	5	47	13.5	1.5	10	46
CODw	$g.l^{-1}$	33.7	1.6	5	116	30.3	2.1	10	104
CODs	$g.l^{-1}$	6.2	0.5	5	21	5.3	0.6	10	18
BOD_5w	$g.l^{-1}$	3.4	0.5	5	12	2.5	0.6	10	9
BOD_5s	$g.l^{-1}$	1.3	0.5	5	5	0.2	0.1	10	1
Kj- N	$g.l^{-1}$	2.3	0.07	5	8	2.3	0.16	10	8
NH_4^+-N	$g.l^{-1}$	1.4	0.03	5	5	1.2	0.09	10	4
pH	-	8.8	0.1	5	30	9.3	0.1	10	32
TOA	$g.l^{-1}$	3.9	0.3	5	13	1.8	0.4	10	6
VFA	$g.l^{-1}$	1.2	0.1	5	4	0.02	0.01	10	0
TIP	$g.l^{-1}$	0.015	0.002	5	0	trace	-	10	0

S.D. = standard deviation
n = number of sample analysis

Comparison of the predicted value of treated (ML) pig slurry with the 1 day RT twice through reactor (i.e. (1+1) day RT) and 2 day residence time

Observed mean values of TS, TSS, CODw and BOD_5w of treated (ML) pig slurry were in good agreement with the model prediction (Evans *et al.*, 1983) using one day residence time for Treatments 1 and 2 (Tables 5.11 and 5.13).

Nevertheless, the overall treatment residence time could be considered as 2 day because the slurry was treated twice at 1 day residence time. The predicted value of TS, TSS, CODw and BOD_5w of treated ML were thus calculated, using 2 day residence time, with equations 2.1, 2.2, 2.3 and 2.4 (Table 5.13).

Table 5.13. Observed and predicted mean values of TS, TSS, CODw and BOD_5w of pig slurry with nominal (1+1) day and 2 day residence times, using equations Evans *et al.* (1983) (Study 1)

	TS	TSS	CODw	BOD_5w
(1+1) day residence time				
Observed ($g.l^{-1}$)	26.8	15.3	30.3	2.5
Predicted (a) ($g.l^{-1}$)	26.9	15.5	28.9	3.7
% difference	0	-1	5	-50
2 day residence time				
Observed ($g.l^{-1}$)	26.8	15.3	30.3	2.5
Predicted (b) ($g.l^{-1}$)	28.0	15.0	31	3
% difference	-4	2	-2	-20
(a-b)/a*100	-4	3	7	20

Note: a = the predicted value using (1+1) day residence time
b = the predicted value using 2 day residence time
% difference = [(observed – predicted)/observed * 100]

The percentages difference between the final observed and predicted values of TS, TSS, CODw and BOD_5w were –4, 2, -2 and -20% respectively. The values of TS, TSS, CODw and BOD_5w of ML were thus in a good agreement with predicted models derived by Evans *et al.* (1983) using 2 day residence time.

The difference between the predicted values of TS, TSS, CODw and BOD_5w, using (1+1) day residence time and predicted values using 2 day RT, were –4, 3, 7 and 20% respectively. This proved that the predicted values would have no great difference between "1+1" day residence time and 2 day residence time in one pass (as with

CODw). This could be explained by there being no great difference between process configurations.

6. LABORATORY SCALE REACTOR TREATMENT : STUDY 2

6.1 Introduction

The laboratory scale continuous steady state aerobic treatment (Chapter 5.2) showed a remarkable performance in odour offensiveness removal for either pig or cattle slurry. The observed results from the preliminary study also concluded that there were similar effects on the "steady state" process in comparison with models derived by Evans *et al.* (1983). Nevertheless, the potential of odour regeneration was significant with a short term aeration process, found in previous experiments (Study 1) and elsewhere (Williams, 1981).

However, in the reality of farm practice, the variable concentration of feed slurry into the treatment system induced a non-steady state process resulting in very variable characteristics of treated slurry (Svoboda, 1993). In order to improve this and to obtain more experimental findings corresponding to the behaviour of odour offensiveness, another process configuration (Figure 6.0) was designed with the following aims:

1. To study the effect of varying feed characteristics on odour offensiveness in treated slurry (ML), in continuous aeration process.

2. To study the effect of daily additions of ML into the feed mixture on the ML characteristics and changes of odour.

3. To study and develop a mass balance on odour offensiveness indicator, in term of VFA concentration, of the system.

6.2 Experimental design and methods

6.2.1 Slurry collection and preparation

Fresh cattle slurry was collected from the floor channel of a cattle unit in Gibbsyard Farm, SAC Auchincruive. The excreta, consisted of faeces and urine, was diluted to a slurry with tap water. Large solid particles of slurry were separated mechanically through a 5 mm sieve before the slurry was used in this experiment.

Before the slurry was used as feed, it was further diluted with tap water and made up into approximately 50 litres. The characteristics of this prepared raw feed slurry are shown in Table 6.1. The prepared diluted slurry was thoroughly mixed before dispensing into 2 identical 25 litres containers, and were stored at 1°C.

Table 6.1. Initial characteristics of feed cattle slurry in Treatment 1 (raw) and Treatment 2 (mixture of treated and raw fresh slurry) in Study 2.

Parameter		Raw		Mixture	
		value	% of TS (w/w)	value	% of TS (w/w)
TS	$g.l^{-1}$	28.8	100	25.5	100
TS(S)	$g.l^{-1}$	11.5	40	10.9	43
TSS	$g.l^{-1}$	8.0	28	14.0	55
VS	$g.l^{-1}$	22.2	77	19.9	78
VS(S)	$g.l^{-1}$	7.6	26	7.1	28
VSS	$g.l^{-1}$	7.6	26	12.8	50
CODw	$g.l^{-1}$	43.5	151	34.6	136
CODs	$g.l^{-1}$	18.0	63	14.1	55
BOD_5w	$g.l^{-1}$	8.2	28	6.7	26
BOD_5s	$g.l^{-1}$	5.4	19	4.5	18
Kj-N	$g.l^{-1}$	2.5	9	2.0	4
NH_4^+-N	$g.l^{-1}$	1.3	4	1.1	8
VFA	$g.l^{-1}$	4.0	14	3.5	14
TIP	$g.l^{-1}$	0.1	0	0.1	0
TOA	$g.l^{-1}$	3.5	12	4.1	16
pH	-	7.3	-	7.6	-

6.2.2 Treatment process and apparatus

The experimental apparatus used in this experiment was the same as in the Study 1 (Chapter 5.2), except for the different feed storage reservoir. A 50 litre PVC container was used as a feed storage reservoir in order to accommodate a larger volume of slurry used in this study. This feed reservoir was surrounded with copper tubing as a cooling coil and insulated with a bubble wrap. The mixing system was also different from the Study 1. The slurry was pumped from the bottom to the top of the feed tank using a centrifugal pump (Type: PV 22, James Beresford Ltd). The slurry was then discharged in the middle of the feed reservoir via a 15 mm ID plastic tubing immersed into the slurry. In order to ensure the homogeneity of feed slurry for

dosing, the slurry was circulated around the feed storage approximately 3 minutes before the dosing pump was switched on.

Treatment process

The treatment conditions, control and monitoring parameters in this experiment were the same as the Study 1, except for modifications described below.

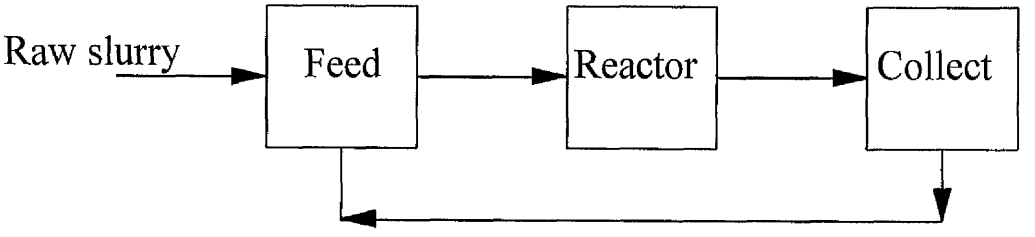


Figure 6.0 Flow diagram of laboratory Study 2

The treatment process was similar to Study 1 as illustrated in Figure 6.0. Cattle slurry treated continuously, two passes through a single stage reactor without intermittent storage. The treated ML was recycled back into the feed storage tank with a 1 day residence (i.e. the total residence time was 2 days). The treatment operating conditions (Table 6.2) were the same as at Study 1.

Table 6.2. Treatment conditions of Laboratory Study 2.

Parameter	Treatment	
	1	2
Nominal residence time, *d*	1	1
Actual residence time, *d*	0.9	0.9
Treatment period, *d*	25	75
Redox potential, mVE_{cal}	-150	-150
Temperature, ^{o}C		
Feed	10	10
Reactor vessel	15	15
Store	10	10

This study was designed to run 2 treatments (i.e. Treatment 1 and Treatment 2). Both treatments are described as below:

Treatment 1:

25 litres of raw cattle slurry were fed regularly, approximately every 10 minutes, from the feed storage tank into a reactor vessel where the slurry was aerated at conditions shown in Table 6.2. The amount of discharged ML was collected in a measuring cylinder and was recorded. It was then refilled back into the feed storage tank daily until the completion of a cycle (25 days), so that the treatment recycling process was achieved. The concentration of the feed slurry was thus changing daily by addition of ML during the treatment period.

Treatment 2:

23 litres of raw cattle slurry (i.e. same slurry characteristics as the raw slurry was used in Treatment 1) was added and mixed with the pre-treated slurry in the feed storage container after Treatment 1. This mixed slurry was then fed into the reactor and treated (Table 6.2) for another 75 days as during the Treatment 1. Therefore, all the slurry was assumed to pass through the reactor twice after approximately 100 days period of total treatment (i.e. Treatment 1 and 2).

6.2.3 Slurry sampling and preparation

As soon as the aeration process had settled down, (i.e. usually after a period equal to 3 to 4 residence time), approximately 500ml samples of feed and treated (ML) slurries were taken twice a week. Both feed and ML samples were well mixed before sampling from the recirculating pipework and ML discharged-measuring cylinder, respectively. These were analysed for TS, VS, TSS, VSS, COD, BOD, Kj-N, NH_4^+-N, pH, VFA, TIP and TOA following standard methods (APHA, 1992).

6.3 Results and discussion

The operating conditions were controlled and recorded from the beginning of the treatment through the monitoring period. The mean values of operating conditions calculated after the steady state conditions was achieved and are shown in Table 6.3.

Table 6.3. Mean values of treatment condition parameters of laboratory Study 2

Parameters	Treatment 1			Treatment 2		
	Mean	S.D.	n	Mean	S.D.	n
Redox value, mV E_{cal}						
Min.	-141.5	4.3	20	-143.3	24.8	72
Max.	-168.0	10.6	20	-155.7	27.7	72
average	-153.8	5.6	20	-150.8	9.2	72
Temperature, ^{o}C						
Reactor	15.0	0.1	20	15.0	0.2	72
Feed storage	10.3	1.1	20	10.4	1.3	72
Reactor working volume, *litre*	0.9	0.0	20	0.9	0.0	72
Daily discharged ML volume, *litre*	0.88	0.1	20	0.92	0.2	72

Note:
S.D. = standard deviation
n = number of measurement

The treatment became stable after 4 days from the start. Temperatures of the reactor and feed slurry storage tank in Treatment 1 and 2 were well controlled. This experiment was carried out between March to June with higher ambient temperature, thus the cooling for feed slurry storage was required to interact with the ambient temperature. The mean temperature of feed slurry storage was thus slightly higher than the set temperature of 10 °C. Redox values were kept within the pre-set range throughout the treatment but the Treatment 1 was less stable than Treatment 2, reflecting the stability of aeration process was increased with treatment time duration. The reason was that the microbial activities had a higher demand for oxygen at the beginning of treatment. The mean residence times of Treatments 1 and 2 were well controlled, the discharge volume of ML was only 7% greater than the controlled volume in Treatment 1 while 2% lower in Treatment 2. These variations were due to various reasons, i.e. the ML was lost by foaming and an inaccurate dosing volume.

The initial characteristics of raw and mixture (raw and treated (ML) slurry) cattle slurry are shown in Table 6.1. During the monitoring period, the chemical and biochemical characteristics of cattle slurry in the feed storage and the discharged ML from the reactor were monitored. Treatment 1 was run for 21 days and approximately 19 litres of the ML was left at the end of this treatment. 23 litres of raw cattle slurry (Chapter 6.2 experimental design and method) was added and mixed with the pre-treated slurry at the day 21 of treatment period and Treatment 2 was started. Treatment 2 was run 80 days and made up the overall monitoring period was 101 days. At the twenty-second days of the monitoring period, the dosing pump was broken and about 90% of slurry was leaked from the feed storage. Some of the slurry was lost and the concentration of the slurry in the feed storage was therefore increased.

Change in the characteristics of feed slurry and ML after Treatments 1, 2 and overall (i.e. initial characteristics of Treatment 1 to the final characteristics of Treatment 2) in study 2 are shown in Table 6.4. All the analytical results are in Appendix D1-D8. The major change in the characteristics of feed slurry and ML are described as below.

Characteristics of feed slurry storage and ML

Total volatile fatty acids (VFA)

The changes of VFA concentration in feed and treated slurries are illustrated in Figure 6.1. The trend of VFA concentration was inversely linear with treatment time in feed and treated slurry (ML) during Treatments 1 and 2. This pattern change was similar to previous findings (Williams, 1984; Thacker & Evans, 1986; Williams *et al.*, 1989; Pain *et al.*, 1990; Burton *et al.*, 1998). VFA concentration in ML was significantly ($p<0.001$) lower than in the feed slurry. Each sample of VFA concentration in ML was below acceptable level (230 $mg.l^{-1}$ of VFA) of odour offensiveness (Williams, 1984). This confirmed that minimal continuous aeration at 1 day residence time can achieve a high degree of odour removal. These VFA values of ML also agreed with the previous experimental results from Chapter 5.

For the Treatment 1 (as described in Chapter 6.2) between day 0 to day 2, the concentration of VFA in the feed slurry decreased sharply, at a rate of approximately 93 $mg.l^{-1}.d^{-1}$ from 3250 $mg.l^{-1}$ down to 1290 $mg.l^{-1}$. In Treatment 2 (i.e. after addition of raw cattle slurry), the removal rate of VFA was found to be 23 $mg.l^{-1}.d^{-1}$, and VFA decreased from 3440 to 1380 $mg.l^{-1}$ (Figure 6.1). These reduction rates of VFA indicate that the removal rate of VFA was inversely proportional to the stored slurry volume. This was because of higher microbial population activity was present in larger volume and causing greater production rate of VFA (Williams, 1981).

Although the VFA was substantially removed by the treatment, its concentration still remained high in the feed storage (daily addition of ML) at the end of the treatment at 1290 $mg.l^{-1}$. There are possible explanations:- (1) The feed slurry was stored under anaerobic condition, hence, anaerobic microbial activity in the feed slurry regenerated a high portion of VFA; (2) The actual daily degradation rate of VFA, by aeration, was therefore only slightly greater than the VFA produced by the anaerobic microbial activity; (3) The daily addition treated (ML) slurry volume of 1 litre was not significant where compared with the volume of the feed slurry (approximately 45 litres).

The treatment period was completed, assuming that all slurry was treated and passed twice through the reactor. Aeration was then stopped and no more aerated slurry was added back to the feed storage. The concentration of VFA then increased slightly (Figure 6.1). This change was because no more VFA was removed whilst VFA was regenerated under anaerobic storage as found by Williams & Evans (1981).

The changes of individual VFA components in feed slurry and ML are illustrated in Figure 6.2 and Figure 6.3 respectively. These concentrations closely followed the pattern as total VFA. The highest component of VFA was acetic acid in both feed slurry (53 to 67%) and ML (70 to 100%). Propionic acid was also considerably high. Thus total VFA concentration was mainly affected by these two acids (acetic and propionic). In feed slurry, the I-butyric, N-butyric and I-valeric acids were detected at much lower concentrations than acetic and propionic acid. N-Valeric acid was only

Table 6.4. Change in the characteristics of feed slurry and ML after Treatments 1, 2 and overall in Study 2. Values were the difference between the initial and end concentrations, and the final reductions expressed in percentages of initial values of feed slurry and ML.

		Feed slurry					
		Treatment 1-reduction		Treatment 2- reduction		Overall reduction	
Parameter		value	%	value	%	value	%
TS	$g.l^{-1}$	1.6	6	2.7	11	3.8	14
VS	$g.l^{-1}$	0.9	4	2.1	11	2.8	14
CODw	$g.l^{-1}$	11.2	25	5.3	15	14.8	33
CODs	$g.l^{-1}$	5.5	27	0.6	4	6.4	31
BOD_5w	$g.l^{-1}$	3.1	38	3.4	53	5.1	63
BOD_5s	$g.l^{-1}$	1.7	34	2.2	54	3.1	62
VFA	$g.l^{-1}$	2	60	2.1	60	1.9	58
TIP	$g.l^{-1}$	0.05	60	0.05	82	0.07	85
TOA	$g.l^{-1}$	1.8	51	2.70	65	2.0	59
Kj- N	$g.l^{-1}$	0.27	11	0.24	12	0.6	27
NH_4^+-N	$g.l^{-1}$	0.07	7	0.24	22	0.22	21
pH	-	-0.7	-9	-0.8	-10	-1.4	-19
		Mixed liquor (ML)					
TS	$g.l^{-1}$	2.3	9	2.8	11	3.8	15
VS	$g.l^{-1}$	1	5	2	11	3.6	18
CODw	$g.l^{-1}$	9.3	23	3.4	11	11.9	30
CODs	$g.l^{-1}$	6.5	40	3.5	24	5.1	31
BODw	$g.l^{-1}$	1.4	29	5.8	74	2.7	56
BODs	$g.l^{-1}$	1.8	69	3.3	79	1.7	67
VFA	$g.l^{-1}$	0.14	78	0.17	97	0.18	97
TIP	$g.l^{-1}$	0.006	75	0.02	100	0.008	100
TOA	$g.l^{-1}$	0.3	43	2.5	82	0.2	24
Kj- N	$g.l^{-1}$	-0.07	-4	0.25	13	0.15	8
NH_4^+-N	$g.l^{-1}$	-0.11	-15	0.17	20	0.08	10
pH	-	-0.1	-1	-0.4	-5	-0.1	-1

Note: Overall reduction of Feed slurry and ML were calculated by the difference between the started value of Treatment 1 and the final value of Treatment 2, and expressed in percentages of the initial values of feed slurry and ML in Treatment 1.

Figure 6.1 Total volatile fatty acids (VFA) in the feed and the ML of cattle slurry during Treatments 1 and 2 (Study 2)

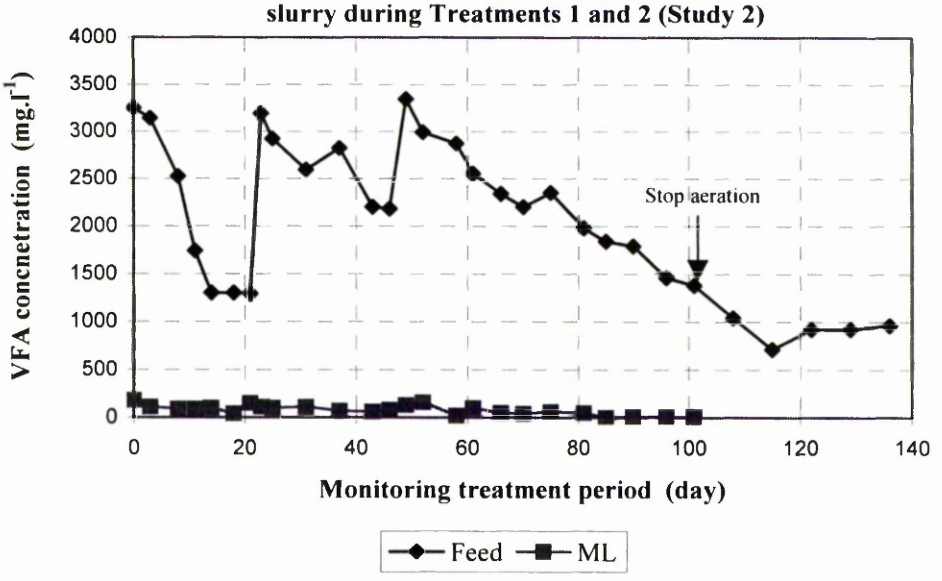
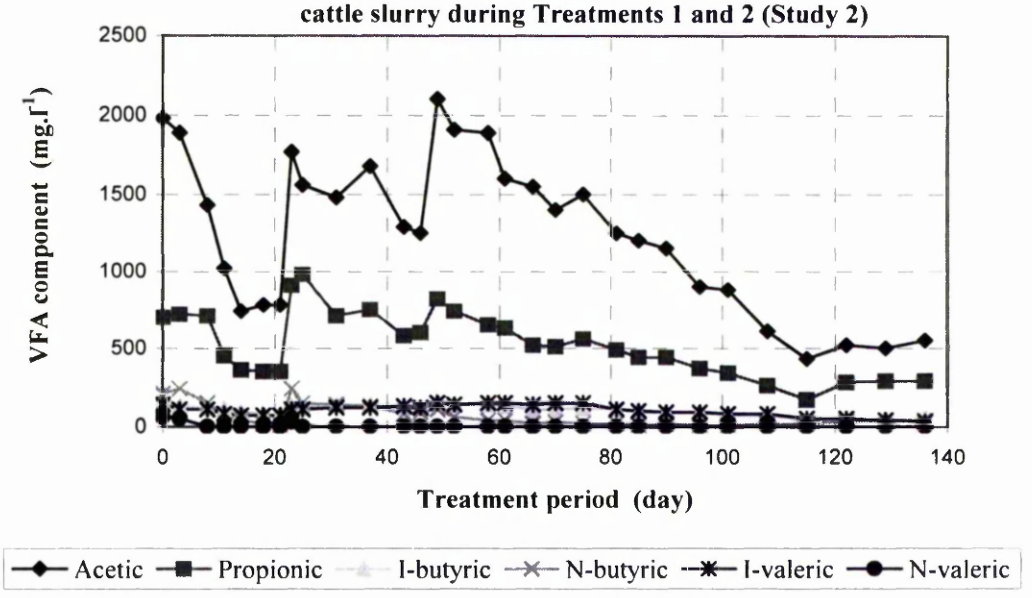


Figure 6.2 Individual volatile fatty acid (VFA) concentration in the feed of cattle slurry during Treatments 1 and 2 (Study 2)



detected at the first 3 days of treatment in feed slurry. The changes of the individual VFA (Figure 6.3) of treated slurry were similar to the feed slurry, but only acetic and propionic acids were detected in low concentration.

Total organic acids (TOA)

Figure 6.4 shows the change of TOA concentration in feed slurry and ML during the treatment period. The close association of its concentration is reflected by the similarity of the pattern of change to VFA. The removal of TOA between feed slurry and ML was between 66% and 80% throughout the Treatments 1 and 2 (Table 6.4). TOA generally was greater than VFA, as VFA is part of TOA, and the ratio VFA/TOA in the feed slurry was between 0.8 to 0.98 during the Treatment 1, and 0.8 to 0.9 during Treatment 2. The ratio VFA/TOA in the ML was 0.1 to 0.3 during Treatment 1 and less than 0.06 throughout the Treatment 2. The ratio in the ML was therefore much lower than in the feed. This probably due to a high VFA removal during the treatment, and was not as complete as removal of TOA.

Total indoles and phenols (TIP)

The change of TIP in the feed slurry and ML during treatment is shown in Figure 6.5. The reduction trend of TIP was very similar to the VFA change in both feed slurry and ML. Concentration of TIP in the feed slurry was much greater than in ML, as with VFA (Table 6.4). The TIP in feed slurry were reduced by 60%, from 80 $mg.l^{-1}$ in the Treatment 1, it was then further decreased down to approximately 10 $mg.l^{-1}$ after Treatment 2. Concentration of TIP was less than 1 $mg.l^{-1}$ throughout the Treatment 1 in the ML, while 13 out of 17 measurements were zero in Treatment 2. It showed that removal of TIP approached 100%, similar to the findings of Williams (1981).

The change of TIP in the feed slurry was mainly affected by phenol and p-cresol (Figure 6.6). Initial concentration of p-cresol was 70 % greater than phenol. P-cresol was reduced by 100 % in Treatment 1 while the concentration of phenol was increased at the first 10 days of treatment, and then reduced in similar pattern change of that of as TIP. This indicates that the removal rate was greater than the

Figure 6.3 Individual volatile fatty acid (VFA) concentration in the ML of cattle during Treatments 1 and 2 (Study 2)

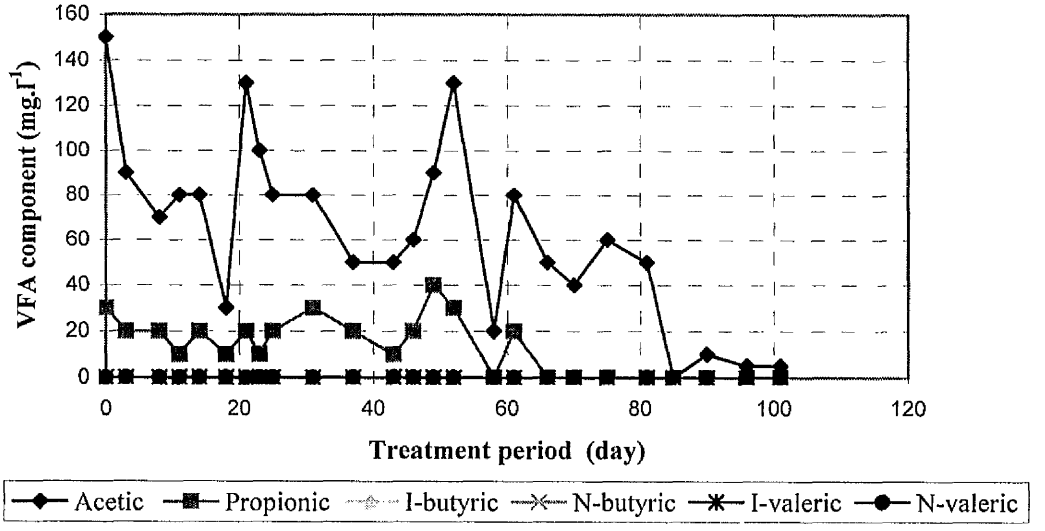


Figure 6.4 Total organic acid (TOA) concentration in the feed and the ML of cattle slurry during Treatments 1 and 2 (Study 2)

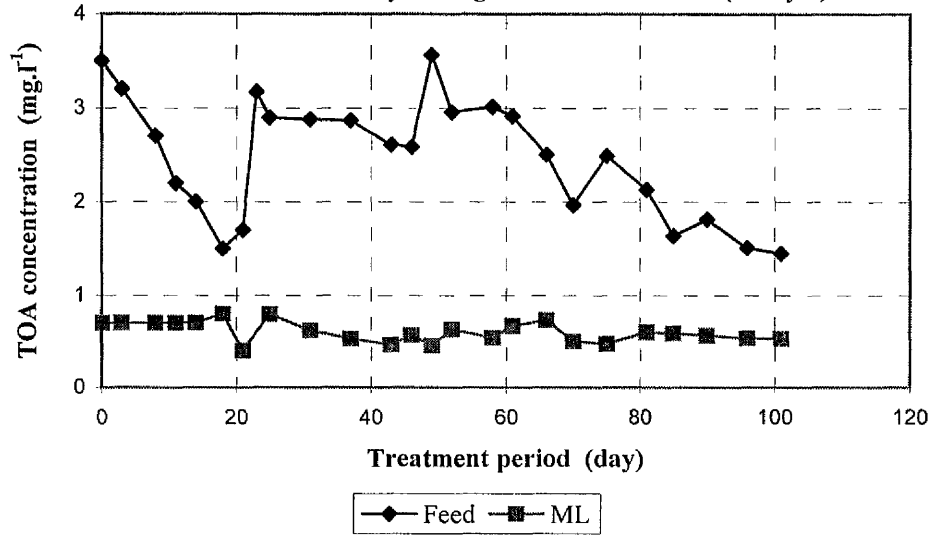


Figure 6.5 Total indoles and phenols (TIP) in the feed and the ML of cattle slurry during Treatments 1 and 2 (Study 2)

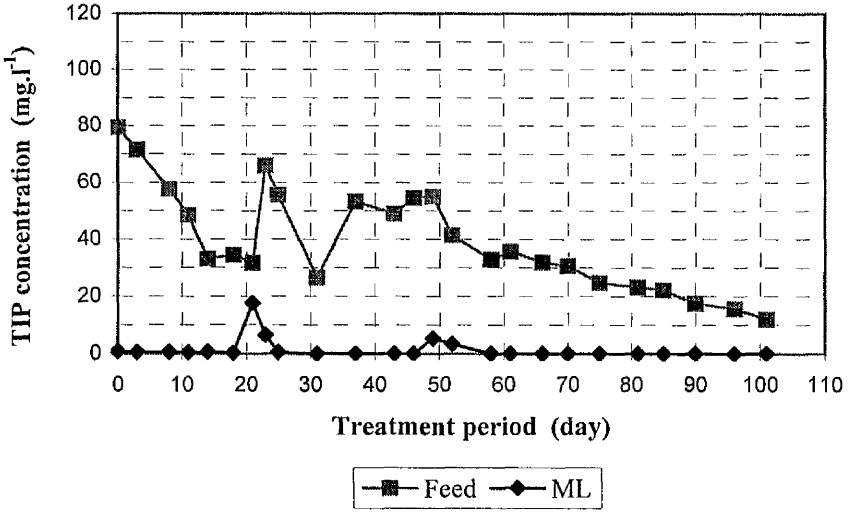
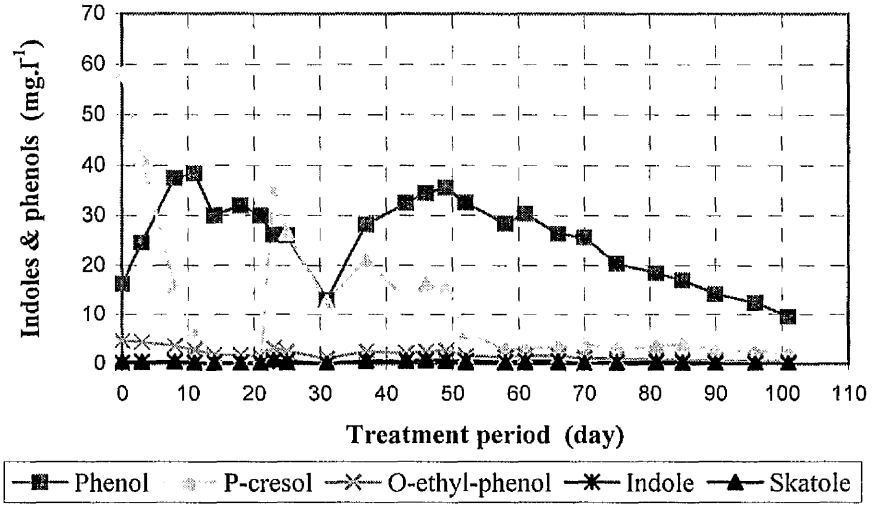


Figure 6.6 Individual indoles and phenols concentration in the feed of cattle slurry during Treatment 1 and 2 (Study 2)



regeneration and shows TIP was mainly affected by the concentration of phenol and p-cresol.

The changes of o-ethyl-phenol, indole and skatole were not significant in feed slurry. This could be explained by the regeneration rate of individual indole and phenol components being close to the rate of removal, resulting in TIP being in equilibrium. The individual indole and phenol components were reduced to trace amounts after treatment (Appendix D-Tables D4 and D8).

5-day biochemical oxygen demand (BOD_5)

The changes of BOD_5w and BOD_5s in feed slurry and ML throughout the treatment period are shown in Figure 6.7. The close relationship between the BOD characteristics with organic odorants is reflected by the similarity of the BOD changes pattern to those of VFA, TOA and TIP. The trend of changes shows that the concentration of BOD decreased linearly with increase of time. Reduction of BOD_5w and BOD_5s was significant between feed slurry and ML in Treatment 1 and 2 and is shown in Table 6.4. Overall reduction (i.e. difference between the initial values of Treatment 1 and the end of the Treatment 2) of BOD_5w was greater (5.1 $g.l^{-1}$, by 63%) than BOD_5s (3.1 $g.l^{-1}$, by 62%) in feed slurry. This suggests that the removal of soluble nutrients in the feed slurry was greater than the insoluble ones, as similarly commented by Farrell (1996).

Chemical oxygen demand (COD)

Figure 6.8 shows the changes of CODw and CODs in feed slurry throughout the treatment period. Again, the general pattern changes of the CODw in feed slurry was similar to the that of VFA, TIP, TOA and BODw, reflecting close relationship of the characteristics with the organic materials. The gradient of CODw in the Treatment 1 (approximately 0.56 $g.l^{-1}.d^{-1}$) was greater than in the Treatment 2 (approximately 0.057 $g.l^{-1}.d^{-1}$), it reflects the rate of oxygen consumption for the microbial activity in the Treatment 1 which was greater than for the Treatment 2. COD of Treatment 1 was reduced more than twice than the Treatment 2, as shown in Table 6.4. The reason for this was probably that the volume of total slurry in the feed storage was

Figure 6.7 Whole and supernatant BOD in the feed and in the ML of cattle slurry during Treatments 1 and 2 (Study 2)

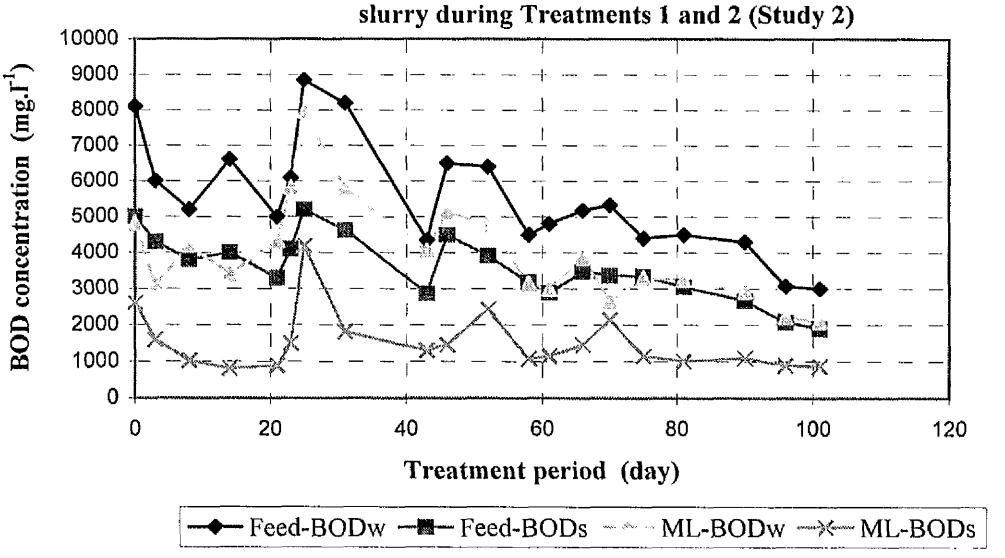
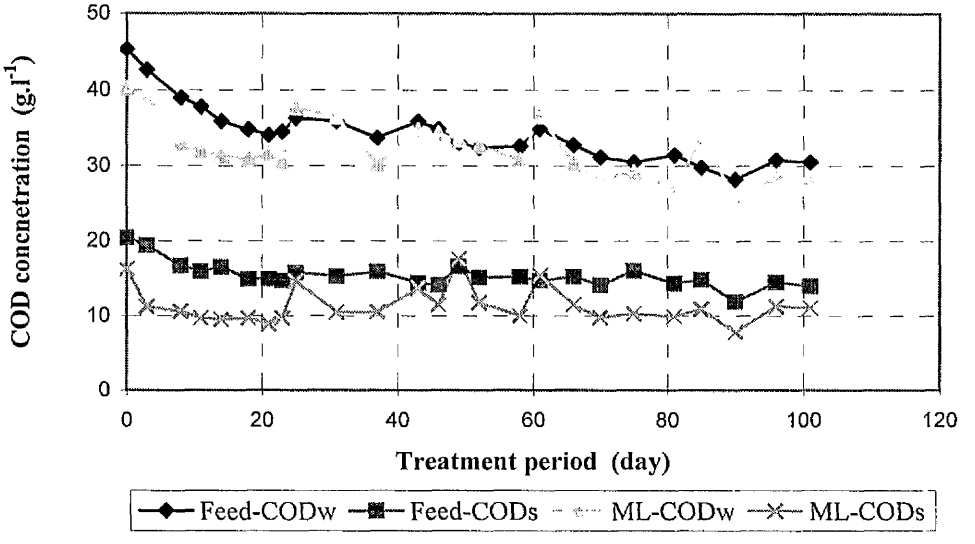


Figure 6.8 Whole and supernatant COD in the feed and in the ML of cattle slurry during Treatments 1 and 2 (Study 2)



much larger during the Treatment 2 (45 litres) than in Treatment 1 (20 litres), causing lower the removal rate of concentration COD. As expected, the CODs concentration of feed slurry was lower than the CODw, the ratio CODs/CODw was in average 0.45. The change of CODs in the feed slurry mixture was only significant in Treatment 1 (from 20 $g.l^{-1}$ to 15 $g.l^{-1}$) and it then fluctuated at 15 $g.l^{-1} \pm 1$ $g.l^{-1}$ during Treatment 2. CODs in Treatment 1 was reduced approximately 8 times more than in Treatment 2. This suggests that the soluble fraction in the Treatment 1 required more oxygen than the second treatment.

Trends of CODw and CODs of feed slurry and ML were similar (Figure 6.8). The ratio CODs/CODw fluctuated between 0.3 and 0.5. CODs of ML was decreased by 40% from 16.2 to 9.5 $mg.l^{-1}$ during Treatment 1. It then fluctuated between 10 and 15 $mg.l^{-1}$ during Treatment 2, with the concentration always lower than the CODs of feed slurry during whole treatment period (Treatment 1 and 2). This would be explained by a rate of degradation of CODs in the feed slurry remaining constant during Treatment 2. This probably due to relatively high amounts of non-degradable or inert material.

The predicted treated (ML) CODw concentrations were calculated by substituting the feed CODw values into equation 2.4 (Evans *et al.*, 1983) during treatment period (Figure 6.9). Change of CODw in the feed slurry was a reflection of predicted COD of ML during treatment using 2 day fixed residence time of calculation. Although the predicted COD concentration was less than the actual observed CODw by 4 to 25%, their pattern changes and magnitudes were closely followed each other. These differences between the predicted and actual observed COD were probably due to the variation of residence time. This could be due to various reasons, such feed slurries being missed, mechanical problem of aeration apparatus and performance of aerator. Therefore, the prediction of treated slurry needs to take into account both the residence time and the COD of feed slurry over the monitoring period in order to obtain better outcome.

Figure 6.9 Predicted and observed CODw of cattle slurry during Treatments 1 and 2 (Study 2)

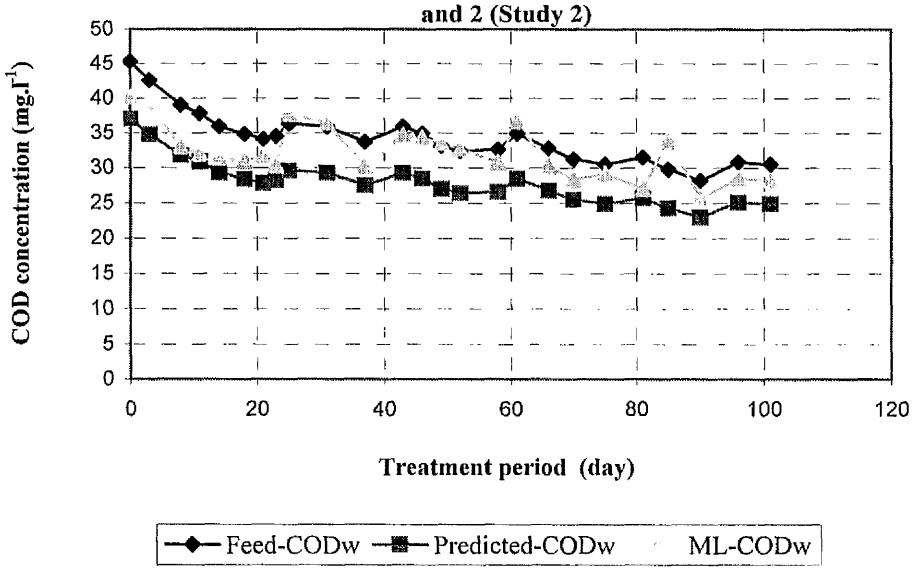
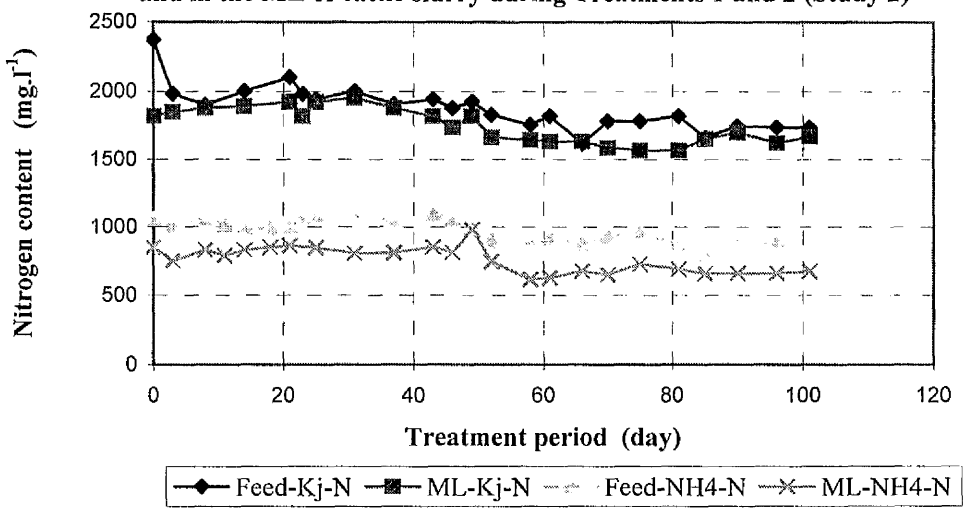


Figure 6.10. Kjeldahl (Kj-N) and ammoniacal (NH_4^+-N) nitrogen in the feed and in the ML of cattle slurry during Treatments 1 and 2 (Study 2)



Nitrogen content

The reduction and change of Kj-N and NH_4^+-N concentration in feed slurry and ML are shown in Table 6.4 and in Figure 6.10 respectively. The overall amount of nitrogen content as Kj-N and NH_4^+-N is relatively constant, reflecting a low loss in both feed slurry and ML. Nitrification and de-nitrification were not significant and thus losses of nitrogen concentration were mainly caused by gas stripping during the treatment because of the minimal aeration at short residence time (Evans *et al.*, 1983, 1985 & 1986).

Solids concentration

The reductions of TS and VS of feed and ML are shown in Table 6.4 and the change of the solids concentration is shown in Figure 6.11. The overall removal of total solids concentration in feed slurry was low, between 2% and 6% during Treatment 1, while 11 % reduction occurring during Treatment 2. This shows that the biodegradation of solid material was low during minimal aeration at short residence treatment times and is occurred with Evans *et al.* (1983).

pH value

The change of pH value in the feed slurry is shown in Figure 6.12. The pH of feed slurry was greater than 7 due to NH_4^+-N concentration. The initial (Treatment 1) pH value was 7.5, and then increased slowly during Treatments 1 and 2 to a maximum 8.9 at the end of Treatment 2. This change was probably due to change of organic acids concentration (VFA and TOA). An initial rapid rise of pH corresponded with the initial rapid degradation of organic acids concentration. The subsequent slow rise of pH value followed the elimination of VFA and probably reflected a gradual increase in the quantities of CO_2 evolved from feed slurry. Similar results were found, in the stored treated slurry (ML), by Stevens & Cornforth (1974). Also, the nitrogen content (described previously) was conserved in the feed slurry resulting higher pH value (>7).

Figure 6.12 shows that the change of pH in ML was not significant (Figure 6.12). The value fluctuated within a range 8.4 to 8.9, giving an average of 8.6 during both Treatments 1 and 2. It is considered that organic acids (VFA and TOA) concentration

Figure 6.11 Solids concentration in the slurry and in the ML of cattle slurry during Treatments 1 and 2 (Study 2)

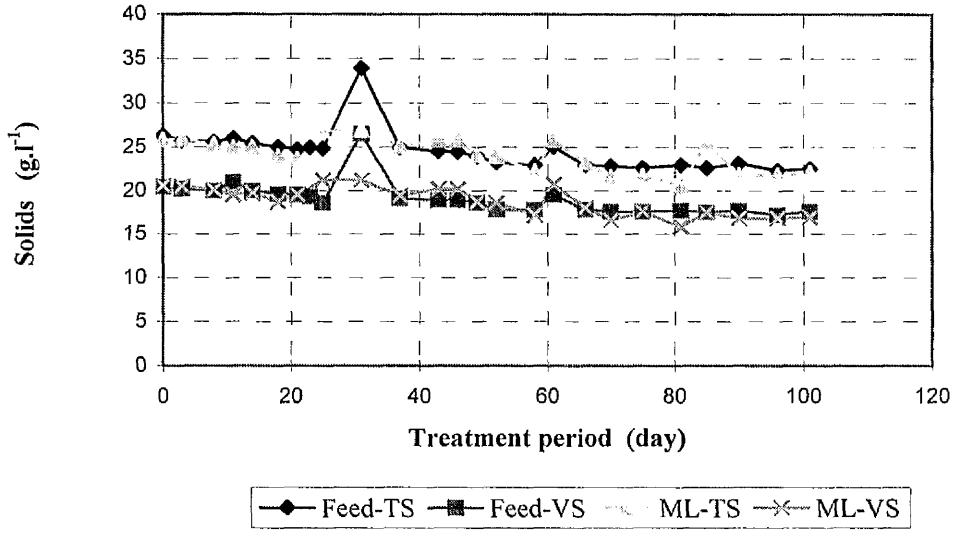
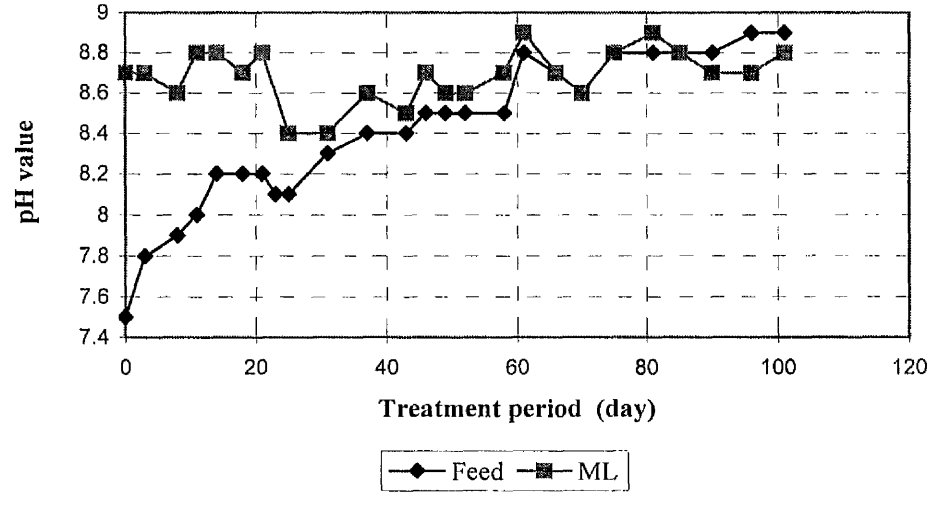


Figure 6.12 pH in the feed and in the ML of cattle slurry during Treatment 1 and 2 (Study 2)



was removed substantially while little ammonia was stripped during the treatment, and this is reflected in a higher pH.

PART C: FULL SCALE AEROBIC TREATMENT OF PIG SLURRY EXPERIMENTAL WORK

7. FULL SCALE SYSTEM DESIGN

7.1 Introudction

This chapter draws upon the theoretical models, laboratory-scale experimental results of previous Chapters (4, 5 & 6) and recent aeration technology (Chapter 2.5), in order to design and build a larger scale plant operated under practical conditions on an existing pig farm. The main objective of this study was to assess the change of slurry characteristics in term of odour offensiveness and environmental polluted parameters, which were related to the cost of treatment. This farm scale aerobic treatment experiment were divided into three trials:

Trial 1: Preliminary study of the aeration process system. Experience gained from this experiment was used to improve techniques for the Trial 2 and 3.

Trial 2: To investigate the effect of continuous aerobic treatment on the change of slurry characteristics with the oxygen requirement and energy consumption for the system.

Trial 3: Optimisation and integration of the control aeration system from Trial 2, in order to reduce the capital and operation cost of treatment.

7.2 Treatment requirement

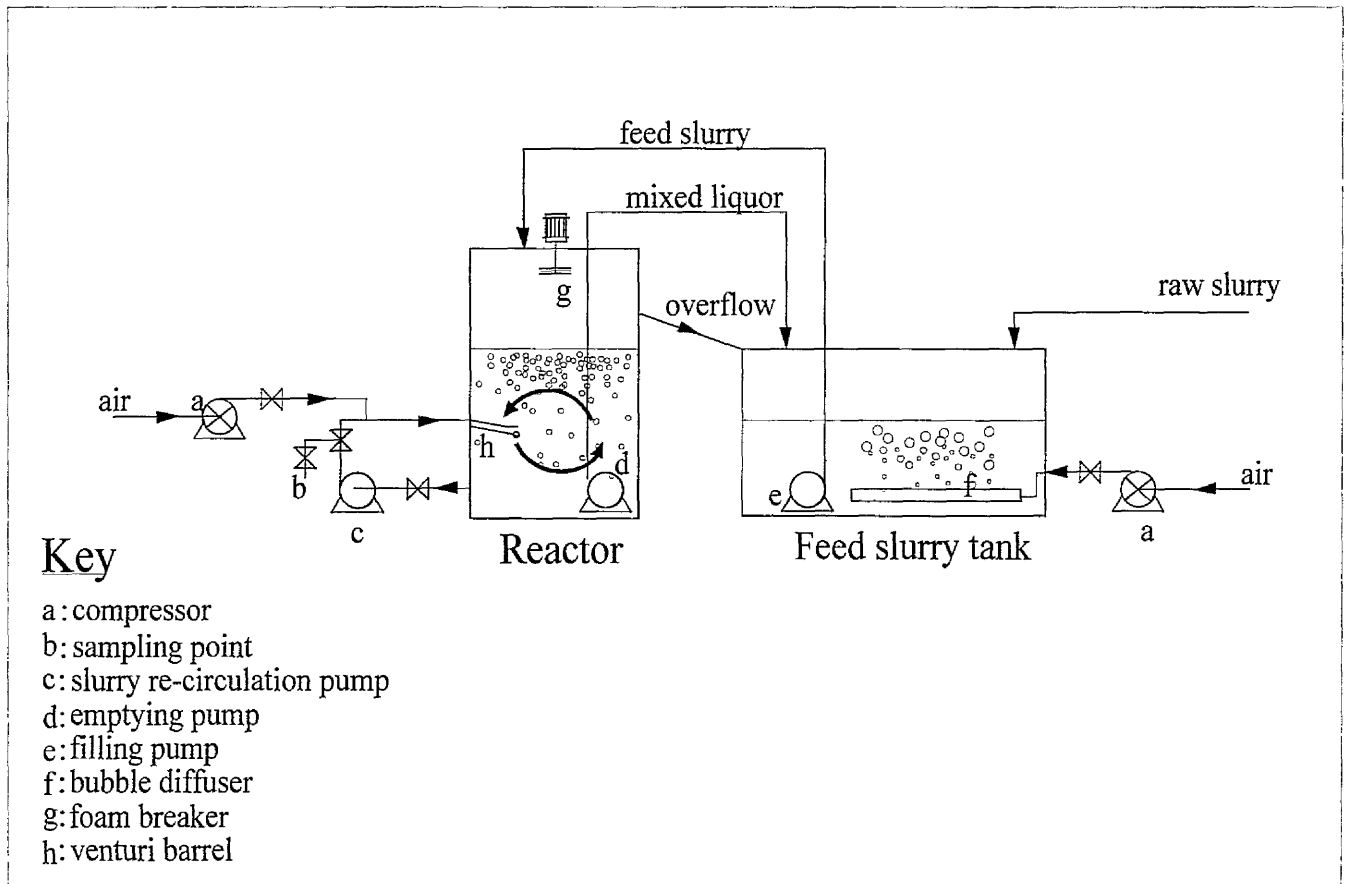
7.2.1 Design requirement

A full scale treatment system (Figure 7.1) was designed to remove the odour offensiveness from pig slurry to an acceptable level. In this study, the odour level was determined by the VFA concentration and the required target value of VFA was below 500 $mg.l^{-1}$. The treatment conditions, residence time, temperature, and redox control level, are described in the following Chapters on individual trials.

7.2.2 Slurry characteristics

The raw pig slurry was separated by a mechanical separator (Carrier), and delivered from the piggery reception pit to a storage tank via a storage lagoon. The characteristics of raw slurry used in these 3 studies are as shown in Chapter 9 (Table 9.1).

Figure 7.1 Flow diagram of farm scale continuous aerobic treatment plant



7.3 Treatment process plant

The treatment plant (Figure 7.2) was installed on a commercial pig farm. The plant was built around the existing slurry handling and storage equipment associated with the pig farm.

A 42.4 m^3 circular tank (Alibert Ltd) with 6 m high and 3 m internal diameter (Appendix E-Figure E1 & E2) was used as the treatment aeration vessel, and was made of high density polyethylene. It has 5 flanges; two flanges were used as windows, two for suction and discharge side of venturi aeration system and one as an overflow discharge. The size of this reactor vessel was based on the farm management such as slurry loading and method of storage. It was governed by a number of factors, usually design requirement, slurry characteristics, oxygen requirement, the existing facility in the field and the location of the treatment plant.

This vessel was free standing on a concrete base, and was adjacent to the slurry storage tank. This storage tank was used as a feed slurry tank. The working volume of aeration vessel was designed to be 31.8 m^3 with 4.5 m slurry depth. The residence time in the reactor was thus maintained by regular pumping of raw slurry in and ML out of the reactor. The feed slurry was pumped from the storage tank into the reactor vessel in intervals and vice versa to achieve the required residence time (see later, the feeding/emptying control) at the local temperature. The slurry in the reactor was circulated near the bottom of the vessel using a venturi/pump system (Figure 7.3) (see oxygen requirement and venturi aerator design) where the air entrainment was taken place. The air was delivered from atmosphere to the venturi jet system using a compressor (see compressed air supply). The ML in the reactor was therefore mixed and aerated by a venturi jet aerator. The generated foam was controlled by an overflow going back to the storage tank, and by a foam breaker (see foam control). The whole plant was run automatically and data were monitored continuously. The details of the process control and monitored parameters are described in the following sections.

7.4 Oxygen requirement and venturi aerator design

Oxygen consumption was calculated from changes in COD, nitrate and nitrite concentration as described in Chapter 2.2. However, in this study only a minimal

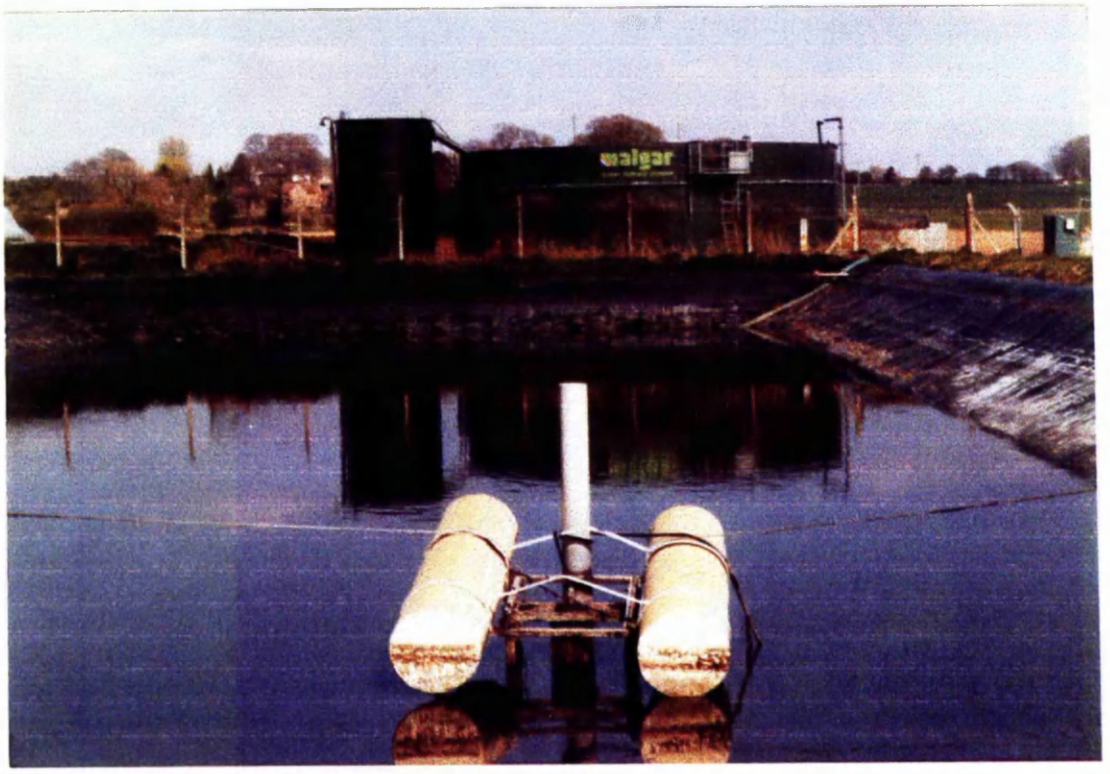


Figure 7.2. Farm scale treatment plant layout

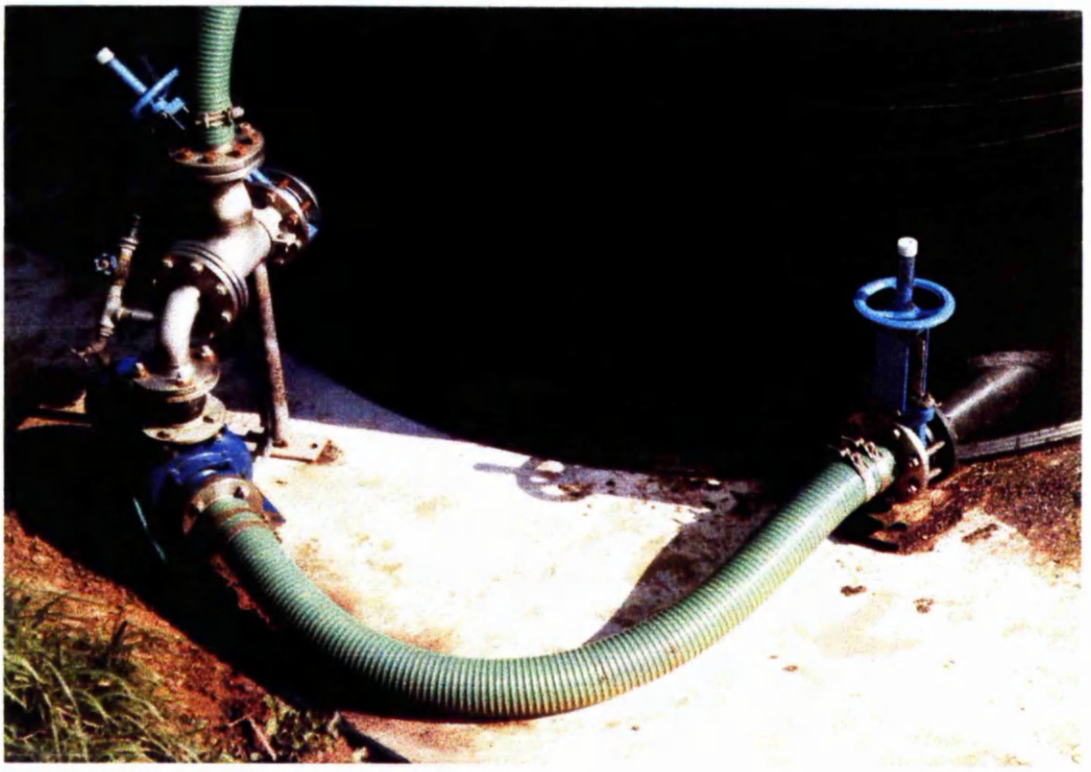


Figure 7.3. Venturi aeration system

aeration was used at a short residence time. Therefore the nitrification had not occurred and the oxygen was required only for oxidising the carbonaceous compounds in slurry.

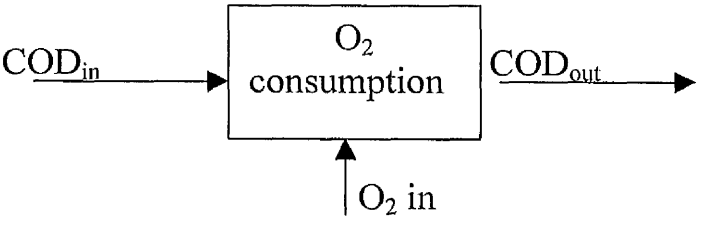


Figure 7.4. Simple oxygen mass balance diagram

The amount of the oxygen required for the full scale system (Appendix E-Tables E1 & E2 for calculation) was based on results from the laboratory Study 1 (Chapter 5) and the models (Evans *et al.*, 1983; Sneath *et al.*, 1992). From the results of laboratory scale reactor, different solids concentration altered the COD content (i.e. the range of total solid between 2.7 % to 7 % (w/v) for the pig slurry, required 5 to 13 kg $O_2.m^{-3}$ of slurry (refer to appendix for the calculation); and for the cattle slurry, the TS between 2.25 % to 6 % (w/v) required 4.9 to 13.1 kg $O_2.m^{-3}$ of slurry). Burton (1992) suggested that typical values of COD breakdown and raw slurry total solid (TS) used in the reactor were 13 $g.l^{-1}$ of COD difference and 3 % (w/v) of TS. Therefore, on the basis of solids concentration, the amount of COD was estimated by using ration of TS concentration 2 to 7% (w/v). Assuming the use of oxygen was 10 % of 21 % (w/v) in air, an extra 30 % of air was also added to allow for the variation in the system and to avoid operating the aerator continuously at its limit.

Venturi aerator

The venturi jet aerator was chosen to use in this study because its capital cost is low, fairly cheap to run and easily maintained. This kind of jet aerator usually provides a good power efficiency. Furthermore, it is an excellent mixing mechanism and has a high oxygen transfer efficiency which makes it particularly relevant to oxidation process. Detailed description of venturi aerator is in Chapter 2.5.

The aeration system use a combination of a venturi jet (E.A Technology) (Figures 7.5, 7.6 & 7.7) and a slurry circulation pump (Hydrostal monobloc pump, specification see Appendix E-Table E3 & E4), with throughput of 11 litre.s^{-1} at a pressure of 12 m water head. All connections to the pump were made with flexible couplings to eliminate the transmission of vibration and to allow for a misalignments. The inlet of pump was connected to the tank with 100 mm diameter semi-rigid medium duty hose, and the outlet was connected to the venturi aerator via rubber flexible connector and a steel elbow fitting. The specification of venturi aerator is shown in Appendix E-Table E4.

The nozzle size used in the venturi aerator was based on the calculation of the pressure loss (see Appendix E-Table E5 for calculation), using Bernoulli's equation (Appendix E). A 35 mm diameter nozzle was thus calculated and used (Appendix E-Table E6 for nozzle calculation) for the venturi, and the discharge outlet of the venturi was connected to a barrel which was extended to the centre of the vessel (Figures 7.6 & 7.7 and Appendix E Figures E3 & E4). Therefore, the slurry with the air could be distributed and well mixed within the vessel by momentum of a jet. The size of the barrel was twice the diameter of the nozzle (i.e. 70 mm) and 10 times as long as its diameter (i.e. 700 mm).

7.5 Process control

The process control system was essentially required for two functions in this full-scale treatment study: firstly for control of residence time and secondly for aeration level.

7.5.1 Mean residence time and feeding/emptying of the reactor

The required residence time of slurry in the reactor was controlled by semi-continuously feeding and emptying operations. The slurry was pumped from storage tank into the reactor vessel via a chopper pump (Piranha S17-2W+D, ABS)(feed pump). This ensured that there were no large particles in the feed slurry, thus reducing the likelihood of blockages. The treated ML was pumped to the storage tank using a submersible pump (emptying pump) of similar capacity to a chopper pump.

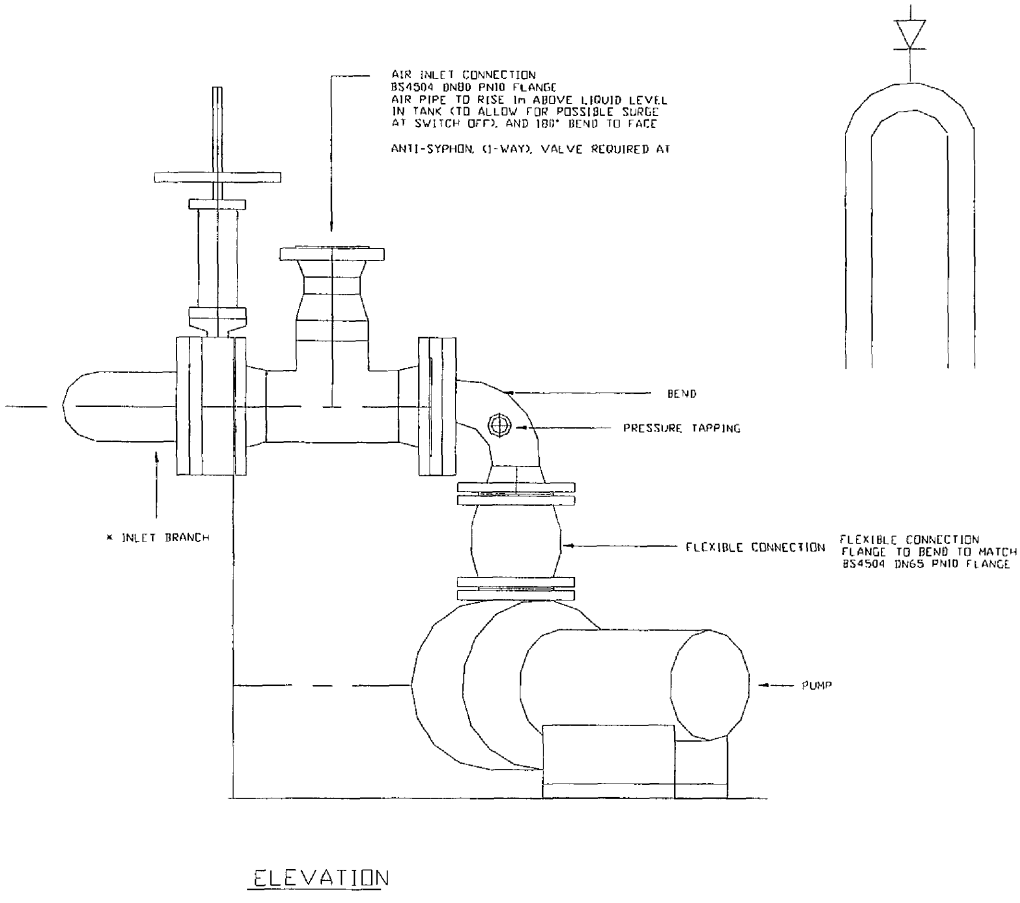


Figure 7.5. Elevation of venturi aerator

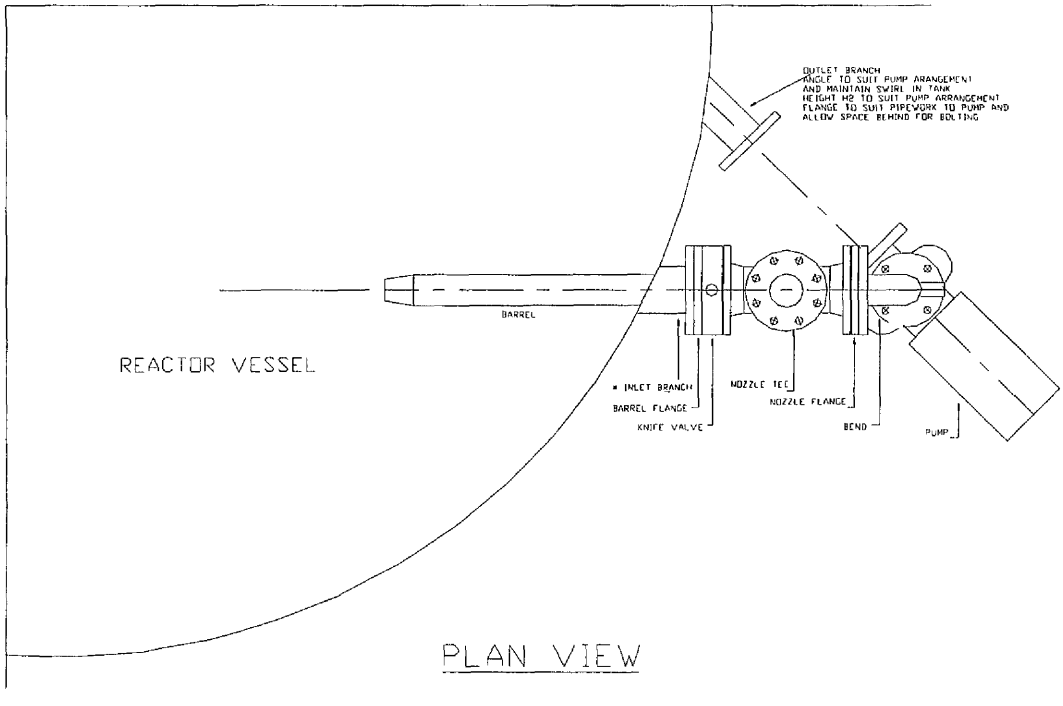


Figure 7.6. Plan view of venturi aerator (1)

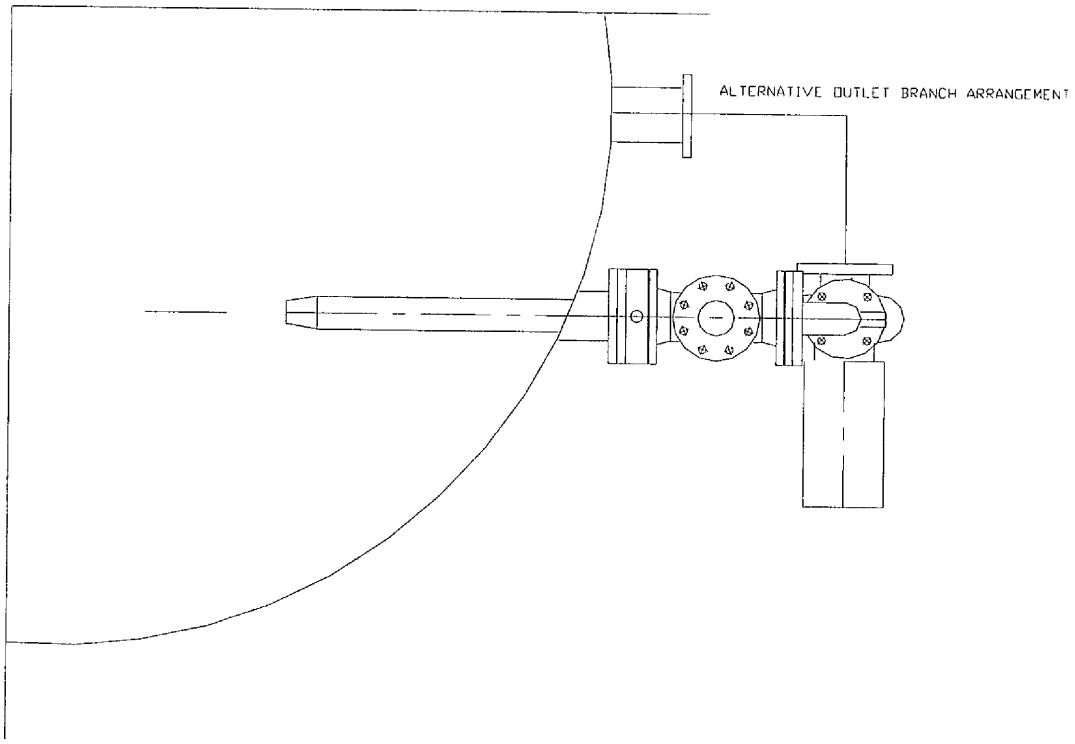


Figure 7.7. Plain view of venturi aerator (2)

The feeding/emptying system was controlled by a timer. However, this control system worked differently for each study trial. The Trial 1 was a preliminary study, while Trials 2 and 3 were optimised using the results obtained from the Trial 1. All three controlling strategies are described below.

7.5.1.1 Trial 1

The emptying pump was operated by a timer and was set to run for approximately 4 minutes at every hour, at a flow-rate of 0.188 $m^3.min^{-1}$. The feeding pump was controlled by a float switch, which turned the feeding pump ON at a slurry depth of around 4.3m and OFF at around 4.6m. This varied depending on whether the compressor was running and causing the turbulence which made the float switch to trigger either earlier or later. The emptying pump was switched off while the feed pump was either running or started to run. The control operation sequence was therefore as follows:

- The emptying pump was switched on, and it would be turned off when the level of ML reached approximately 4.3m in depth.
- As soon as the emptying pump was switched off, the feeding pump was started and refilled the reactor to an appropriate level (i.e. 4.6m), then the feeding pump was stopped.

7.5.1.2 Trial 2

The residence time was unstable during the Trial 1. It was because the mixed liquor was lost from the reactor by excessive foam generation. This foam overflow to the feed slurry storage tank as a liquid phase while the slurry in the feed storage tank was continuously pumped into the reactor, thus causing inadequate level in the reactor. Therefore, in order to achieve a correct residence time, the feeding and emptying control system was modified for Trial 2 and is described below.

The feed pump was now controlled by the timer controller and was set to run for 2.5 minutes every 20 minutes (i.e. 180 minutes per day), at the flowrate of 0.171$m^3.min^{-1}$. The emptying pump was controlled using a float switch. When the depth of slurry in the reactor vessel reached 4.6m, the emptying pump was turned on and it stopped when the slurry was discharged until the depth was reduced to 4.3m. Then the level

gradually rose again as the feeding pump run every 20 minutes. However, the feeding and emptying pumps could not run at the same time; the feeding pump always had priority. Therefore if the emptying pump was running while the timer activated the feeding pump to run, then the emptying pump was stopped and the feeding pump would have priority to run for its timed cycle of 2.5 minutes. After that, the emptying pump was started again and continued to run until the level of slurry was reduced to 4.3m. Also if the feeding pump was running while the float switch activated the emptying pump to running, this emptying pump was not actually run until the feeding pump had stopped its timed cycle.

7.5.1.3 Trial 3

The feeding and emptying pump were controlled in exactly the same way as Trial 2.

7.5.2 Air supply

The air was supplied from the atmosphere to the reactor vessel via a venturi aerator by a compressor (manufactured by Kaeser, SR015; supplied by HPC Engineering), which was capable of delivering 264 $m^3.hr^{-1}$ of air at 1 bar pressure or 318 $m^3.hr^{-1}$ at 0.1 bar. A 75 mm internal diameter flexible hose was connected from the outlet of the compressor to the air inlet of the ventrui via a 75 mm internal diameter steel pipe. The flexible hose was used to isolate the vibrations and any misalignments. The steel pipe (inverted U shape) fixed on the side and mounted up to the top of the reactor vessel, was a safety feature used to avoid the slurry flow back to the compressor when compressor and the recirculation pump were not used.

7.5.3 Aeration control

The compressed air was controlled by the redox potential. The set point was continuously adjusted until the system has become steady and stable. The final set point was adjusted to be –150 mVE_{cal} for Trial 1, -190mVE_{cal} for Trial 2, Trial 3 see later. The amount of air entering to the reactor depended on the speed of the compressor. The compressor speed was controlled by an inverter drive (ABB Ltd) using Proportion Integrated Derivative (PID) control mechanism (Coughanowr, 1991), which was varied according to the redox set point. This control system strategy was used in this preliminary aeration control study. The venturi recirculation

pump was always run regardless of the redox level. The speed of the compressor can be controlled from 0 to 4470 rpm (i.e. 0 to 50 Hz of inverter drive), but it was set to run from 0 to 1790 rpm maximum for the Trial 1 and 2. When the speed was at the minimum value (i.e. 0 rpm), the compressor was turned off. If the set maximum speed of compressor (i.e. 1790 rpm) was reached without achieving the redox set point, the compressor continued to run at its maximum speed.

7.5.4 Foam control

The foam was controlled using overflow system in Trials 1, 2 and 3, and with an additional foam breaker for Trials 2 & 3. An overflow point (flange 4) with 300 mm OD, was located 0.5m below the top of the reactor. When the foam was generated and reached the overflow point, the foam flew through a 300mm OD pipe into the storage tank by gravity. Once the foam was generated excessively and reached the overflow discharge point, then the foam breaker was turned on and kept as much mixed liquor (ML) as possible in reactor.

A foam breaker was used to control excessive foam in the reactor for the Trials 2 and 3. The foam breaker with 0.5 kW electric motor was positioned near the top of the reactor. 4 stainless steel blades (foam cutter) were attached to the bottom end of a steel shaft, which was turned radially at 900 rpm by an electric motor. This foam cutter (blades) was located on the opposite side and 10 cm below the overflow level. A metal bar was located at the same level as overflow discharge point. This metal bar was extended 300mm away from the side of reactor and was connected to a wire, which was attached to the wall of the reactor. The electric motor was switched on automatically when the foam rose and touched the bottom end of the metal bar, i.e. Once the bottom end of the metal bar was touch by the foam, then the electrical circuit was completed and the motor was activated and foam breaker was on.

7.5.5 Mixing

Good mixing of ML is essential for achieving an efficient aerobic treatment process. Both on the micro and macro-scale it involves three effects: (1) bulk turnover to ensure uniformity of composition and temperature throughout the whole volume; (2) high shear to prevent aggregation or dumping of organisms; (3) maximum turbulence to enhance oxygen transfer (Cumby, 1987b & 1990).

In this study, the mixing of ML was achieved by the vigorous venturi jet forces (Appendix E Figures E3 and E4) and the recirculation of slurry through the venturi aerator by a centrifugal pump. Horizontal tangential and vertical liquid motions were thus generated inside the reactor.

In the storage tank, a diffuser system was used to mix the feed slurry content. The disk diffusers were controlled by a timer and set to run 4 times a day, for 10 minutes. To ensure the adequate mixing of the slurry content, an extra 10 minutes of mixing was added manually just before sampling.

7.6 Monitoring and Recording of plant parameters

The monitoring and recording parameters included:

a. Temperature (ambient, slurry in reactor (ML) and slurry in storage tank)
c Redox
d Dissolved oxygen
e Compressor speed
f Feeding and emptying pump (running time)
g Power consumption of compressor

The parameters, stated above except power consumption and dissolved oxygen (DO), were monitored and recorded every 10 minutes remotely using a Campbell Scientific CR 10X data logger. The CR logger was interrogated remotely via a GSM modem, so that all the parameters were checked and saved in the computer daily and hence the conditions of the treatment plant were monitored. The individual parameters are described briefly as follows.

7.6.1 Temperature

The temperature readings of ambient, ML and slurry in the storage tank were measured using a thermistor type sensors. Due to the vigorous turbulence in reactor, the sensor used for the reactor vessel was fixed on a rigid metal structure within the ML. All the temperature sensors were connected to a data logger as described above and were checked against a reference device after installation.

7.6.2 Redox potential and dissolved oxygen (DO) level

Redox potential was measured using a redox electrode probe (GLI instrument). This redox probe was calibrated by the Standard method (APHA, 1992) as described in the Chapter 3 after installation in the reactor and was connected to a data logging system. The minimum, maximum and average value of redox potential were thus monitored and recorded. DO level was measured using a DO electrode (GLI instrument) which was fixed together with the redox probe and was also connected to the data logger via DO meter. The DO measurement was only used for DO monitoring, not a control of DO in the ML. Therefore it was checked and noted twice a week manually.

7.6.3 Compressor speed

The speed of the compressor was controlled via an inverter drive (AAB Ltd) that generated a 4 – 20 mA signal that was recorded by a data logger. The minimum, average and maximum compressor speeds were thus recorded by frequency of inverter drive in Hz.

7.6.4 Running time of feeding and emptying pump

The running times of feeding and emptying pump were measured using a timer control, which was connected to the CR data logger. Therefore the power consumption (kWh) of these pumps could be calculated.

7.6.5 Power consumption

The power consumption was measured and recorded using a Profile data logger. The measurement of the power consumption was checked and noted twice a week manually.

7.7 Optimisation of control system for Trial 3

7.7.1 Monitoring

In the Trial 3, all the treatment control and monitoring parameters were same as in Trial 1 and 2. However, a electricity consumption data logger (Profile) was fitted in a control box near to the reactor, so that the power consumption of feeding pump, emptying pump, venturi recirculation pump and foam breaker were measured and recorded. And the temperature of ambient, reactor ML and the storage tank, redox,

DO, compressor speed were monitored using the CR data logger via their appropriate connections as described previously Trials 1 & 2.

7.7.2 Control system

Following the Trials 1 and 2, it was obvious that the system could be operated much more efficiently. This centred around two main areas:

1. The capacity of the aeration system was so much greater than the oxygen demand of the treated effluent (ML) that the compressor ran for only a small percentage of the day. However, the venturi recirculation pump ran continuously and this was responsibly for approximately 70% of the total energy use. Therefore, the energy savings could be increased if the venturi recirculation pump was operated only when aeration was called for by a redox sensor (i.e. by a set point value of redox potential). The venturi pump was run periodically to avoid solids settling in the reactor and inaccurate redox measurements due to poor mixing.

2. Although the Proportional Integrated Derivative (PID) control of the compressor speed was ideal from the point of view of stable oxygen levels in the reactor theoretically, it made some differences practically. This was due to the slow response of the redox sensor and limitations within the PID controller built into the inverter drive. Therefore the compressor was operated at the fixed speed. This would improve the efficiency of the compressor. In a commercial installation the choice of an appropriately sized compressor would remove the need for an inverter drive and hence reducing the capital cost.

In order to make the application of this control system simpler to implement, the control of venturi circulation pump; compressor; feeding/emtying pump and foam breaker were configured and a simple Programmable Logical Controller (PLC) (AC model, Crouzet Millenium) was used.

7.7.2.1 Control of aeration system (Trial 3)

Aeration was controlled according to the redox potential in the reactor vessel. The amount of air entering the reactor was constant (1.18 $m^3.min^{-1}$), at a set fixed compressor speed of 1340 rpm (i.e. 15 Hz of inverter drive). The compressor was activated by a feedback system from the Redox set point between high (-150 mVE_{cal}) and low (-200 mVE_{cal}). These control set points were set in the redox controller to switch a relay output, which was connected to the PLC controller.

If the redox fell below –200mV E_{cal}, the aeration system was turned on until it rose above –150mV. A minimum operating time of 5 minutes for the aeration system was set in order to avoid excessive cycling of the compressor/venturi recirculation pump operation. In addition, the venturi recirculation pump was run for 15 seconds before the compressor was turned on to reduce the spike loads on the electricity supply, and to provide extra times for the venturi aerator to stabilise before supplying air. Similarly, the compressor was turned off before the venturi recirculation pump, so that the shut down was smoother.

To avoid problems with the solids settlement and inaccurate of redox measurements during periods of no aeration, the venturi pump was set to run for 1 minutes every 20 minutes irrespective of the redox level.

7.7.2.2 Feeding/emptying pump

The operation sequence of feeding and emptying pump were worked exactly the same as in Trial 2. The feed pump was operated in time intervals using a PLC controller. The running time cycle of the feed pump was set in the controller and was activated to run for 2 minutes and 20 seconds every 10 minutes. While the emptying pump was controlled by a float switch via a PLC controller. The high and low control levels of float switch were the same as in Trial 2.

7.7.2.3 Foam breaker

The foam breaker, was controlled by a level switch via a PLC controller, and to avoid excessive running. Foam breaker was activated when the foam reached the level of 10 cm below the overflow discharge point.

8. STANDARD OXYGEN TRANSFER OF FULL SCALE VENTURI AERATOR

8.1 Introduction

Oxygen transfer mechanism was briefly reviewed in Chapter 2.52. In this present study, the oxygen transfer performance of farm scale venturi aeration system was undertaken with tap water and untreated pig slurry. In order to assess how effective and how much of oxygen was transferred into the liquid within the reactor per unit time in a practical system, the overall oxygen mass transfer coefficient, oxygenation capacity and aeration efficiency were determined.

8.2 Experimental design and method

The standard oxygen transfer rate (SOTR) of a venturi aeration system was tested with a series of air flowrates; 0.42, 2.73, 3.45, 4.63 and 5.80 $m^3.min^{-1}$ in tap water and 1.18$m^3.min^{-1}$ in pig slurry, under operational conditions (at normal atmospheric pressure and testing local water temperature) as in Table 8.2. Initially, the reactor vessel was filled with tap water to a depth of 4.5m giving a working volume of 31.8 m^3. The water was de-oxygenated with sodium sulphite and cobalt chloride was used as a catalyst. The characteristics of pig slurry used for this test are shown in Table 8.1.

Table 8.1. Characteristics of pig slurry for SOTR test

Parameters		Value
Total solids, TS	$g.l^{-1}$	11
Volatile Solids, VS	$g.l^{-1}$	5.5
Total suspended solids, TSS	$g.l^{-1}$	3.1
CODw	$g.l^{-1}$	23
BOD_5w	$g.l^{-1}$	4.5
pH	-	7.8

The detail of determination of overall mass (oxygen) transfer coefficient (K_La) and oxygenation capacity are described in Chapter 3.

8.3 Results and discussion

Table 8.2 shows the operating conditions during the standard oxygen transfer rate testing.

Table 8.2. Operating conditions during SOTR test.

Blower speed	Airflow	Temperature of slurry	Pressure	Power to Blower	Total Power input
rpm	$m^3.min^{-1}$	°C	mbar	kW	kW
895	0.42	18.0	75	0.80	3.44
1340*	1.18*	15.0*	150*	1.50*	4.14*
2240	2.73	17.7	175	2.20	4.84
2680	3.45	17.0	200	3.39	6.03
3580	4.63	17.6	300	4.68	7.32
4470	5.80	16.6	350	5.97	8.61

Note: (*) indicates the test was with pig slurry
Airflow = compressed air through the blower
Pressure = pressure across blower
Total power input = power to the blower and power of venturi pump

The DO concentration was measured for a different speed of compressor in water and slurry during the venturi aeration system test. The calculated oxygen deficit (Cs-C) against time (logarithmic) at each compressor speed is shown in Appendix F (Figures F1-F6). All of these (logarithmic graphs) figures have a common feature that deficit oxygen dropped very sharply after certain time reflecting the reached of the saturated DO concentration. The results of the aeration tests give a general indication of the relative oxygenation capacity and aeration efficiency, summarised in Table 8.3. They are commonly used as the criteria of aerator performance.

Table 8.3. Performance of the full scale venturi aeration system with water and pig slurry.

Airflow rate	$K_La(T)$	K_La (20)	Oxygenation capacity	Aeration efficiency	Oxygen transfer efficiency
$m^3.min^{-1}$	hr^{-1}	hr^{-1}	$kgO_2.hr^{-1}$	$kgO_2.kWh^{-1}$	%
0.42	9.3	9.8	2.8	0.8	37.0
1.18*	11.4*	12.8*	4*	1.0*	18.8*
2.73	23.0	24.3	7	1.4	14.2
3.45	24.0	25.8	7.4	1.2	11.9
4.63	21.5	22.8	6.5	0.9	7.8
5.80	21.5	23.3	6.7	0.8	6.4

Note: (*) indicates the test was with pig slurry.
$K_La(T)$ = K_La at its testing temperature
K_La (20) = K_La standardised at 20 °C

Increasing the airflow rate from 0.42 to 3.45 $m^3.min^{-1}$ resulted in an increase of the volumetric oxygen mass transfer coefficient K_La from 9.3 to its maximum level of 24 hr^{-1} in water. $K_L.a$ not increased any more even when the flow rate further increased to 4.63 and 5.8 $m^3.min^{-1}$. This result shows that the optimal air flow rate for a maximum oxygen transfer was 3.45 $m^3.min^{-1}$. Truesdale *et al.* (1958) found that K_La increases with temperature of the water by about 2% per °C increase in temperature within the range 5 to 25 °C. On contrast, Howe (1977) has found that decreasing relationship between temperature, but Brown & Stenstrom (1980) have shown that his conclusion cannot be supported statistically. Thus, the standardised K_La is chosen at the temperature of 20°C. In this present test, the K_La values obtained at their respective temperature of water were corrected to 20°C according to equation 2.21 (Chapter 2.4.2, and where $\theta = 1.024$) as shown in Table 8.3.

Similarly to K_La, the standard oxygenation capacity was increased from 2.8 to 7.4 kg $O_2.hr^{-1}$ with increasing air flow rate from 0.42 to 3.45$m^3.min^{-1}$ (Table 8.3), with further increase the air flow rate, the OC decreased slightly to approximately 6.5 kg $O_2.hr^{-1}$. This decrease could be explained that the higher airflow generated a high speed plume which was vigorously injected into the water. Although this provided good mixing, the injected air was retained for only short time in the water before being lost to the surface as gas rather than being absorbed. Hence oxygen transfer rate was reduced while aeration intensity become quite constant above approximately 3.5 $m^3.min^{-1}$. The result shows the OC has close relationship with K_La; this was due to K_La being a function of OC. However, the efficiency of oxygen uptake was decreased with airflow (Figure 8.1).

The aeration efficiencies of venturi aerator of different air flow rates are shown in Table 8.3. The aeration energy consumption was accounted from a recirculation pump and a blower. The highest aeration efficiency was 1.4 $kgO_2.kWh^{-1}$ using 2.73 $m^3.min^{-1}$ of air flow rate. This was similar to the finding (1.1 $kgO_2.kWh^{-1}$) from a full scale aeration system with three venturi aerators (Morgan *et al.*, 1983), but it was much greater than that of found elsewhere (Wall *et al.*, 1979; Morgan & Littlewood, 1979).

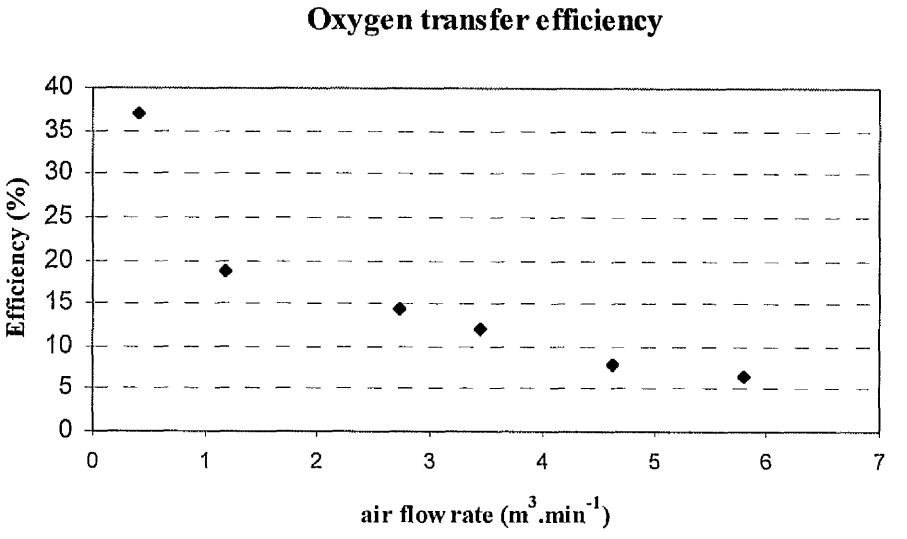


Figure 8.1. Efficiency of oxygen transfer in water with different airflow rate.

1.18$m^3.min^{-1}$ of air flow rate was used for testing the oxygen transfer performance for the pig slurry. The oxygenation capacity, volumetric oxygen mass transfer coefficient and aeration efficiency were determined to be 4$kg.O_2.h^{-1}$, 11.4 h^{-1}, and 1.0 $kgO_2.kWh^{-1}$ respectively. Finally, the oxygen transfer efficiency (SOTE) of venturi aeration system was calculated to be 19% (Figure 8.1), which was close to the value reported by Williams (2000). He found the oxygen transfer efficiency was 21% with 0.55 $m^3.min^{-1}$ of airflow rate in a pilot scale 500L reactor with tap water.

However, the performance of the aeration system is affected by a number of parameters which were reviewed by Cumby (1987c). In this test with pig slurry, the results were no different from the tap water, probably because the slurry was too diluted, (less than 1% of DM w/v). However, solids concentration could affect the aeration and transfer efficiency of the aeration system because of the flocculation of the suspended solids (van der Kroon, 1969; Pain *et al.*, 1987). Therefore, any conclusion from the results of the present test must take into account the variable conditions, such as temperature, pressure, mixing characteristics and the vessel

geometry (as indicated by the correction factors of α, β and γ reviewed in Chapter 2.5). This reflects the possible latitude of error associated with varying oxygen transfer rate in the system.

9. FULL SCALE AEROBIC TREATMENT: TRIAL 1 (reactor commissioning)

9.1 Introduction

This chapter describes a commissioning trial, which was conducted to meet the following objectives:

a) To commission the farm scale treatment system to enable evaluation of the preliminary concept assorted in laboratory in terms of practicalities and performance.
b) To test the operation of the apparatus on a treatment plant with an automated control system and with a recycling, continuous aeration process for pig slurry.
c) To identify a suitable parameter of pig slurry that can be used as an indicator of the quality of the treated ML in relation to treatment time.

9.2 Experimental design and methods

9.2.1 Treatment process and apparatus

The experimental treatment aeration process and apparatus used in this study are described in Chapter 7.

About 450 m^3 of fresh raw pig slurry were pumped from the slurry lagoon into the slurry feed storage tank. This slurry was treated continuously *at 2 day residence time* at ambient temperature in the reactor.

To generate an adapted microbial culture for aerobic treatment of pig slurry, it was necessary to propagate and encourage the growth of micro-organisms that were selectively dominant in using nutrients contained within slurry. Therefore, the reactor vessel was filled with 31.8 m^3 of raw pig slurry as a working volume before supplying air. The slurry was aerated in the reactor until the steady state condition was achieved. The normal automated operating control system as described in Chapter 7 was started with slurry from the storage tank.

During the monitoring period, the treatment condition parameters of redox, ambient temperature, the temperature in the feed slurry and mixed liquor (ML), and speed of a

compressor were monitored and recorded. These recorded values were then processed to an average value in every 6 hours. Chemical analyses were started at the beginning of the experiment. The following characteristics were analysed by standard methods (APHA, 1992), as described in Chapter 3:- Total solids (TS); Volatile solids (VS); Chemical oxygen demand (COD); 5-day Biochemical oxygen demand (BOD_5); Kjeldahl nitrogen (Kj-N); Ammoniacal nitrogen (NH_4^+-N); Volatile fatty acids (VFA); Total organic acid (TOA); Total indoles and phenols (TIP) and pH value.

9.2.2 Sampling of feed slurry and mixed liquor (ML)

Pig slurry was collected twice a week from the storage tank. This was stirred with air using the bubble diffusers described in Chapter 7.2 for 10 minutes before a one litre sample was taken with a dip bucket.

Mixed liquor (ML) was collected twice a week from the reactor by a sampling tap located at the discharge side of the slurry circulation pump. One litre of ML sample was taken after homogenising the ML in the reactor vessel for a minimum time of 3 minutes.

Both feed slurry and ML were tightly packed with an ice pack and placed in a polystyrene box before sending them from the treatment plant (Warwickshire) to the laboratory (SAC, Auchincruive) by carrier. Samples were received in the morning of next day. Both feed slurry and ML were homogenised with a magnetic stirrer before sub-sampling for chemical analyses.

9.3 Results and discussion

The initial characteristics of raw slurry are shown in Table 9.1. Raw slurry generally contained a large fraction of liquid due to the rainfall and farm management requiring large amounts of water for washing. The condition in the reactor became stable within 4 days of the start of treatment. Feed slurry and ML were observed as grey and brown in colour, respectively. Similar colours were also found by other researchers (Svoboda, 1993; Allen, 1996). All the analytical raw data of this trial are detailed in Appendix 9.

The operating temperatures (ambient, ML and feed slurry) during treatment are shown in Figure 9.1. General trend of all these temperatures was similar, and reflecting the effect of the ambient temperature on the temperature of ML and slurry in the feed storage tank. The temperature of ML started to increase at the beginning of the treatment, from approximately 5 ^{o}C to a maximum level of 15.5 ^{o}C after the first 200 hours (8.3 days) of treatment, and it was always greater than the slurry temperature in the slurry storage and the ambient temperature. This change of temperature in ML indicates that the heat was released by microbial activity during treatment (i.e. an exothermic reaction process), as observed by Svoboda (1993).

Slurry characteristics

The results of full chemical analysis from this preliminary study of aerobic treatment are shown in Appendix G (Tables G1 – G6). The key individual parameters, VFA, TOA, TIP, COD, BOD_5, of the feed slurry from storage and treated slurry from the reactor are summarised in Figures 9.2 to 9.8. The solids concentration and the loss of nitrogen content were not significant affected by the treatment as expected for the short treatment residence time and minimal aeration.

The reduction of all the characteristics of feed slurry and ML after treatment was expressed as percentages as shown in Table 9.1.

Table 9.1. Initial characteristics of raw feed pig slurry of farm scale treatment Trials 1, 2 and 3.

Parameter		Trial		
		1	2	3
TS	$g.l^{-1}$	8.7	10.1	9.6
TSs	$g.l^{-1}$	6.1	7.8	6.2
TSS	$g.l^{-1}$	-	1.1	2.6
VS	$g.l^{-1}$	4.3	5.2	5.5
VSs	$g.l^{-1}$	2.7	2.9	2.6
VSS	$g.l^{-1}$	-	1.0	2.4
CODw	$g.l^{-1}$	22.4	12.1	13.2
CODs	$g.l^{-1}$	10.5	8.5	8.8
BOD_5w	$g.l^{-1}$	3.8	4.6	6.5
BOD_5s	$g.l^{-1}$	2.5	2.8	5.4
VFA	$g.l^{-1}$	3.4	4.1	6.9
TIP	$mg.l^{-1}$	42.4	39.9	64.0
TOA	$g.l^{-1}$	2.9	3.95	7.21
Kj- N	$g.l^{-1}$	1.9	2.4	1.9
NH_4^+-N	$g.l^{-1}$	1.5	2.1	1.6
pH		8.1	8.1	8

Note : Trial 1 referred to Chapter 9
Trial 2 referred to Chapter 10
Trial 3 referred to Chapter 11

Figure 9.1 Temperature profiles during the treatment period of Trial 1

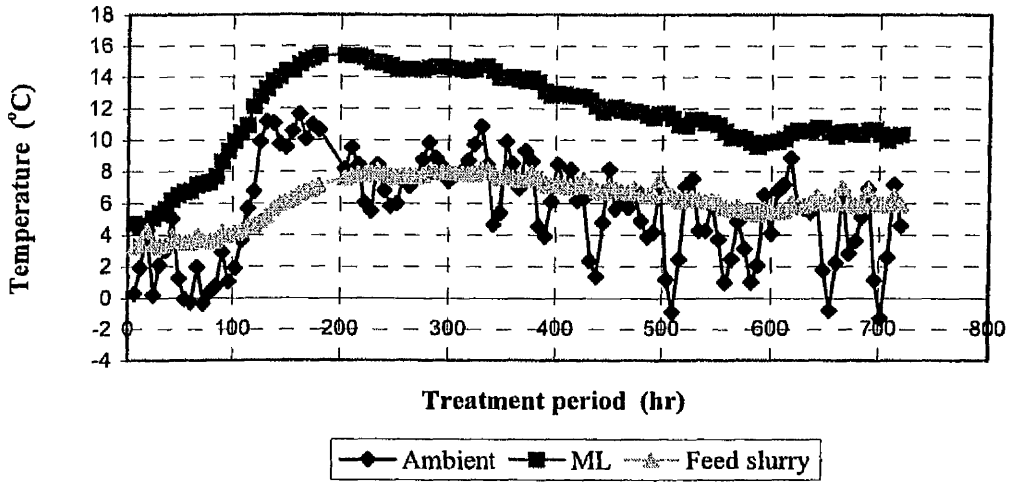
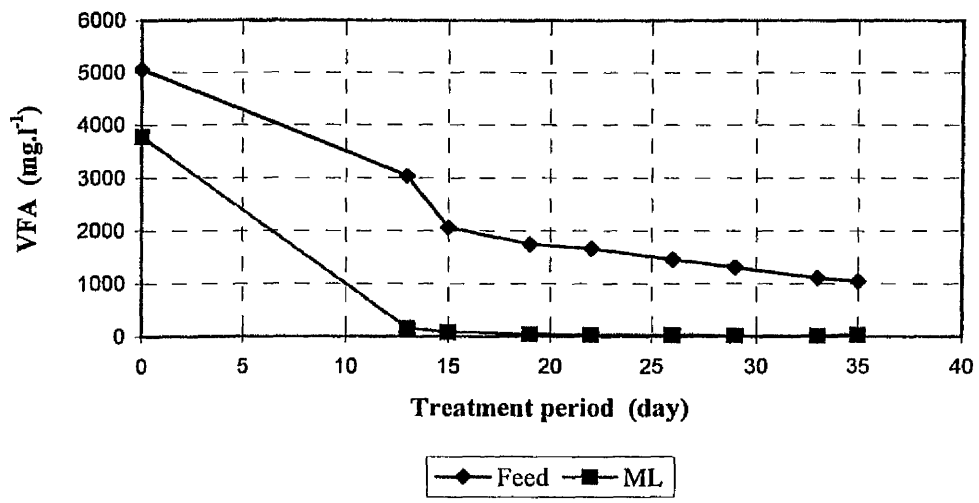


Figure 9.2 Total volatile fatty acids (VFA) concentration in the feed and ML of pig slurry during Trial 1



The effect and change of odour characteristics of feed slurry and ML during treatment

Volatile fatty acids (VFA)

The destruction of VFA was between 95 to 99% in the ML after treatment, reflecting the high performance of VFA removal through the reactor. This percentage of VFA removal was similar to removal in the cattle and pig slurries results obtained from previous laboratory experiments (Chapters 5 and 6).

Since the ML was semi-continuously pumped out from the reactor into the storage tank, and mixed with the stored slurry which was then pumped back into the reactor, again semi-continuously. The change of VFA in feed slurry therefore corresponded to the VFA of ML as shown in Figure 9.2. Concentration of VFA in the feed slurry decreased by 60% from 5060 $mg.l^{-1}$ following the first 15 days of treatment. It then decreased linearly with time to 1040 $mg.l^{-1}$ by the end of the treatment.

The total VFA concentration of feed slurry was mainly affected by level of the acetic and propionic acids. The highest contribution to the total VFA was acetic acid (Figure 9.3). The trend in the reduction for VFA in the ML was similar to the trend of feed slurry; it dropped rapidly by 99% to 50 $mg.l^{-1}$ following the first 15 days of treatment. It then fluctuated between 10 to 30 $mg.l^{-1}$ until the end of the treatment. These values indicate that the VFA concentration was about 4.5 times less than the acceptable level (230 $mg.l^{-1}$ of VFA) of odour offensiveness (Williams, 1984), which correlates with an inoffensive odour.

Total indoles and phenols (TIP)

The trend in reduction of TIP (Figure 9.4) in the feed slurry and ML was similar to the pattern of VFA, indicating a close relationship to reduction in the organic odorants. The reduction of TIP in feed slurry was from 26 to 7 $mg.l^{-1}$ and for ML was 13 to 1 $mg.l^{-1}$, approaching a complete removal. The destruction of TIP was significant ($p<0.001$) and varied between 50 to 96% throughout the treatment. The changes of individual indole and phenol components in feed slurry are shown in Figure 9.5. The highest contribution to the TIP was p-cresol; it decreased from 20 $mg.l^{-1}$ to a minimum 2.1 $mg.l^{-1}$ at day 19 of treatment and then fluctuated between 2.1

Figure 9.3 Individual volatile fatty acid (VFA) concentration in the feed of pig slurry during Trial 1

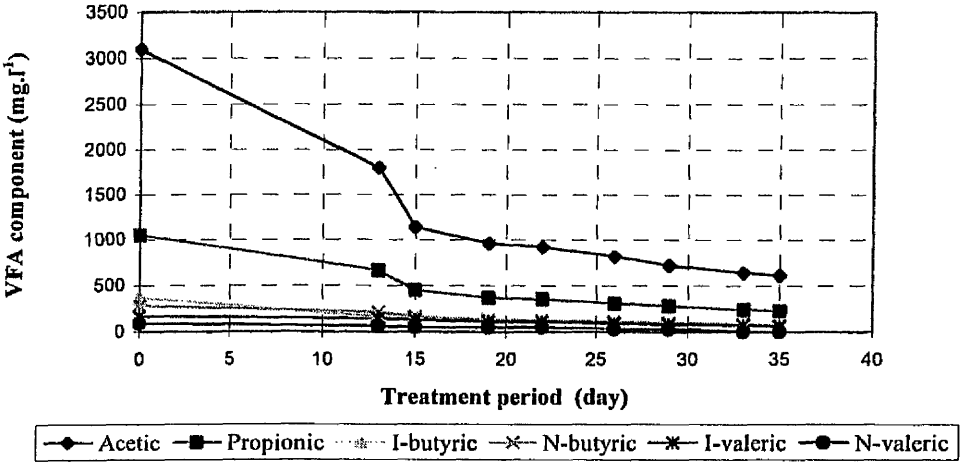


Figure 9.4 Total indoles and phenols (TIP) concentration in the feed and the ML of pig slurry during Trial 1

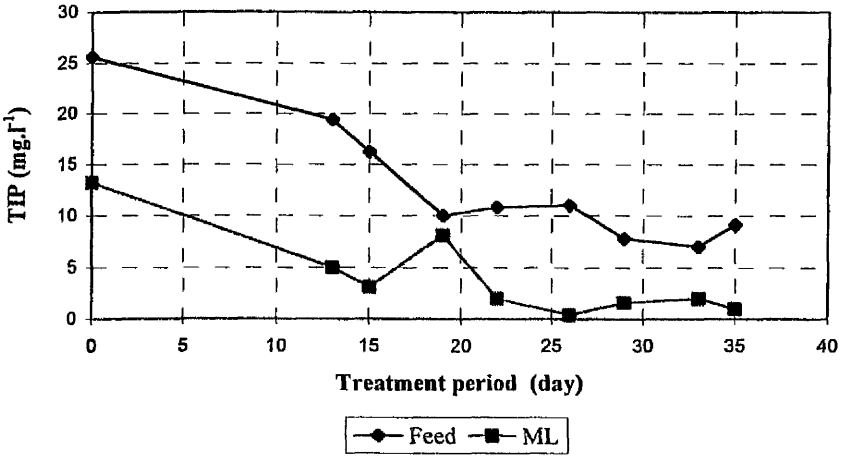


Figure 9.5 Individual indoles and phenols in feed slurry during Trial 1

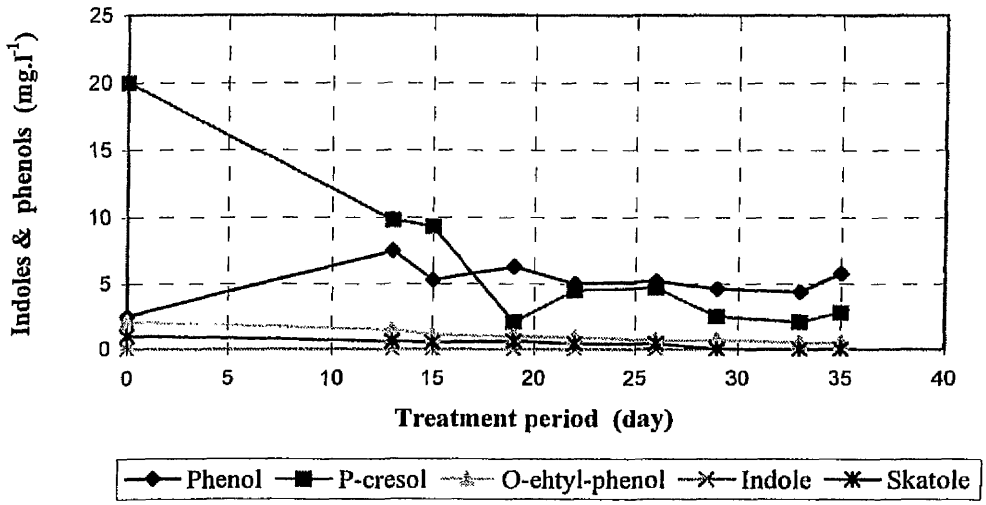
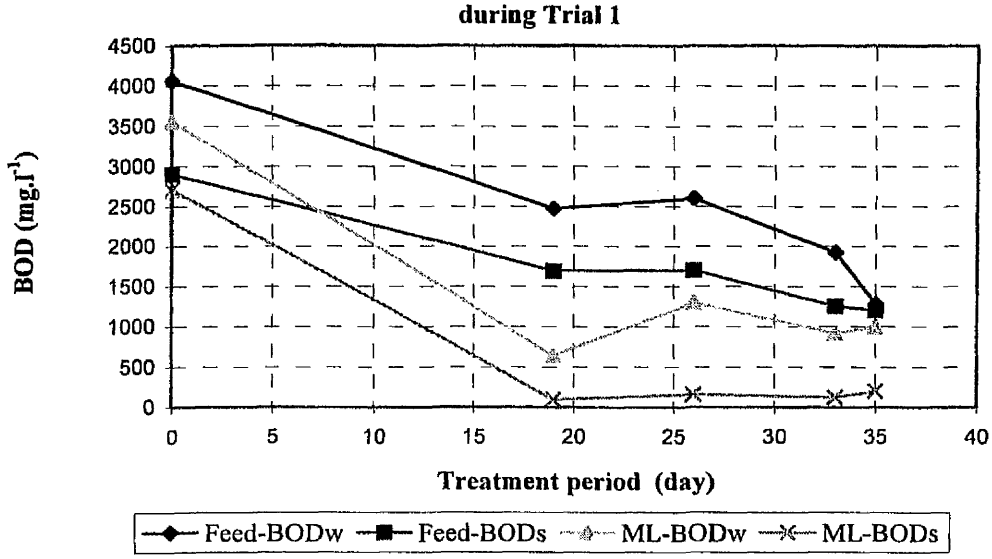


Figure 9.6 Whole and supernatant BOD in the feed and in the ML of pig slurry during Trial 1



to 4.8 $mg.l^{-1}$. After 17 days of treatment, p-cresol decreased below the concentration of phenol, which did not change substantially during treatment. Indole was not detected at any stage during treatment.

Supernatant BOD_5 and total organic acid (TOA)

Williams (1983) found that the relationship of BOD_5s and TOA was highly significant ($r = 0.96$) in a continuous aerobic treatment of pig slurry in the laboratory. He also (Williams, 1984) found that the most widely applicable odour indicator was supernatant BOD_5, which correlated linearly with odour offensiveness when expressed logarithmically. Changes in BOD_5s of feed were directly reflected in the BOD_5s of ML (Figure 9.6). The destruction of BOD_5s varied between 12 to 74% throughout the treatment. The BOD_5s in feed slurry decreased from 2900 to 1200 $mg.l^{-1}$, while BOD_5s in ML was reduced from 2710 to 95 $mg.l^{-1}$, the minimal level after 19 days of treatment. It then fluctuated from 100 to 200 $mg.l^{-1}$.

The reduction trend (Figure 9.7) of TOA concentration in feed slurry and ML was very similar to the change of BOD_5s. This indicates the similarity in the pattern of changes as with VFA and TIP. The destruction of TOA was between 30 and 76%. TOA in feed slurry was reduced from 3.5 to 0.5 $g.l^{-1}$. A measurement of TOA dropped dramatically to 0.7 $g.l^{-1}$ at day 19 of treatment, then rose to the changing pattern. This drop was probably caused by a sampling problem. However, the concentration of TOA was decreased from 3.5 to 0.5 $g.l^{-1}$ after 15 days of treatment. It then fluctuated between 0.7 and 0.3 $g.l^{-1}$ at the end of the treatment.

Chemical oxygen demand (COD)

The changes of CODw and CODs in feed slurry and ML are shown in Figure 9.8. The destruction of CODw was 5 to 50 %, while CODs destruction was higher, 30 to 66%. The CODw and CODs of feed slurry decreased in a similar magnitude, by 51% from 10.5 $g.l^{-1}$ and 53 % from 7.5 $g.l^{-1}$, respectively. CODw and CODs of ML were reduced by 51% from 10 $g.l^{-1}$ and by 74% from 7.3 $g.l^{-1}$, respectively.

The changes in CODw and CODs of the feed slurry were a direct reflection of the COD of the ML. Sneath *et al.* (1992) found that the changes in the predicted COD values of 2-day RT and in observed values were in agreement under farm scale trial,

Figure 9.7 Total organic acid (TOA) concentration in feed and ML of pig slurry during Trial 1

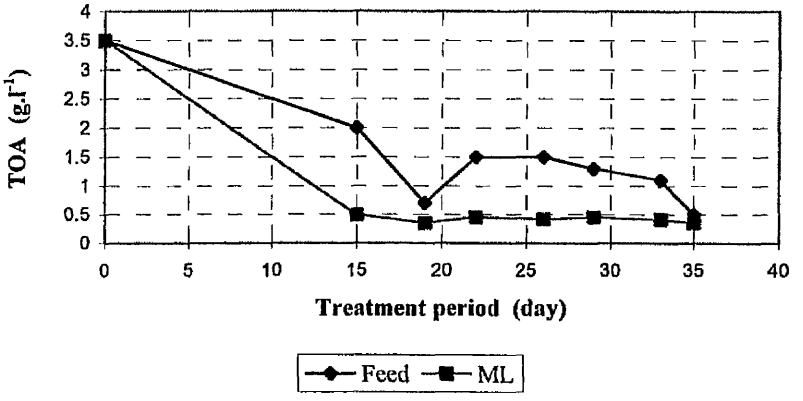


Figure 9.8 Whole and supernatant COD in the feed and ML of pig slurry during Trial 1

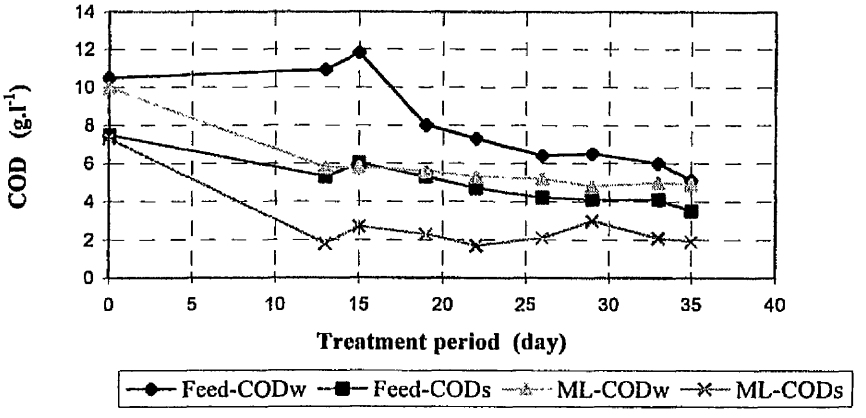
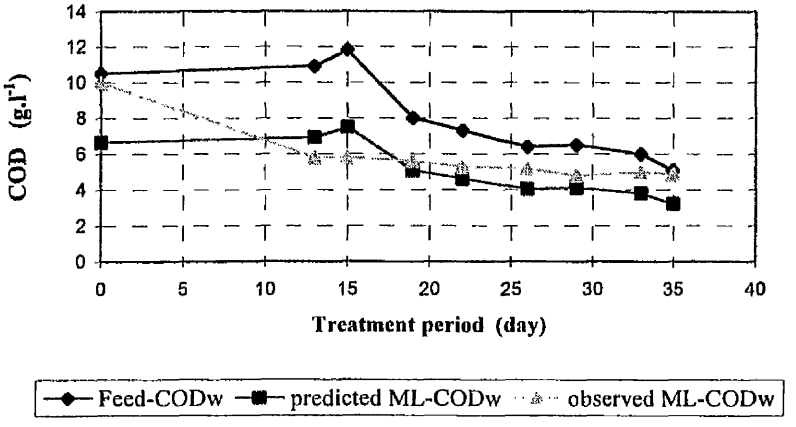


Figure 9.9 Predicted and observed CODw of ML during Trial 1



although they were dissimilar in magnitude. In the present study, the predicted COD of ML was calculated from a model derived by Evans *et al.* (1983) for 2 day residence time. Although the predicted values of COD (Figure 9.9) of ML did not agree exactly with the observed values, the change pattern was similar. This was probably due to the variation of the treatment temperature of ML and of the exact treatment residence time during this commissioning trial. Variations of the residence treatment time was caused by excessive foam generation and mixed liquor (ML) was thus lost from the reactor. Also the control value of redox was continuously adjusted to reach optimal value causing the condition of ML was to be unstable. However, the predicted values of COD became closer to the observed values after 19 days of treatment. This could be due to the conditions (temperature, redox potential values, and residence time) of ML as it became relatively stable.

Plant operational problems

Operational problems cannot be avoided in any slurry treatment practice. Problems come mainly from the mechanical facilities. For instance in this study, the treatment system was turned off after two days of the system reaching stability because of a faulty contactor in the slurry circulation pump (Venturi circulation pump). The system was switched on again 3 days later.

The major problem was the foaming during start-up of the trial and during the monitoring period in the preliminary study. After 5 days of start-up, the foam was generated excessively and the foam over-flow discharge could not cope. This seriously caused the inaccuracy in the treatment residence time. Therefore, the intensity of treatment was reduced in order to cut down the amount of air entering the reactor vessel. The maximum running speed of the compressor was reduced from 4,475 to 1,900 rpm. Apart from the problems stated above, there were no other complications observed in either the control of system or other mechanical apparatus, such as the aeration devices or pumps.

Foaming would definitely affect accuracy of chemical analyses (i.e. loss of solids). A foam cutter was therefore included in the next trial.

10. FULL SCALE AEROBIC TREATMENT: TRIAL 2

10.1 Introduction

This trial was conducted to upgrade the system of the first commissioning trial by drawing on all experiences from the preliminary Trial 1.

10.2. Experimental design and method

The treatment process and its apparatus (described in Chapter 7) were similar to the preliminary Trial 1. The only difference between Trials 1 and 2 was the residence time and the slurry discharging and filling operation control (as described in Chapter 7). In Trial 2, the treatment residence time in the reactor was 1 day, and all the slurry contents in the slurry storage tank were passed through the reactor two times (i.e. assuming the total treatment residence time was 2 days). The slurry discharging pump was controlled by a float switch, while the slurry filling pump was controlled by a timer switch, which was set to run for around 160 seconds every 20 minutes, as described in Chapter 7. A foam breaker (Figure 7.1 and Chapter 7) was installed and run continuously during this trial in order to improve control of foam. The set point of the redox potential was –188 mVE_{cal}. The initial maximum speed of the compressor was set at 2,240 rpm (i.e. 25 Hz on the inverter drive), which was adjusted by the PID control (see Chapter 7) settings during early stages of the trial to optimise stability.

As in Trial 1, the slurry used was ca 450 m^3 of fresh pig slurry recently pumped from the slurry lagoon into the storage tank. Approximately 31m^3 of treated slurry (ML) were left over in the reactor after Trial 1, so that the culture was readily established and was used for starting up the Trial 2. The experiment of Trial 2 was stopped as soon as the target VFA level at 500 $mg.l^{-1}$ was reached in the slurry feed.

The chemical analyses were started at the beginning of the experiment. Methods of sampling, preparation and analysis of the feed slurry and ML were the same as in Trial 1, and are described in Chapter 9.22. An extra slurry sample was prepared for the anaerobic storage experiment as follows.

10.2.1 Anaerobic storage of aerobically treated slurry during treatment

The stability of the feed slurry and of the ML during a subsequent period of anaerobic storage was examined to investigate the regeneration of odour offensiveness as indicated by the VFA concentration.

Sub-samples of the slurry feed and ML from the prior chemical analyses were stored anaerobically. Samples from each of the slurry feed and ML were well mixed before being dispensed into duplicate identical 28 ml plastic vials on each sampling day. Each vial was filled to the top of the vials and lid was screwed tightly shut to ensure that no air was present during anaerobic storage. Vials were stored at the temperature of 10°C, which was checked regularly, 3 times a week. Each sample from the vial of slurry feed and ML was then well mixed before analysing the concentrations of VFA after either 10 (VFA(10)) or 20 (VFA(20)) days of storage.

10.3 Results and Discussion

The initial characteristics of raw slurry are shown in Table 9.1. Raw slurry contained a large fraction of liquid, approximately 1% TS (w/v), which was slightly higher than the TS of raw slurry in Trial 1. The starting ML in the reactor was left from the Trial 1, therefore the ML was relatively stable at the beginning of the Trial 2. As in Trial 1, the feed slurry was grey while the ML was brownish and also contained highly suspended solids. Change in the characteristics (i.e. values were the difference between the initial and end concentrations, and the final reductions expressed in percentage of initial values) of feed slurry after Trial 2 treatment are shown in Table 10.1. All the analytical raw data of this trial are detailed in Appendix H.

Table 10.1. Change in the characteristics of feed slurry after farm scale treatment in Trial 2. Values were the difference between the initial and end concentrations, and the final reductions expressed in percentages of initial values.

Parameter		Trial 2	
		Reduction value	% reduction
TS	$g.l^{-1}$	2.8	28
TSs	$g.l^{-1}$	1.8	23
TSS	$g.l^{-1}$	N.D	N.D
VS	$g.l^{-1}$	2.4	46
VSs	$g.l^{-1}$	1.2	41
VSS	$g.l^{-1}$	N.D	ND
CODw	$g.l^{-1}$	8.2	68
CODs	$g.l^{-1}$	6.5	76
BOD_5w	$g.l^{-1}$	4.2	91
BOD_5s	$g.l^{-1}$	2.6	92
VFA	$g.l^{-1}$	3.9	97
TIP	$g.l^{-1}$	0.04	100
TOA	$g.l^{-1}$	3.7	93
Kj- N	$g.l^{-1}$	0.35	14
NH_4^+-N	$g.l^{-1}$	0.26	12
pH	-	-0.3	-4

Note: N.D = Not detected

Figure 10.1 shows the temperature profiles of ambient, feed slurry and ML in the reactor. The ambient temperature was very variable. The feed slurry temperature appeared to follow the ambient temperature. Although the temperature of ML in the

reactor was relatively independent, it was affected by the ambient temperature and increased from 11°C at the beginning of the treatment to a maximum of 20 °C during treatment. The temperature of the ML in the reactor was always above the temperatures of feed slurry and ambient. This was due to the exothermic reaction process by the microbial activity throughout the treatment period as shown in Figure 10.1.

Change of slurry characteristics during treatment

Volatile fatty acids (VFA)

The change in VFA concentration of the feed slurry and of the ML is illustrated in Figure 10.2. The VFA concentration of the feed slurry decreased logarithmically with time, except for the sample of day 11, from 4,100 to 90 $mg.l^{-1}$ after 47 days of treatment. The VFA concentration of day 11 was (3,290 $mg.l^{-1}$) remarkably high, probably due to high concentration portion of this sample associated with inadequate mixing. The target VFA value (500 $mg.l^{-1}$) in Trial 2 was reached after 32 days of treatment, which was immediately after all the slurry had passed through the reactor two times over. The change pattern (Figure 10.3) of acetic, propionic, I-butyric, N-butyric and I-valeric acids followed closely with the change of total VFA. The highest contributing component to the VFA concentration was acetic acid by 70%. Propionic acid was considerably high. The lowest contribution to VFA was N-valeric acid, which was not detected any more after 12 days of treatment.

The change in VFA concentration of ML was different (Figure 10.2). It was reduced below 500 $mg.l^{-1}$ at the first day of treatment. After that, it continuously decreased to 10 $mg.l^{-1}$ at day 27 of treatment, and then fluctuated between 20 and 70 $mg.l^{-1}$ until the end of treatment. These values were below the lower limit of the acceptable level (230 $mg.l^{-1}$ of VFA concentration) of odour offensiveness. The majority of the VFA component was acetic acid, which contributed by 60 to 100 % of total VFA concentration. I-butyric and N-butyric acids were only detected in small amount by 7% of total VFA, from 2 out of 15 measurements. I-valeric and N-valeric acids were not detected throughout the treatment.

Figure 10.1 Temperature profiles during Trial 2

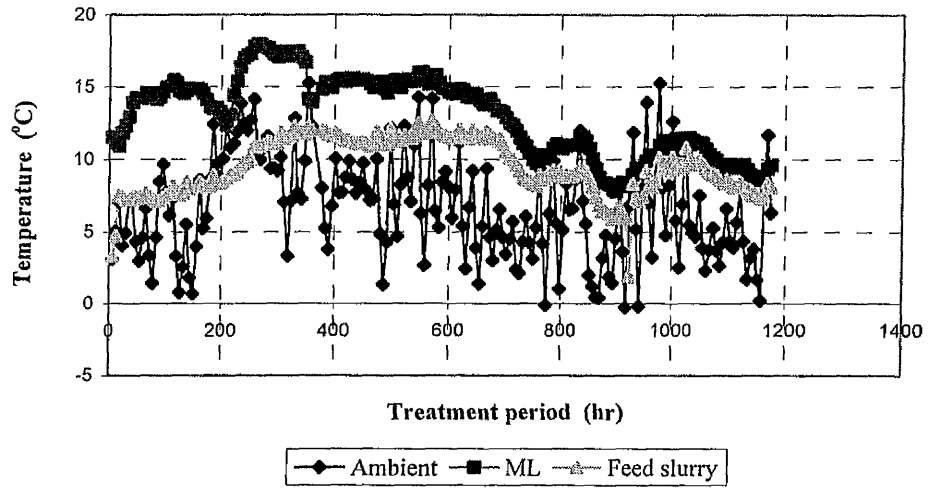


Figure 10.2 Total volatile fatty acids (VFA) concentration in the feed and the ML of pig slurry during Trial 2

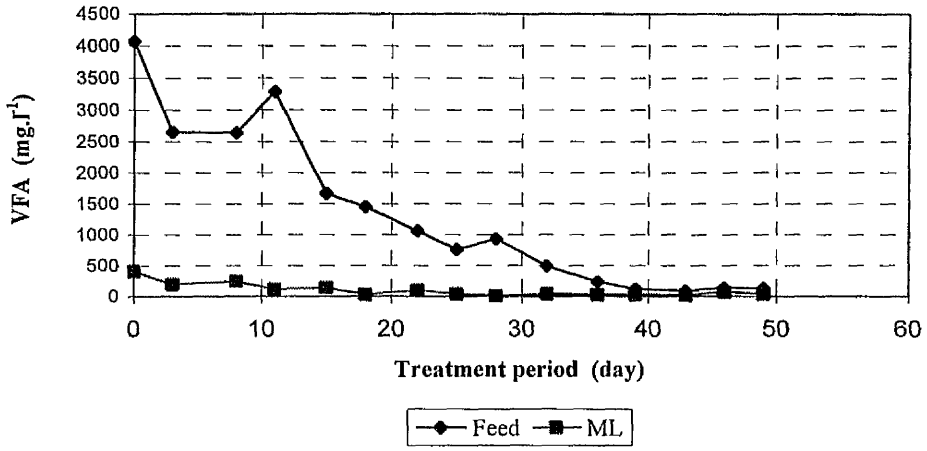


Figure 10.3 Individual volatile fatty acid (VFA) concentration in the feed of pig slurry during Trial 2

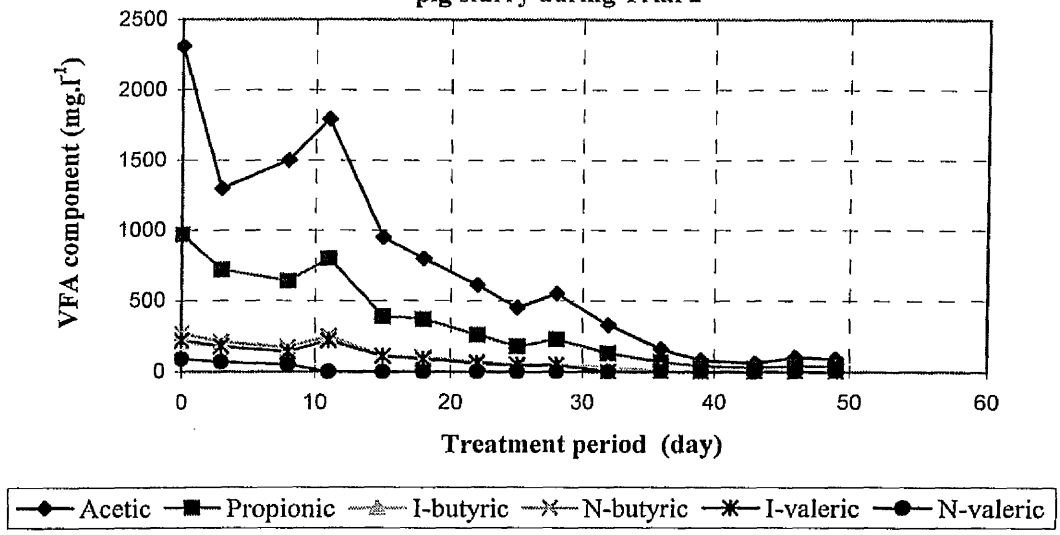
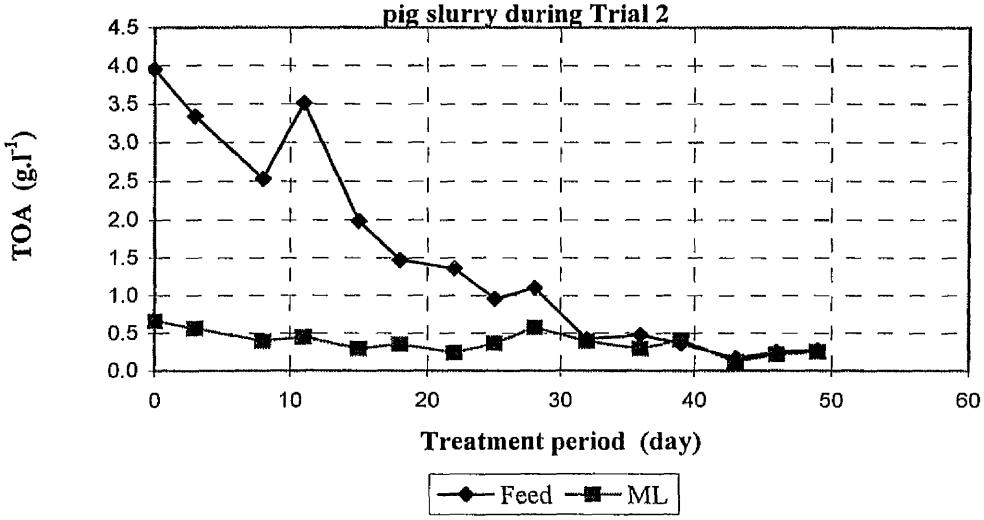


Figure 10.4 Total organic acid (TOA) concentration in the feed and the ML of pig slurry during Trial 2



Total organic acid (TOA)

Reductions in TOA of the slurry feed and in the ML are shown in Table 10.1. Change of TOA in slurry feed was greater than in the ML (Figure 10.4). It decreased logarithmically by 93% from 3.95 $g.l^{-1}$, which was similar to the change in VFA. Although the whole treatment lasted for 49 days, the minimal level (0.27 $g.l^{-1}$) of TOA was achieved after 43 days of treatment. This value indicates an odour offensiveness rating "very faintly offensive", using the following equation (Thacker and Evans, 1986):

$$\text{Odour offensiveness} = 2.378 \times \log(\text{TOA}) + 2.327 \qquad \text{Equation (10.1)}$$

The VFA/TOA ratio of slurry feed was 1.1 when the concentration of VFA was approximately 4.1 $g.l^{-1}$ at the beginning of treatment. This result agreed with the findings of Williams (1983). He found that the ratio of VFA/TOA increased as acid concentrations rose, with a ratio of 1.1:1 when the concentration of VFA reached 4.5 $g.l^{-1}$. This ratio of 1.1:1 may seem contradictory. It was because acids other than VFA are detected by the TOA test, but with acetic acid being used as standard in the test (Chapter 3). As the test actually measured carboxylic acids groups, it follows that longer chain acids give a lower response than acetic acid on a weight for weight basis. Williams (1983) also found that the VFA are the single most important group of acids in the TOA analyses. Formic, di-carboxylic, long chain fatty and amino acids could also contribute to TOA.

The reduction of TOA between the feed slurry and ML was substantial by the aerobic treatment. By applying equation (10.1), the odour offensiveness rating decreased from "faintly offensive" to "inoffensive" in between feed slurry and ML. The percentage destruction of TOA decreased with increase time, from approximately 85% (3.95 to 0.66 $g.l^{-1}$) a the start of the treatment to 7% (0.27 to 0.25 $g.l^{-1}$) by the end of the treatment. This change was because the reduction of TOA in ML was not as great as in the feed slurry. The highest reduction of TOA of ML was 56% during the first 15 days of treatment. It was then fluctuated between 0.57 and 0.12 $g.l^{-1}$. However, the concentrations of TOA in the feed slurry and in the ML nearly overlapped after 39 days treatment. This was probably because the minimum TOA concentration was reached (reflecting maximum reduction of TOA was achieved) for

this particular treatment conditions. Svoboda (1993) found that the TOA concentrations in the ML were 1.1, 0.89 and 0.91 $g.l^{-1}$ from their respective feed slurry concentrations of 7.3, 6.3 and 7.2 $g.l^{-1}$ in a farm scale treatment at mesophilic temperatures and low dissolved oxygen concentration.

Total indoles and phenols (TIP)

The changes of TIP in feed slurry and ML during treatment are illustrated in Figure 10.5. TIP with maximum concentration of 40 $mg.l^{-1}$ in the feed slurry decreased logarithmically, similarly to VFA, from 40 $mg.l^{-1}$ to a non-detectable level after 43 days of treatment. The highest removal rate was achieved during the first 25 days when approximately 95% of TIP were metabolised by aerobic micro-organisms. Trends of individual indole and phenol components in the feed slurry are shown in Figure 10.6. The change of p-cresol concentration followed closely that of TIP. The TIP concentration was therefore mainly affected by the concentration of p-cresol, which contributed to the total TIP by 50 to 85% throughout the treatment. Phenol was detected in small amounts in the slurry feed during the treatment. It fluctuated between 4.1 to 1.5 $mg.l^{-1}$, whereas the o-ethyl-phenol was detected in trace quantity only. Skatole was only detected in one measurement (1 $mg.l^{-1}$) and indole was not detected during treatment.

The ML contained small amounts of TIP, detected in only 5 out of 15 analyses during the treatment. Phenol was the only component detected in the ML. Therefore, the concentration of TIP was equal to the concentration of phenol, with its maximum concentration of 1.6 $mg.l^{-1}$. TIP was removed almost completely.

5-day biochemical oxygen demand (BOD_5)

The change and reduction of BOD_5w and BOD_5s in feed slurry and in the ML are shown in Figure (10.7) and Table (10.1) respectively. BOD_5w decreased from 4590 to 425 $mg.l^{-1}$, by 91%, while BOD_5s decreased from 2770 to 210 $mg.l^{-1}$, by 92%. BOD_5w and BOD_5s did not decrease any further after 32 days of treatment.

Figure 10.5 Total indoles and phenols (TIP) concentration in the feed and the ML of pig slurry during Trial 2

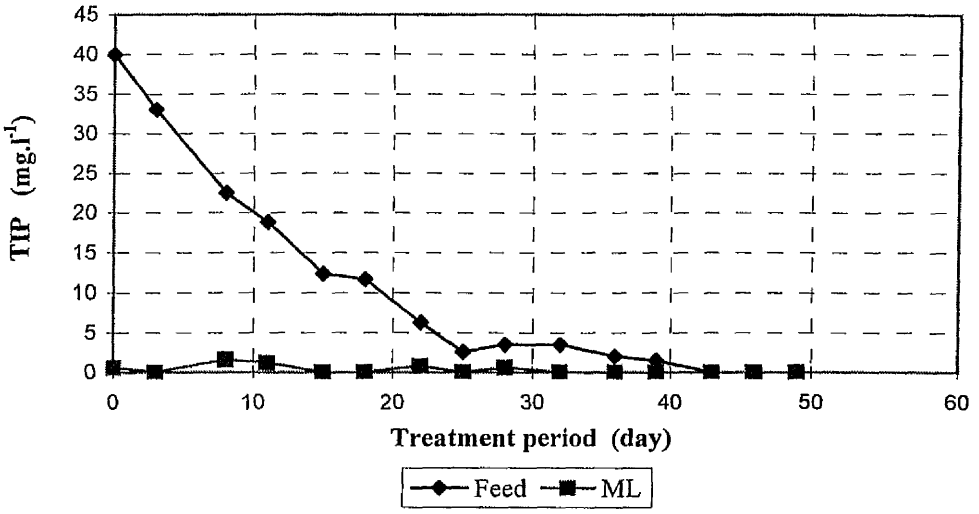
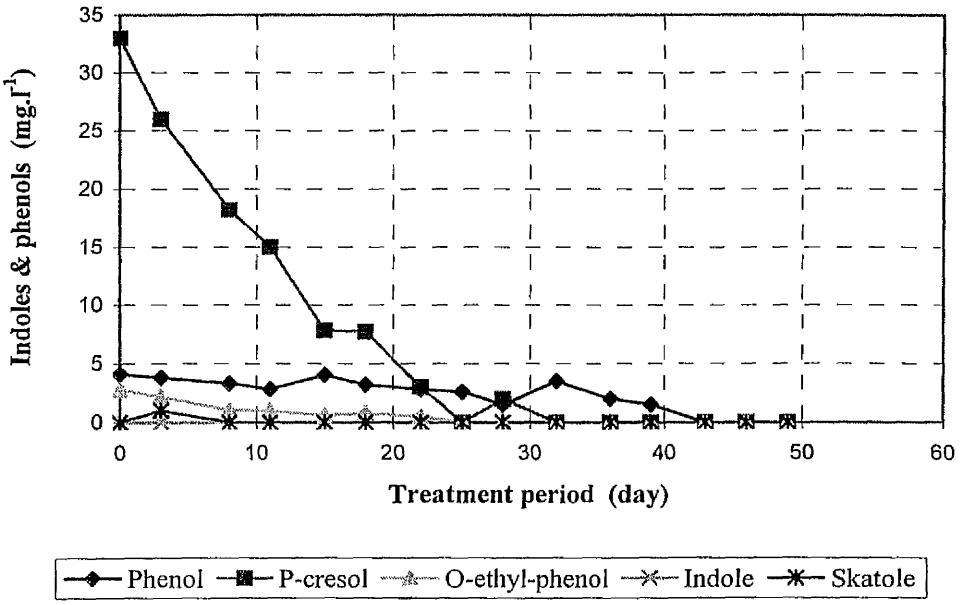


Figure 10.6 Concentration of individual Indole and Phenol in the feed of pig slurry during Trial 2



The trend of BOD_5w in the ML had a similar pattern as BOD_5w of slurry feed which decreased from 1490 to 390 $mg.l^{-1}$, by 74%. The change of BOD_5s was relatively low, the highest reduction of ML BOD_5s, mainly occurred during the first 3 days of treatment (Figure 10.7), by 60% from 520 to 210 $mg.l^{-1}$. It then further decreased slowly from 210 to 120 $mg.l^{-1}$ to the end of treatment. These values show that the BOD_5s reached its minimal level of 120 mg.l-1 for this particular treatment conditions.

The effect of the aerobic treatment on the reduction of BOD_5w and BOD_5s was significant and were decreased with increase time. The reduction percentage of BOD_5w, between feed slurry and ML, decreased from 68% (4590 to 1490 $mg.l^{-1}$) to 8% (425 to 392 $mg.l^{-1}$), while BOD_5s decreased from 93% (2770 to 520 $mg.l^{-1}$) to 20% (210 to 120 $mg.l^{-1}$). The reduction (between the feed slurry and ML) in BOD_5s was greater than the BOD_5w, indicating faster degradation of soluble materials.

Chemical oxygen demand (COD)

The general trends of CODw and CODs in both feed slurry and ML were similar in Figure 10.8., but CODw of both feed slurry and the ML increased slightly at the beginning of the treatment, then decreased again. This was probably due to the initial inadequate mixing and causing the samples were in non-homogenous states. Generally, concentration of CODw in the feed slurry was decreased from 12.1 to 3.9 $mg.l^{-1}$, while CODs was decreased from 5 to 2 $mg.l^{-1}$. The ratio of CODs/CODw was between 0.32 to 0.71 during the treatment.

The destruction of CODs in the ML was greater than CODw. CODw of ML decreased from its initial concentration of 7 to 2.9 $mg.l^{-1}$ while CODs fluctuated between 1.4 to 2.9 $mg.l^{-1}$ throughout the treatment. The ratio of CODs/CODw of ML varied, between 0.18 to 0.66.

Figure 10.7 Whole and supernatant BOD in the feed and in the ML of pig slurry during Trial 2

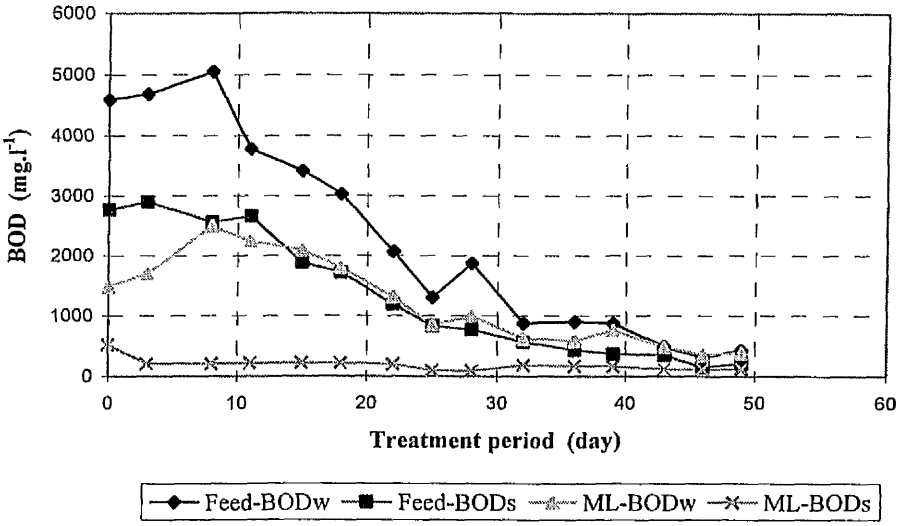
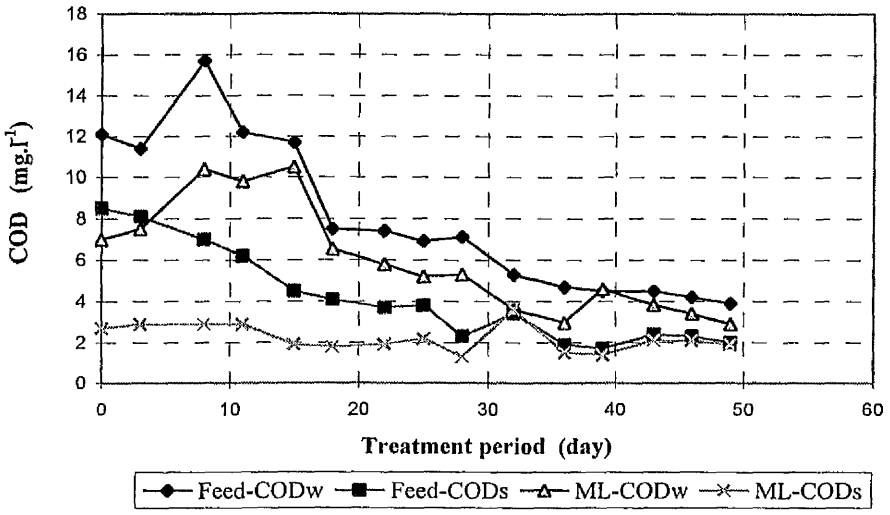


Figure 10.8 Whole and supernatant COD in the feed and in the ML of pig slurry during Trial 2



The CODw of ML can be predicted using the equation 2.3, which was derived by Evans *et al.* (1983), with nominal 2 day residence time. The change (Figure 10.9) in these predicted values and in the observed values were in agreement, the difference between both values were from 0 to 30%. Although they did not match each other perfectly, their trends were of a similar magnitude. This was most likely due to the concentration of feed slurry and residence time varying during treatment.

Nitrogen content

The changes of Kj-N and NH_4^+-N in the feed slurry and in the ML during treatment are shown in Table 10.1, Figures 10.10 and 10.11 respectively. Loss of nitrogen content caused by the minimal aeration treatment was minimal. Kj-N in both the feed slurry and the ML decreased, from 2410 to 2060 $mg.l^{-1}$ and from 2170 to 2050 $mg.l^{-1}$ respectively. A with CODw, the concentration of Kj-N increased slightly, from the initial value of 2410 $mg.l^{-1}$ to a maximum of 2700 $mg.l^{-1}$ at the beginning of the treatment. Also, concentration of Kj-N in the feed slurry was slightly less than the Kj-N of ML. As for COD, this could be explained by there being a higher concentration of insoluble material in the reactor than in the storage tank. This was probably due to independent mixing at the beginning of the treatment.

Concentration of the NH_4^+-N in the feed slurry and in the ML decreased, from 2100 to 1840 $mg.l^{-1}$ and from 1890 to 1790 $mg.l^{-1}$, respectively. The ratio of NH_4^+-N/Kj-N in the feed slurry varied between 0.75 to 0.89, and 0.67 to 0.87 for the ML. These high ratios of NH_4^+-N/Kj-N reflect the low quantity of organic nitrogen (the difference between Kj-N and NH_4^+-N) present in the slurry.

Figure 10.9 Predicted and observed CODw of ML during Trial 2

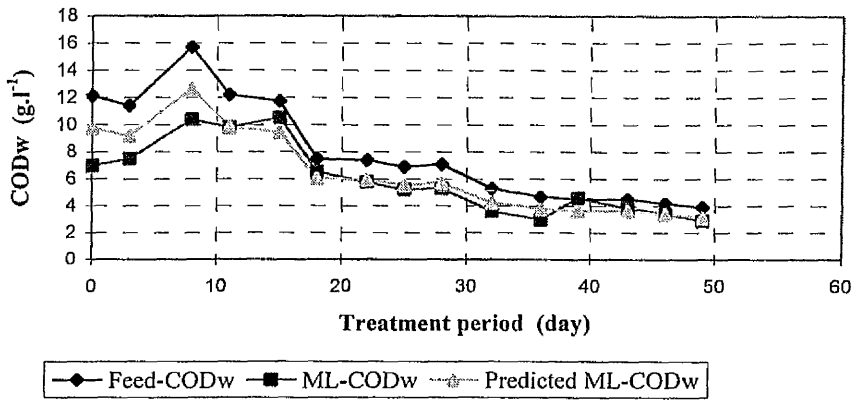


Figure 10.10 Kjeldahl nitrogen (Kj-N) in the feed and in the ML of pig slurry during Trial 2

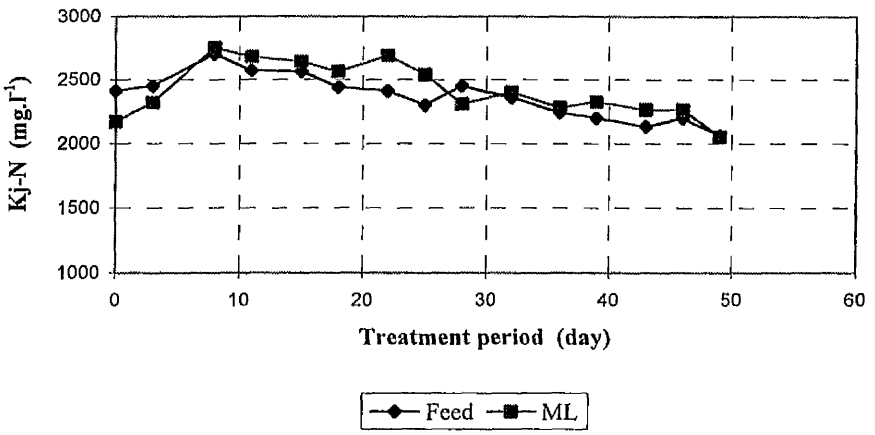
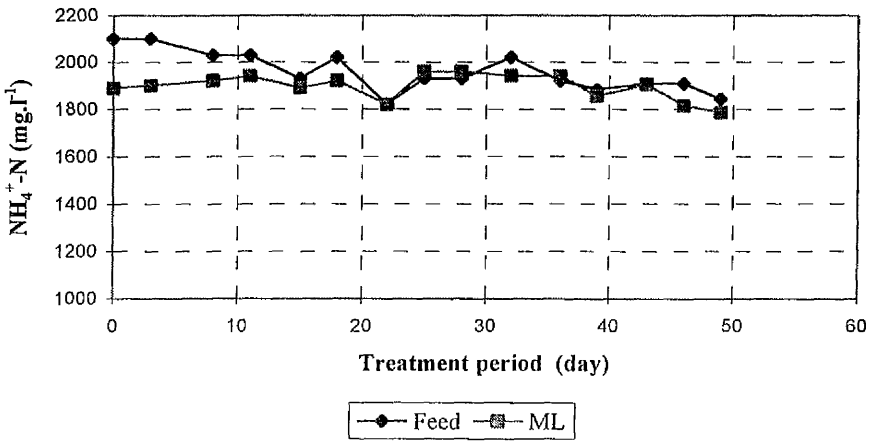
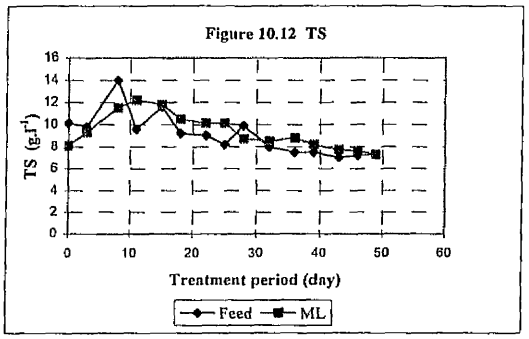
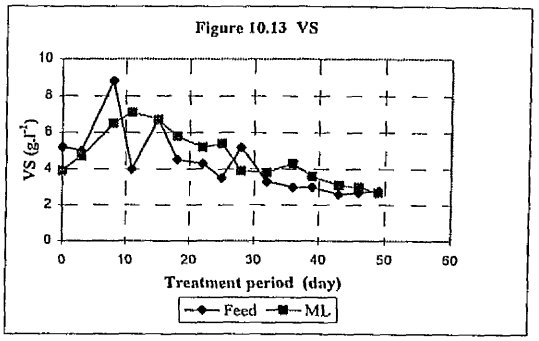
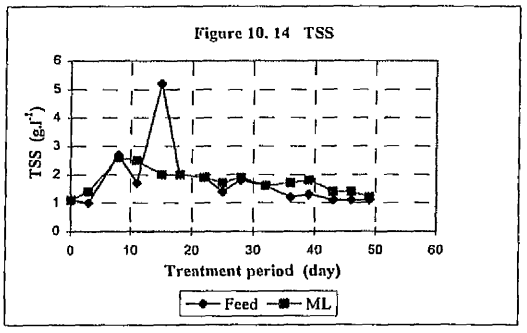


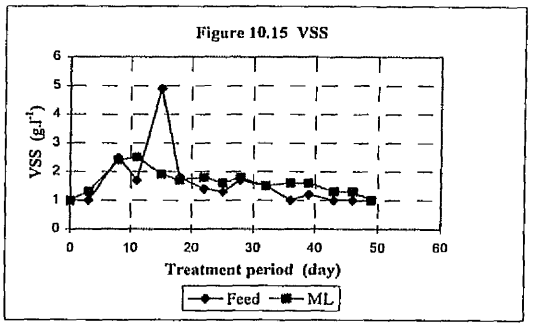
Figure 10.11 Ammoniacal nitrogen (NH_4^+-N) in the feed and the ML of pig slurry during Trial 2

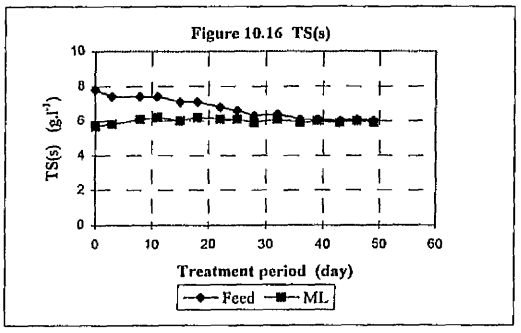


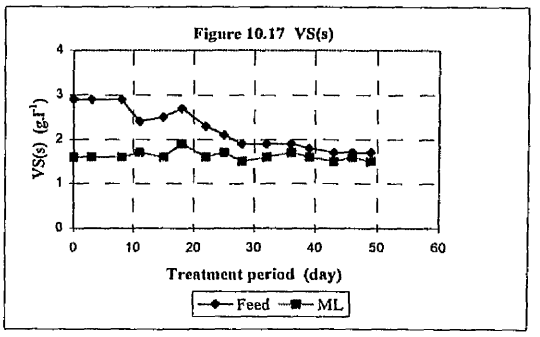












. Figure 10.12-10.17 Change of the solids concentration in the feed and in the ML of pig slurry during Trial 2

Solids concentration

Figures 10.12 – 10.17 show the changes of solids concentration (TS, VS, TSS, VSS, TSs, VSs) during treatment. Concentrations of TS, VS, TSS and VSS in the ML were greater than in feed slurry reflecting higher solids concentration in the reactor vessel than in the slurry storage tank due to inadequate mixing. Since the pig slurry used for this trial was very weak, the maximum concentration of TS was only 14 $g.l^{-1}$ (1.4% DM). TS of feed slurry was increased from 10.1 to 14$g.l^{-1}$ maximum during the first 8 days. It then decreased to 7.3$g.l^{-1}$. This changing pattern was similar for VS, TSS and VSS. The overall reduction of these solids concentration in the feed slurry and in ML are shown in Table 10.1. The greatest reduction was VS, by 43% in feed slurry and 41% in ML. This could be explained by organic matter in the slurry being degraded easily. The changes of supernatant of TS and VS were very similar to the pattern change of BODs and CODs. TSs and VSs of slurry feed decreased linearly with time, while TSs and VSs of ML were relatively constant.

pH

The changes of pH in the feed slurry and ML are illustrated in Figure 10.18. The trends of both pH values were similar. The pH of feed slurry increased slightly, from 8.1 to 8.4, and pH of ML increased from 8.2 to 8.5. These alkaline values indicated the great decrease of acids (VFA) concentration with ammoniacal nitrogen remaining high.

Figure 10.18 pH in feed slurry and ML during Trial 2

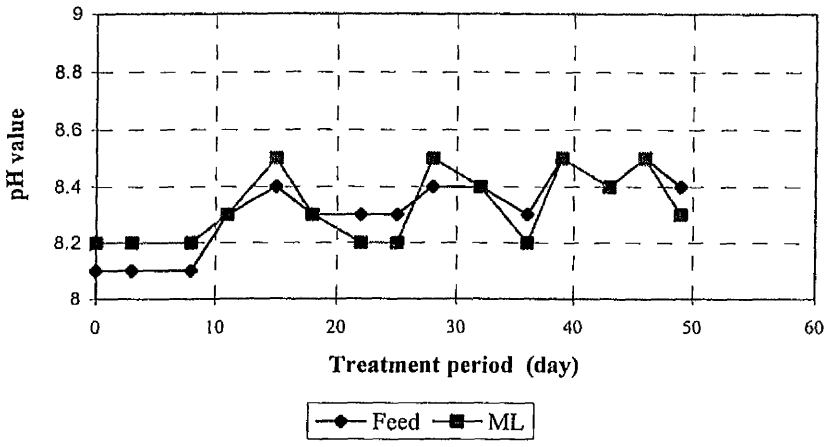


Figure 10.19 Total volatile fatty acids (VFA) concentration in feed slurry during Trial 2 after anaerobic storage for 10 and 20 days

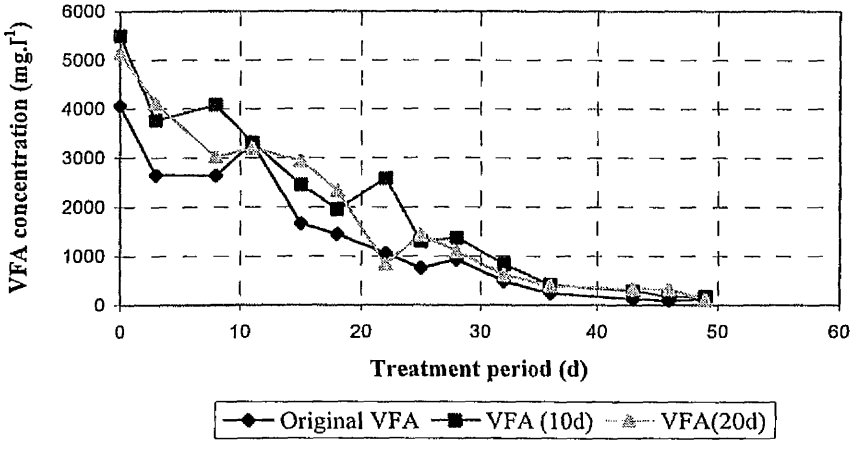
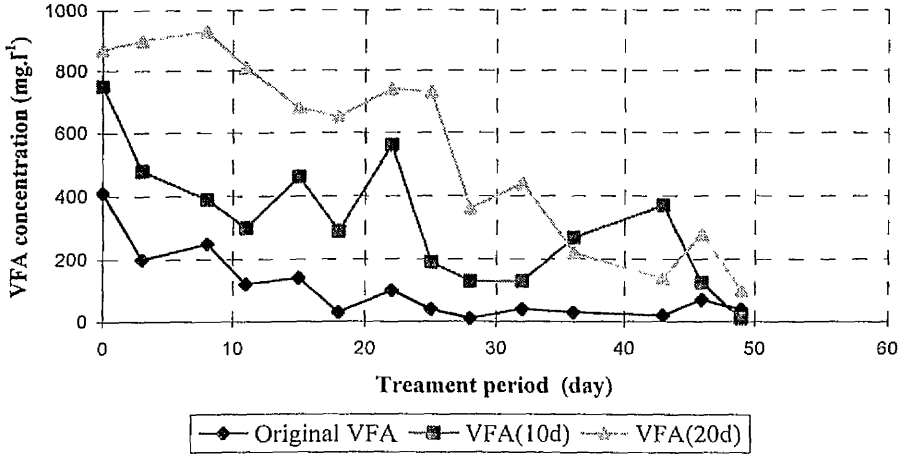


Figure 10.20 Total volatile fatty acids (VFA) concentration of ML during Trial 2 after anaerobic storage for 10 and 20 days



Effect of anaerobic storage in the feed slurry and ML on VFA regeneration (Trial 2)

All the analytical data of anaerobic storage of the feed slurry and ML are shown in Appendix H-Tables H7.

Feed slurry

The change in VFA concentration of the feed slurry during anaerobic storage after aerobic treatment is shown in Figure 10.19. The changes of VFA of 10 day and 20 day stored slurry followed the changes in the original VFA throughout the treatment.

Moreover, the concentrations of VFA (10d) and VFA (20d) of each sampling day were slightly greater than respective original samples throughout the treatment. As the treatment time increased, the differences between the original VFA with VFA(10d) and VFA (20d) decreased. This shows that the stability of VFA in the feed slurry was increased with aeration time, as was found by Williams *et al.* (1984). Williams (1981) also found that the production of VFA during anaerobic storage was inversely related to the aeration period.

Mixed liquor (ML)

Figure 10.20 also shows that there was not much difference between VFA(10d) and VFA(20d) of same sampling day during treatment, indicating the regeneration of VFA was minimal and there was not significant difference in regeneration of VFA with storage time less than 20 days at 10 °C. This could be due to a highly diluted feed slurry. However, Sneath *et al.* (1990) found that the concentration of VFA in ML (18 $g.l^{-1}$ TS), at 2 day residence time treatment, was increased from about 0.06 $g.l^{-1}$ to 0.52 $g.l^{-1}$ after 10 days of anaerobic storage.

Figure 10.20 shows clearly that the change pattern in the concentration of VFA(10d) and VFA(20d) of ML followed closely the original VFA concentration of the initial sample of each sampling day during storage. But the stored samples (i.e. VFA(10) and VFA(20)) increased considerably, with respect to the original VFA throughout the Trial 2 treatment. During the Trial 2, the regeneration of VFA in the ML generally declined as the treatment duration increased. This was because the amounts

of substrate were gradually decreased. But each sample was increased considerably high respective to the day of sampling throughout treatment during anaerobic storage.

Comparing the changes in VFA of stored feed and ML, the VFA(10) and VFA(20) increased were markedly higher in the ML samples. This could be explained by that the higher solids concentration in the ML was higher than in feed slurry. The higher concentration of solids, with a high proportion of organic material (3000 - 7000 mg $VS.l^{-1}$). Therefore, the larger quantity of VFA can be produced during anaerobic storage by VFA-producing microbial population activity.

Although the VFAs ((VFA(10) and VFA(20)) concentration were increased in each sample and above the acceptable level of odour offensiveness (230 $mg.l^{-1}$ of VFA concentration), they were not increased greater than 230 $mg.l^{-1}$ after 25 day of 10 day storage and 36 days of 20 day storage, and compared with the original VFA which below 230 $mg.l^{-1}$ after day 4 of treatment. This proved that VFA production increased with storage time.

11. FULL SCALE AEROBIC TREATMENT: TRIAL 3

11.1. Introduction

From the experiences and observations of Trials 1 and 2, it was desired that PID control was unsatisfactory for this type of effluent treatment in terms of the capital and operating cost. The main objectives of the Trial 3 were to optimise and simplify the aeration control system in order to reduce the energy consumption. The treatment process, apparatus, slurry sampling and preparation were the same as in Trial 2.

11.2 Experimental design and methods

Similar to Trial 2, approximately 450 m^3 of raw fresh pig slurry were pumped from the slurry lagoon to the slurry storage tank. This slurry was from the permanently housed pigs fed on a dry diet. Characteristics of raw slurry are shown in Table 9.1. The reactor vessel was not emptied after Trial 2. Consequently, the ML was used for starting the microbial culture; its initial characteristics are shown in Table 9.1. After the steady state conditions were reached, the temperature, redox value and the speed of inverter drive were monitored and recorded during the treatment period. Operation of the treatment system was stopped after the target level of VFA (500 $mg.l^{-1}$) was achieved.

Control system

The control system of the reactor in Trial 2 was optimised, using a new control system with a programmable logical controller (PLC) (Crouzet Millennium) to integrate all functions as described in Chapter 7.7. The compressor was run at a fixed constant speed (1,340 rpm) regardless of the redox potential value. The compressor was switched on at a redox value of -200 $mV E_{cal}$ and off at -150$mV E_{cal}$. Also the foam breaker was controlled by a foam level switch to avoid excessive running. The full detailed aeration control system is described in Chapter 7.

Methods of sampling, preparation and analysis for feed slurry and ML were the same as those in Trials 1 and 2 as described in Chapter 9.22.

11.2.1 Anaerobic storage of aerobically treated slurry during treatment

Similar to Trial 2, the stability of aerobically treated ML, when subsequently stored anaerobically, was examined with regard to regeneration of odour offensiveness generated during storage. Therefore, extra samples of feed slurry and ML were prepared for the anaerobic storage experiment at each sampling day as described in Chapter 10.2.1. The same slurry samples were used in this trial as those were used for the prior chemical analysis. Hence, the samples stored for 10 days (i.e. VFA(10)) and for 20 days (i.e. VFA(20)) could be compared with the sample without storage (i.e. original VFA) at the same sampling day throughout the treatment period.

11.3 Results and discussion

As in Trials 1 and 2, the feed slurry was in grey and the ML was brown because it contained highly suspended solids. Change in the concentrations of feed slurry after treatment Trial 3 are shown in Table 11.1. These values were the difference between the initial and end concentrations, and the final reductions expressed in percentage of initial values. All the analytical results are detailed in Appendix I (Tables I1 – I8).

Table 11.1. Change in the characteristics of feed slurry after farm-scale treatment in Trial 3. Values were the difference between the initial and end concentrations, and the final reductions expressed in percentages of initial values.

Parameter		**Trial 3**	
		reduction value	% reduction
TS	$g.l^{-1}$	2.4	25
TS(s)	$g.l^{-1}$	1.2	19
TSS	$g.l^{-1}$	0.5	19
VS	$g.l^{-1}$	2.4	44
VS(s)	$g.l^{-1}$	1.1	42
VSS	$g.l^{-1}$	0.6	25
CODw	$g.l^{-1}$	8.9	67
CODs	$g.l^{-1}$	7.2	82
BOD_5w	$g.l^{-1}$	5.9	91
BOD_5s	$g.l^{-1}$	5	93
VFA	$g.l^{-1}$	6.5	94
TIP	$g.l^{-1}$	0.06	100
TOA	$g.l^{-1}$	6.7	94
Kj- N	$g.l^{-1}$	0.01	1
NH_4^+-N	$g.l^{-1}$	0.3	17
pH	-	-0.2	-2

Variations in temperature (Figure 11.1) illustrate the changes in treatment conditions during the treatment. In this trial, temperatures of ambient, ML in reactor and slurry in storage tank were generally higher than at the previous two trials (Trials 1 and 2) but their change patterns were similar. This was because the Trial 3 was carried out in the period of middle of summer whilst the Trials 1 and 2

Figure 11.1 Temperature profiles during Trial 3

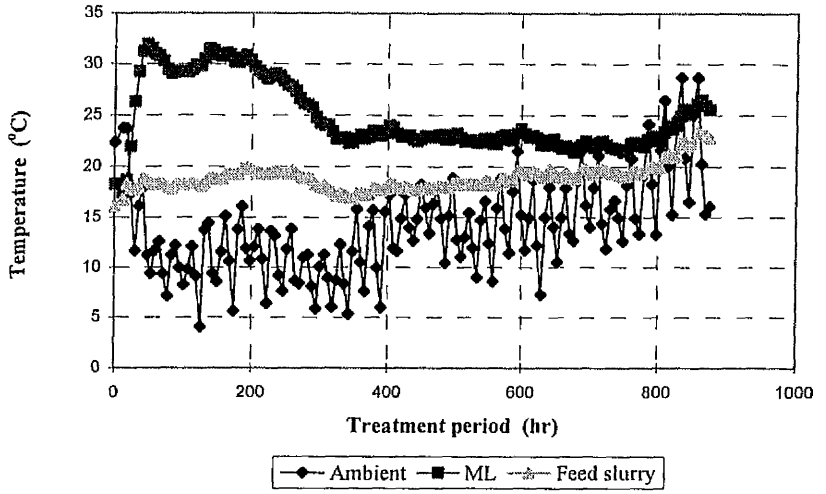
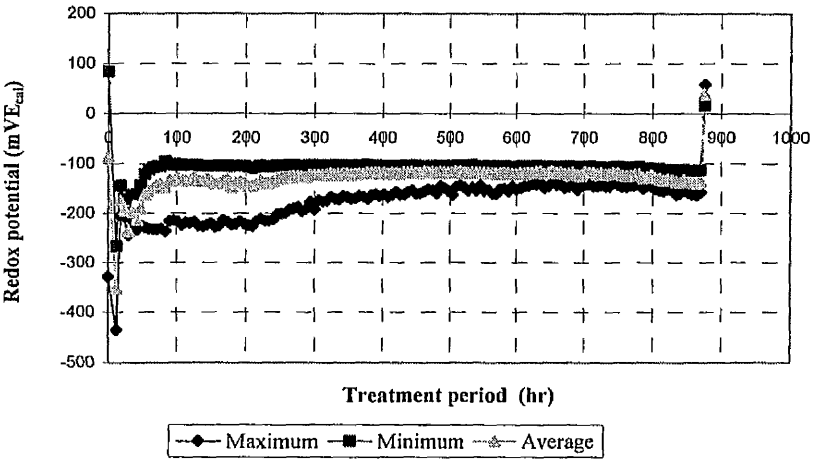


Figure 11.2 Redox potential profiles during Trial 3



were conducted in spring. The temperature of feed slurry in the feed slurry storage tank was relatively constant at approximately 17°C; this was mainly affected by changing of ambient temperature with an average around 15 °C. The temperature of ML was largely independent of the ambient temperature. It increased from 15 to 32 °C. This change was dramatic in the first 3 days, then decreased to approximately 22°C after 14 days and maintained this level thereafter. This change indicates that the microbial activity was very high (i.e. high level of microbial activity per unit volume of reactor) during the beginning of treatment, and then became stable.

Figure 11.2 illustrates the change of redox (maximum, average and minimum) values, indicating the dissolved oxygen level in the ML during the monitoring period. During the first 3 days, the redox values were very unstable reflecting the microbial activity in an unstable condition. It became stable after the third day and this was in agreement with statement by Evans *et al.* (1979). The maximum (-100 mVE_{cal}) and average (-120 mVE_{cal}) values of redox fluctuated during the treatment period. The minimum redox value approached the control set point of –150 mVE_{cal}, and maintained at this level after 18 days. This change indicates the microbial populations were growing in the ML, reaching a peak during the treatment.

11.3.1 Change of slurry characteristics during treatment

Volatile fatty acids (VFA)

Concentration of VFA decreased exponentially from 6890 to a minimum level of 410 mg.l^{-1} during the treatment and reached the target level of 500 mg.l^{-1} after 32 days of treatment (Figure 11.3). The general pattern of change was similar to that of Trials 1 and 2.

The changes of individual VFA components are shown in Figure 11.4. Similarly to Trial 1 and 2, the highest proportion of the total VFA in feed slurry was acetic acid (3100 to 380 mg.l^{-1}), which contributed by 45 to 93% to the total VFA

Figure 11.3 Total volatile fatty acids (VFA) concentration in the feed and the ML of pig slurry during Trial 3

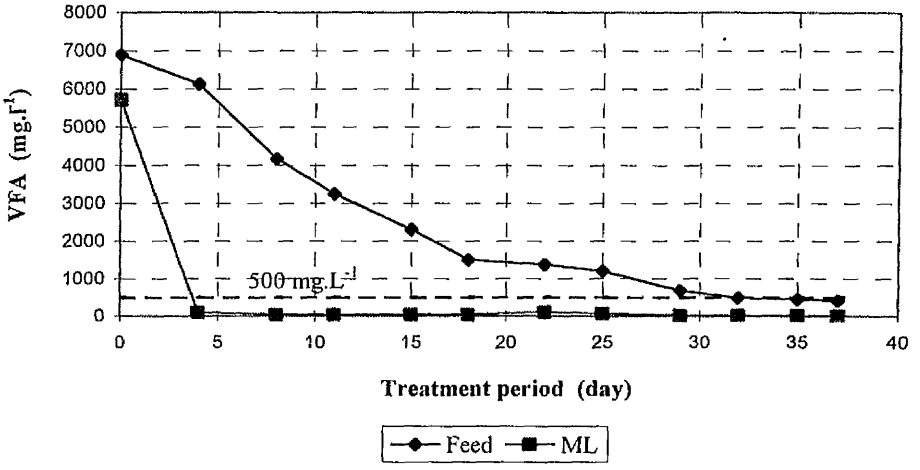
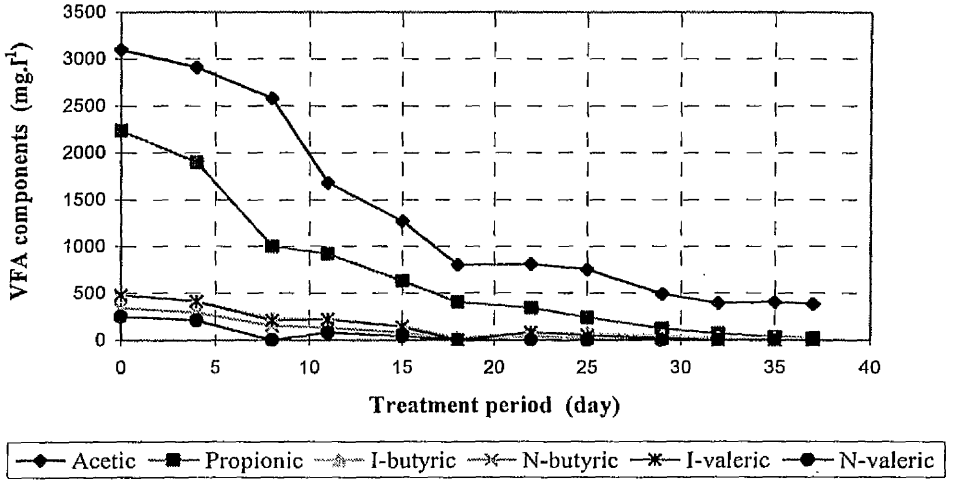


Figure 11.4 Individual volatile fatty acid (VFA) concentration in the feed of pig slurry during Trial 3



concentration. The concentration of propionic acid was also considerably high, from 2250 to 20 $mg.l^{-1}$ throughout the treatment.

The removal of VFA was 92 to 99% throughout the treatment. Except for the first sample, VFA concentration in the ML was below 110 $mg.l^{-1}$, which was about 50% less than the acceptable level (230 $mg.l^{-1}$ of VFA) of odour offensiveness. All these values indicate the removal of VFA was significant in the reactor. Therefore, it further confirmed that the VFA was removed substantially using minimal aeration with 1 day residence time and slurry passing two times through the reactor. Acetic acid dominated in the ML, it contributed by 54 to 100% to the total VFA while I-butyric, N-butyric, I-valeric and N-valeric acids were only detected approximately in 5 % of the total VFA in the first sample.

Total organic acid (TOA)

The trends of TOA in the feed slurry and ML were very similar to the VFA, as shown in Figure 11.5. Concentration of TOA in feed slurry was decreased almost exponentially from 7.2 to 0.46 $g.l^{-1}$ during the treatment. The highest reduction rate of TOA in ML was achieved during the first 4 days treatment, by 94%. It then fluctuated within 0.48 to 0.2 $g.l^{-1}$ until the end of treatment. The VFA/TOA ratio during treatment in feed slurry and ML was 0.75 – 0.96 and 0.05 - 0.8, respectively.

Total indoles and phenols (TIP)

Figure 11.6 illustrates the changing pattern of TIP in the feed slurry and ML, which is very similar to the pattern of TOA and VFA. Concentration of TIP decreased from 64 $mg.l^{-1}$ to an undetectable level after 35 days of treatment. Therefore, a complete removal of TIP in feed slurry was achieved by the treatment. Figure 11.7 shows that TIP in feed slurry consisted mainly of p-cresol, which contributed 75 to 100% to TIP. Except for the first sample, only a low concentration (0.4 $mg.l^{-1}$ or less) of p-cresol in ML was detected until 15 days treatment, showing the concentration of TIP was minimal after treatment.

Figure 11.5 Total organic acid (TOA) concentration in the feed and the ML of pig slurry during Trial 3

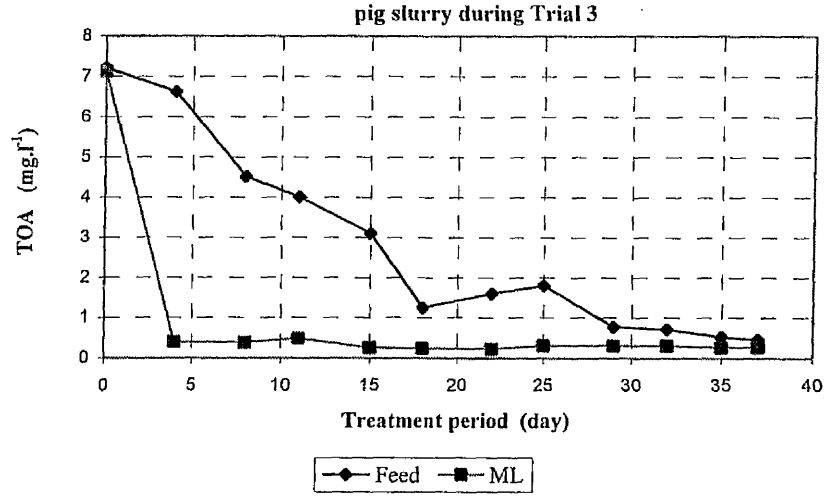


Figure 11.6 Total indoles and phenols (TIP) concentration in the feed and the ML of pig slurry during Trial 3

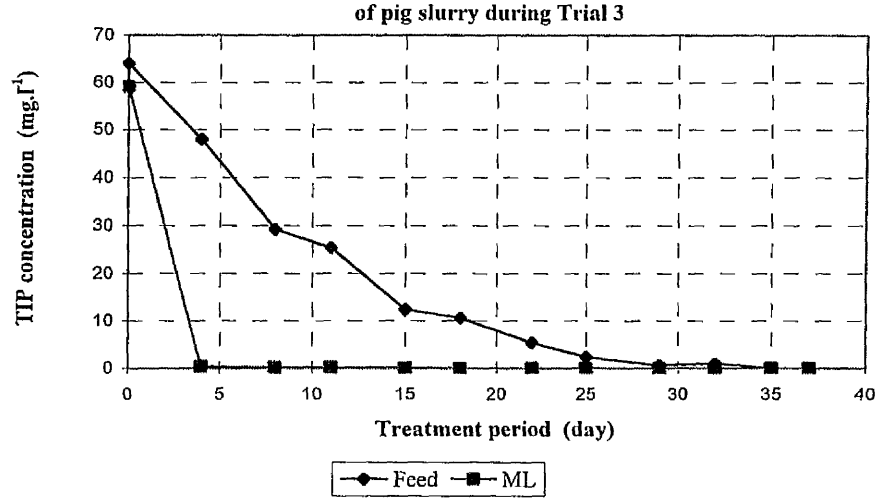


Figure 11.7 Concentration of individual Indole and Phenols in the feed and in the ML of pig slurry during Trial 3

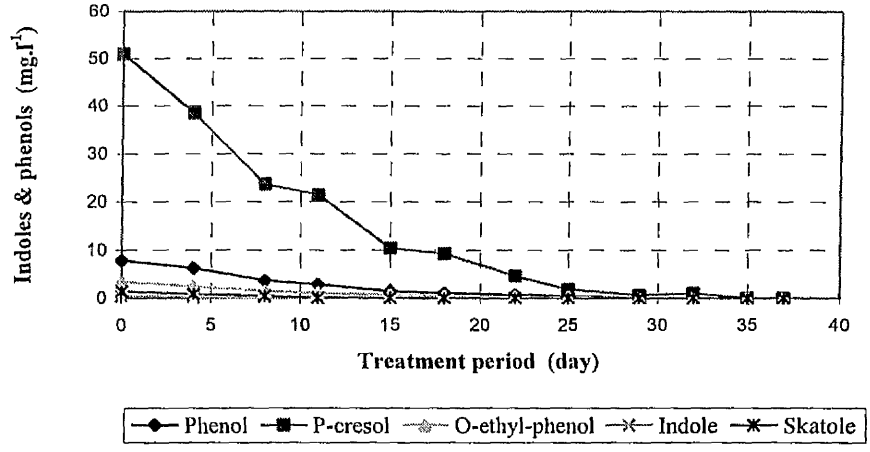
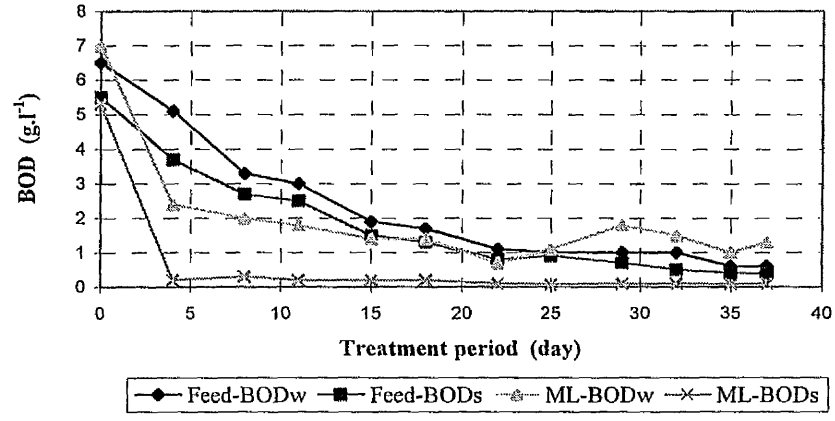


Figure 11.8 Whole and supernatant BOD in the feed and in the ML of pig slurry during Trial 3



5-day biochemical oxygen demand (BOD_5)

Changes of BOD_5w and BOD_5s in feed slurry and ML during treatment are shown in Figure 11.8. Trends of both BOD_5w and BOD_5s in feed slurry were closely associated with each other and as with the organic odorants (VFA, TOA and TIP). The reduction of BOD_5s was slightly greater than BOD_5w. BOD_5w decreased from 6500 to 600 $mg.l^{-1}$, by 91% while BOD_5s decreased from 5350 to 360 $mg.l^{-1}$ by 93%, throughout the treatment.

During the first 4 days of treatment, the highest removal rates of 65% and 96 % of both BOD_5w and BOD_5s respectively in the ML were achieved. Concentration of BOD_5w decreased from 6950 to 560 $mg.l^{-1}$ after the first 22 days, and then fluctuated around 1000 $mg.l^{-1}$ until the end of treatment. After the first 4 days, BOD_5s in ML decreased slowly from approximately 300 to 70 $mg.l^{-1}$.

The change pattern of BOD_5s in feed slurry and in the ML was similar to the changes of the organic odorants during treatment. This suggests that the concentration of BOD_5s is very closely related to the concentration of odorants. Therefore, BOD_5s was a good indicator of odour offensiveness. Williams (1984) found a highly significant ($p<0.001$) correlation between the logarithm of the BOD_5s concentration and odour offensiveness of piggery slurry. An improved model has been developed using fresh and aerobically treated slurry (Thacker and Evans, 1985) with BODs, as below:

$$\text{Odour offensiveness} = 1.453 \times \log (BOD_5s) + 2.320 \qquad \text{Equation (11.1)}$$

By substituting the BOD_5s, in $g.l^{-1}$, of slurry storage into the equation 11.1 above, the odour offensiveness was reduced from "definite" (3.4) to "very faint"(1.7). Similarly, the odour offensiveness of ML was between "very faint" and "inoffensive" after the first day of treatment.

Figure 11.9 Kjeldehl nitrogen (Kj-N) in the feed and the ML of pig slurry during Trial 3

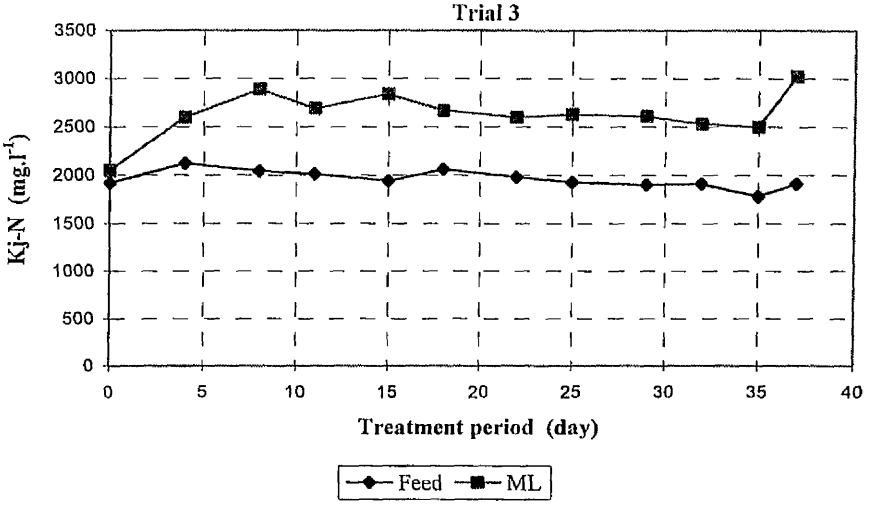
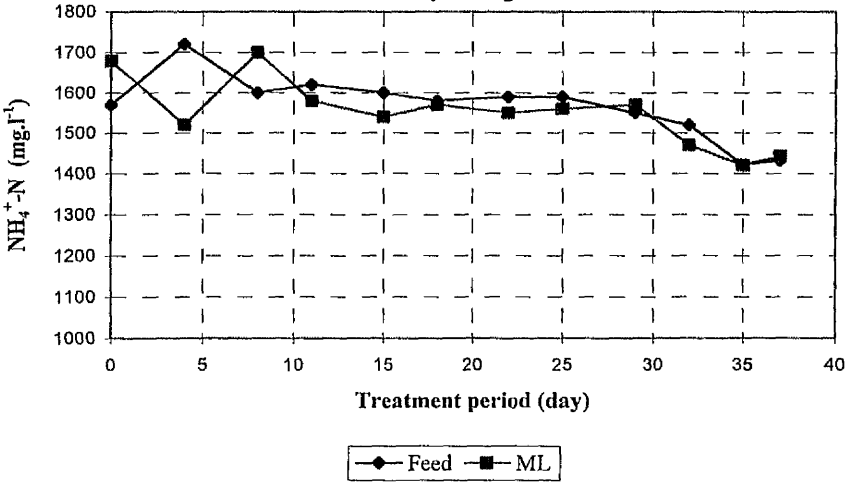


Figure 11.10 Ammoniacal nitrogen (NH_4^+-N) in the feed and the ML of pig slurry during Trial 3



Nitrogen content

Figure 11.9 shows the change of total nitrogen (Kj-N) in feed slurry and in the ML during treatment period. The Kj-N in the slurry remained relatively constant and fluctuated within 1900 to 2100 $mg.l^{-1}$. The Kj-N of the ML was increased from 2050 to 2890 $mg.l^{-1}$ during the first 8 days. The change of concentration of NH_4^+-N in the feed slurry and in the ML were similar as shown in Figure 11.10. A slightly greater reduction of NH_4^+-N in ML (14%) than in the slurry storage (9%) was observed. Concentration of Kj-N in the ML was greater than in feed slurry. This was probably because higher insoluble material (i.e. consisting mainly of cellulose material) was present in the ML, and was caused by inadequate mixing.

Solids concentration

Figures 11.11-11.16 illustrate the changes of all solids (TS, TSS, VS, VSS, TSs, VSs) concentration during treatment. Generally, solids concentration was relatively low and little changed in feed slurry due to a short treatment time. TS was approximately 0.7 to 1% (w/v) in feed slurry and 1 to 2 % (w/v) in ML. Concentration of TS, TSS and VSS in ML was greater than in the feed slurry while the supernatant of TS and VS were higher in the feed slurry. This indicates that the dissolved materials in feed slurry was higher than in the reactor vessel.

It is interesting to see that the change pattern of solids concentrations were in groups, such as TS and VS; TSS and VSS; and TSs and VSs were grouped, indicated that the VS is part of TS and VSS is part of TSS. The ratio of VS/TS and VSS/TSS were 0.43 to 0.57 and 0.73 to 0.92 respectively in feed slurry while in ML were 0.55 to 0.75 and 0.77 to 0.94 respectively.

Chemical oxygen demand (COD)

The changes of CODw and CODs in the feed slurry and in the ML during treatment are shown in Figure 11.17. The reduction of CODw in the feed slurry was 67% and while CODw in the ML increased by 10%. The result of CODw were totally unexpected, CODw in the feed slurry were always less than the CODw in the ML. This was probably due to the greater solids concentration in the feed slurry than in

Figure 11.11 TS

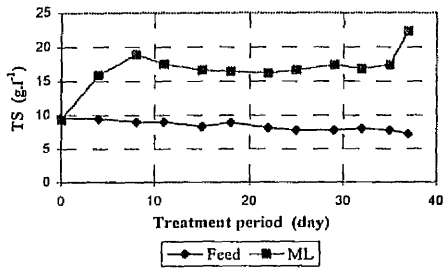


Figure 11.12 VS

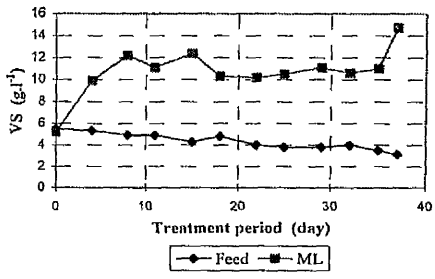


Figure 11.13 TSS

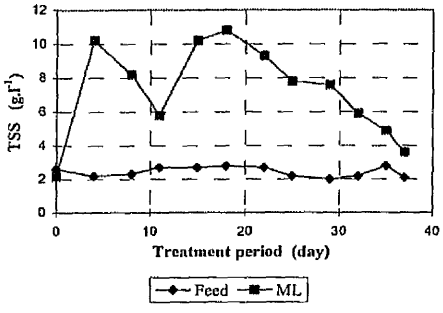


Figure 11.14 VSS

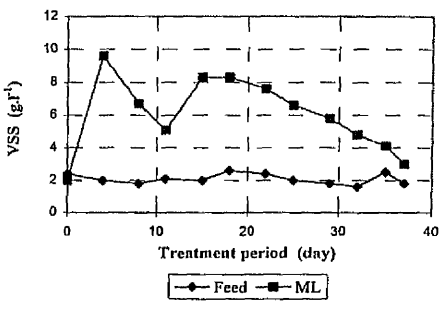


Figure 11.15 TS(s)

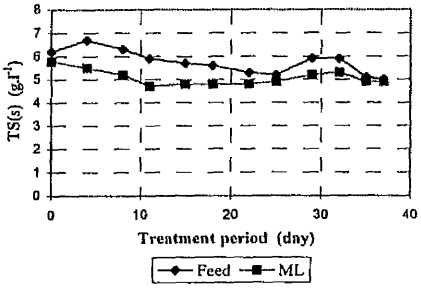


Figure 11.16 VS(s)

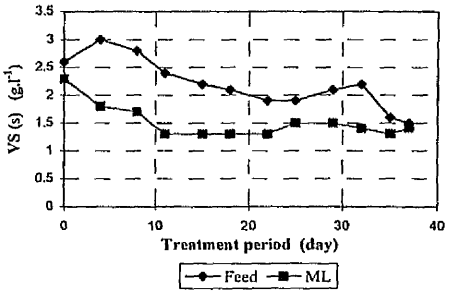


Figure 11.11 - 11.16 Change of solids concentration in the feed slurry and in the ML of pig slurry during Trial 3.

Fgiure 11.17 Whole and supernatant COD in the feed and in the ML of pig slurry during Trial 3

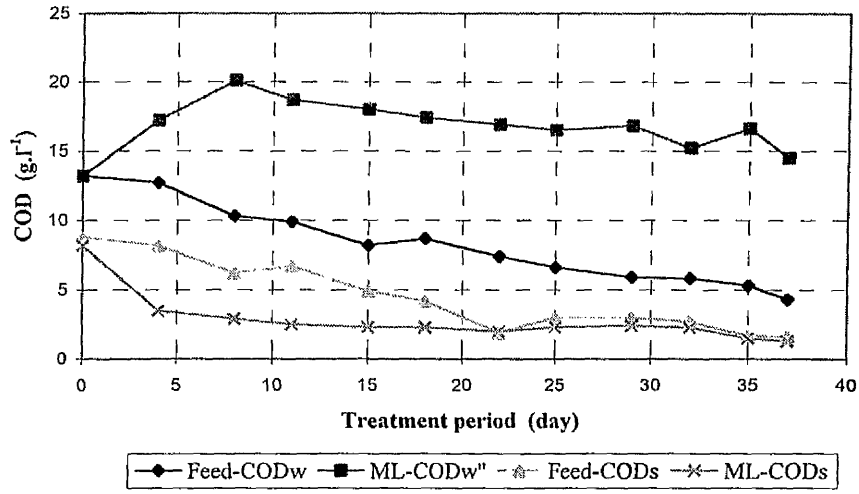
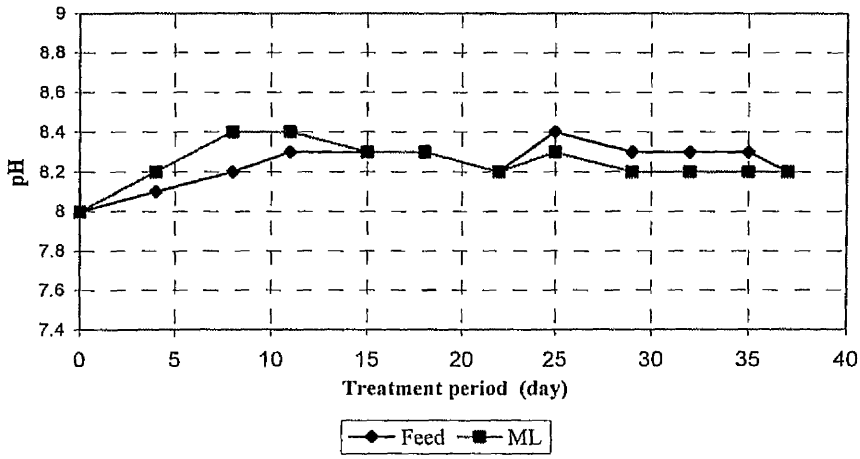


Figure 11.18 pH value in the feed and in the ML of pig slurry during Trial 3



the ML. Svoboda (1993) found the high correlation relationship between the CODw and TS (R^2 = 60.3%) and with VS (R^2 = 63%). He also commented that there was a greater influence of VSS on CODw rather than on TS.

The results of CODw and solids concentration were observed to be similar in this trial. They were not observed in the laboratory studies previously. These were probably due to a problem in practice. The explanations are discussed below.

As in this trial and even in larger tanks and lagoons, a settling of solids will inevitably occur.

1. Inadequate mixing must have occurred in the feed slurry due to the large slurry tank volume.

2. Cellulolytic and other materials settled and probably firmly stick to the bottom of the slurry storage tank, but the air diffusers were unable to re-suspend them into the slurry.

3. Solids were left behind in the reactor from the previous trial. They were not transferred into the storage tank, probably due to the position of the emptying submersible pump in the reactor.

Another reason for the solids accumulation may have been an inadequate mixing occurring in the tall reactor vessel. Despite the vigorous ML motion in the reactor caused by the jet force of air entrainment from the venturi aerator, solids may have been circulated near the position of the venturi or near the bottom of the reactor. When taking the ML sample (sampling point was located at the discharge side of the venturi pump), high solids fraction were included. This could be improved by use of a powerful mechanical mixer following which the sample could be taken in the slurry input or in the outlet pipeline.

pH

The change in the pH of both feed slurry and ML was similar (Figure 11.18). As in Trial 2, pH of the feed slurry was increased slightly, from 8 to 8.2, and fluctuated at 8.2 ± 0.1 to the end of the treatment. The pH of the ML increased from 8 to 8.4, then gradually decreased to the value of 8.2 after 23 days and maintained this value till the end of the treatment. The change of these values also show that acids content, such as VFA and TOA, were removed substantially in both feed slurry and ML, while the nitrogen contents (Kj-N and NH_4^+-N) remained high.

Effect of anaerobic storage in the feed slurry and ML on VFA regeneration (Trial 3)

All the analytical data of anaerobic storage of the feed slurry and ML are shown in Appendix I-Table I8.

Feed slurry

Figure 11.19 illustrates the change in the original VFA concentration (i.e. feed slurry sample without storage), concentration of VFA after 10 days storage (VFA(10d)) and concentration of VFA after 20 days storage (VFA(20d)) of the feed slurry from each sampling day throughout treatment period. Concentrations of VFA(10d) and VFA(20d) were very similar to the original VFA, as found in the previous study (Trial 2), showing that the regeneration of VFA(10d) and VFA(20d) of feed slurry was not significant during storage. This indicates that the level of VFA was removed substantially by aerobic treatment and the slurry was relatively stable after treatment.

Mixed liquor (ML)

Figure 11.20 illustrates the change in, original VFA concentration, concentration VFA(10d) and VFA(20d), of the ML from each sampling day throughout the treatment period. Concentrations of VFA(10d) and VFA(20d) were greater than the original VFA and these three VFAs became close together after 21 days of

Figure 11.19 Total volatile fatty acids (VFA) concentration in the feed of pig slurry during Trial after anaerobic storage for 10 and 20 days

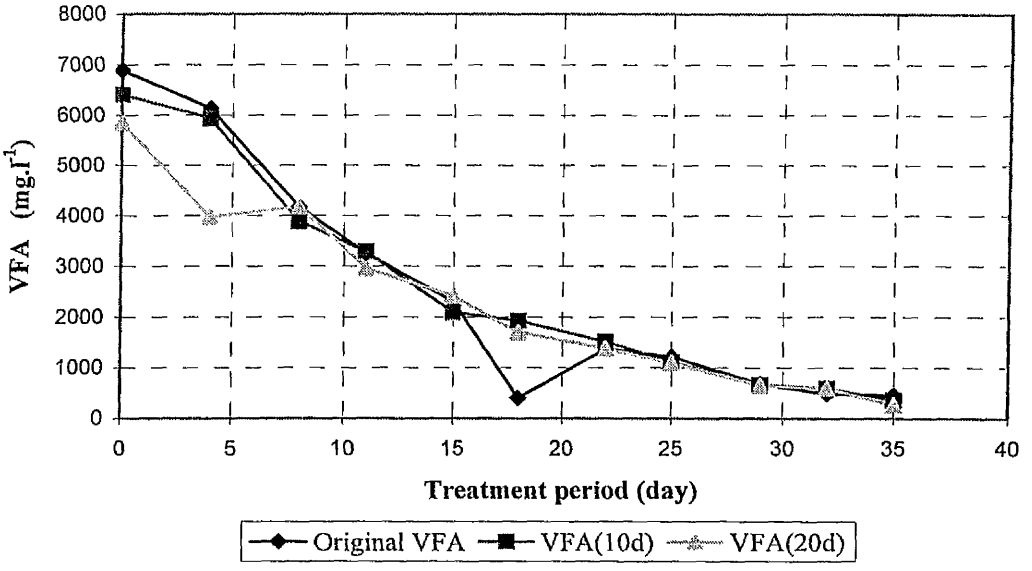
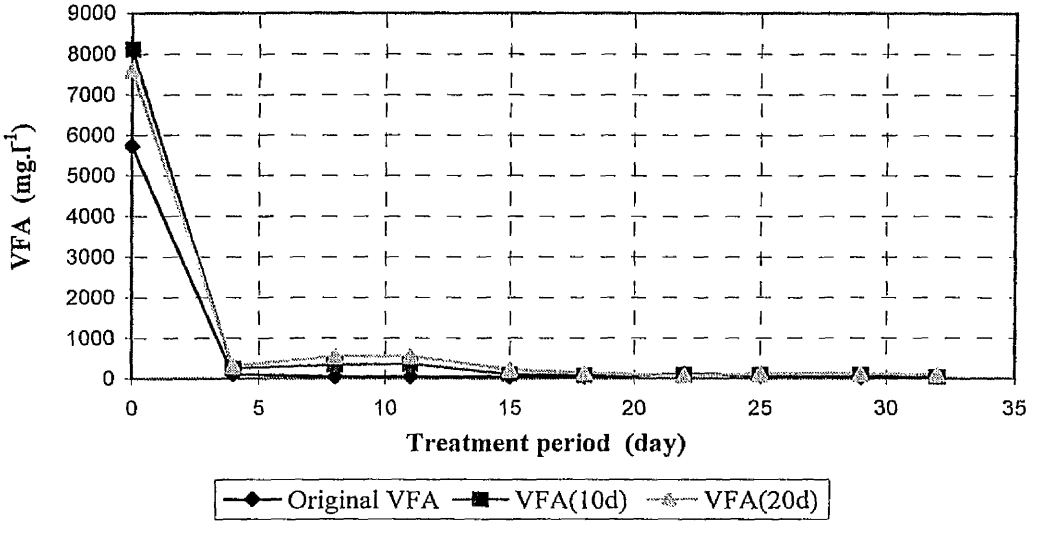


Figure 11.20 Total volatile fatty acids (VFA) concentration in the ML of pig slurry during Trial 3 after anaerobic storage for 10 and 20 days



treatment. This could be due to the low solids concentrations of slurry used for the treatment causing the substrates to be limited for VFA production and less readily degradable. Similar behaviour was observed by Williams *et al.* (1984), who commented that VFA production would be less after prolonged aeration, since the substrate concentration was low during storage after treatment. However, longer storage time produced greater amount of VFA (e.g. VFA(20) > VFA(10) > original VFA) was observed in this study (as with Trial 2). This change was in agreement with the previous laboratory findings (Chapters 4 and 5) and Williams & Evans (1981). During anaerobic storage, except the first measurement, original VFA was below the acceptable level of odour offensiveness, while concentration of VFA(10d) and VFA(20d) were above and approached down to this level after days 13 and 15, respectively.

12. PROCESS ECONOMICS OF FULL SCALE TREATMENT

12.1 Introduction

Two main costs of the project to be considered are:- (a) the capital cost (purchase capital) of the plant and (b) the operating/running cost. This a simple treatment plant involves fewer items of equipment than a sewage treatment works. However, in any costing exercise, the assumptions necessary to make a reliable estimate are often countered by the unexpected!

The capital cost for the treatment plant covers an aeration vessel, venturi jet, compressor, pumps, control and electrical devices, and minor equipment such as fittings and pipeline, etc. A model used to estimate the cost of an aeration vessel and aerator cost was developed by Williams *et al.* (1989). Additionally, some costs are attributed to the cost of installation, such as site preparation, plant commissioning, etc. The cost of installation is dependent on the complexity of the treatment, and normally between 1 and 4 times the purchase price of the plant parts should be allowed (Burton *et al.*, 1997).

The depreciation is the repayment of the capital cost, and it ought to be for a shorter period of time than the expected life of the plant (Burton *et al.*, 1997). Normally, there is no commercial value of this kind of treatment plant, in that no profit can be incurred. The cost of treatment can be only related directly to the animals produced, or the amount of slurry to be treated, which is given as cost per animal ($£.pig^{-1}$ or $£.cow^{-1}$) or cost per volume of slurry ($£.m^{-3}$). The cost of energy is an important factor in the comparative ranking of alternative processes.

12.2 Capital cost

Details of purchase capital required are summarised in Appendix J (Table J1). Table 12.1 illustrates the percentage contribution to the overall capital cost from each major component, in this farm scale continuous aerobic treatment plant.

The total purchase capital required for this aeration treatment plant was £20,900. The highest contribution to the capital requirement was the aeration vessel and its auxiliary components, 36 % of the total capital cost. Using the model derived by

Williams *et al.* (1989), the cost of the aeration vessel was estimated to be £3500, which was about 50% less than the one used (£6,870) in the present study. The cost of aeration devices was the sum of the blower, venturi jet and the slurry circulation pump, together approximately 28% of the total capital. The data logger contributed the highest, about half the cost of the control and instrumentation, which was also high overall, 27 % of the total capital cost.

Table 12.1. Total capital cost of farm scale aerobic treatment plant.

Item	Cost (£)	% of total cost
Aeration vessel and its auxiliary	7,456	36
Venturi aerator system	5,778	28
Control and instrumentation equipment	5,577	27
Installation and commissioning	1,035	5
Filling and emptying pumps	1,020	5
Total	20,866	100

The capital costs in Trials 1 and 2 were greater than in Trial 3, because the inverter drive was not used in Trial 3. This component contributed to approximately 17% of the total control and instrumentation cost.

However, the total purchase capital requirement could be lower in a practical commercial treatment plant than in these experiments. This was because the blower was oversized at the beginning of the farm scale study. It could well be the case that a considerably smaller blower might suffice on a commercial treatment because very low running speeds would be required. The emptying pump was used to improve control over the exchange of slurry; whereas a level overflow pipe between the storage tank would suffice in practice. Some devices were used only for experimental purposes, e.g. the inverter drive and the data logger. Such sophisticated devices would not be necessary in a practical treatment unit.

12.3 Operating costs

In this study, the cost of the energy for the treatment was considered as the only operating cost. The continuous aeration process required a continuous supply of compressed air, so the main contribution to the overall operating cost was the

energy consumed by the compressor, pumps and a foam breaker (Chapter 12.3.1 Oxygen and energy requirement). The cost of the rest of the miscellaneous items could also be included in an estimate (Burton *et al.*, 1997) such as:-a) maintenance and services for all kinds of equipment; b) labour costs; c) consumables if required (e.g. chemical additives); d) capital charges; e) depreciation costs; f) tax relief and incentives if applicable; g) penalty costs.

12.3.1 Oxygen and energy requirements

Table 12.2 summarises the oxygen and energy requirements in farm scale treatment Trials 2 and 3. Detailed calculation of oxygen and energy requirements for Trials 2 and 3 are shown in Appendix J.

12.3.1.1 Trial 2

An indication of the oxygen consumption during treatment is the difference between the COD of input slurry and the COD of treated slurry, as described in Chapter 2. In the present study (Trial 2), a daily oxygen requirement was needed to achieve the target VFA level of 500 $mg.l^{-1}$ in the stored slurry. Therefore, the overall mass of oxygen consumption in the reactor vessel (i.e. the mass of daily COD removal over the whole treatment period) was found to be 3,175 kg as shown in Table 12.2. This required an aeration energy (i.e. electricity consumed by blower and slurry circulation pump) of approximately 3,320 kWh, and resulted in an aeration efficiency of 0.96 $kgO_2.kWh^{-1}$ (see Appendix J Tables J2 and J3). This figure was only 4% different from the standard SOTE (1.0 kg $O_2.kWh^{-1}$) as previously noted in Chapter 8, which was tested with pig slurry of similar characteristics, and this figure also compares well with the findings by Sneath *et al.* (1992). They found that venturi aerators gave mean aeration efficiencies of 0.6 and 0.7 $kgO_2.kWh^{-1}$ for pig slurry for 2 and 1 day residence times respectively. Cumby (1987c) also gives similar figures for the range of venturi aerators, 0.35 to 1.0 kg O_2 kWh^{-1} for the tests in water, and slightly lower figures when using slurries.

Similarly, the summation of the daily reduction in VFA was calculated to be 1890 kg, given that 0.57 kg of VFA was removed per kWh. Therefore, with TS less than 1% (w/v) in pig slurry, 1.7 kg of oxygen was required to remove 1 kg of VFA (1.7 $kgO_2/kgVFA$), which was 24% greater than the theoretical value (1.7

Table 12.2. Oxygen and energy requirements for VFA removal

		Reactor (ML)		Whole process (Feed)	
		Trial		Trial	
		2	3	2	3
O_2 requirement (ΔCODw), kg		3175	1980	5370	4050
VFA removal, kg		1890	2559	1810	2860
Energy input, kWh		3320	1690	3940	2150
Air input, m^3		34425	26370	-	-
VFA removal efficiency, kg VFA.kWh^{-1}		0.57	1.5	0.46	1.34
Aeration efficiency, $kgO_2.kWh^{-1}$		0.96	1.2	1.36	1.9
Specific power, $kWh.m^{-3}$		2.1	1.1	8.7	4.7
O_2 transfer efficiency, %		30	25	-	-
Ratio of :	$kgO_2/kgVFA$	1.7	0.77	2.97	1.41

Note:

Reactor

- O_2 requirement was calculated by the difference between the daily feed slurry(CODw) and the ML(CODw) for Trials 2 and 3.
- VFA removal was calculated by the difference between the daily feed slurry(VFA) and the ML(VFA) for Trials 2 and 3.
- Energy input was the aeration energy and was the sum of the energy of the blower and recirculation venturi pump for Trial 2 and 3.
- Air input was the amount of air entering the reactor.
- VFA removal efficiency = [daily feed slurry(VFA) - ML(VFA)]/Energy input.
- Specific power = Energy input/$455m^3$.
- O_2 transfer efficiency = [daily feed slurry(CODw) - ML(CODw)]/(Air input * 0.21)*100.

Whole process

- O_2 requirement was calculated by the difference between the max. feed slurry(CODw) and the min. feed slurry(CODw) for Trials 2 and 3.
- VFA removal was calculated by the difference between the max. feed slurry(VFA) and the min. feed slurry(VFA) for Trials 2 and 3.
- Energy input was the total energy consumption for the treatment process in Trials 2 and 3.
- VFA removal efficiency = [max. feed slurry(VFA) - min. feed slurry(VFA)]/Energy input
- Specific power = Total energy input/$455m^3$.

$kgO_2/kgVFA$). The theoretical value of oxygen consumption was calculated by the difference between the feed slurry CODw and the predicted CODw of ML (Appendix J Table 10 for calculation), as shown in Table 12.3.

Also, a calculation method for the oxygen consumption was used with the relationship of VFA concentration and COD supernatant (Williams 1981) (Table 12.3 and Appendix J Tables J8 and J9). This was because the oxygen demand for VFA breakdown increases, per unit weight, as the size of the skeleton increases from two carbons group to five carbons group (C_2 to C_5). (Williams, 1981) found that the oxidisable elements (carbon and hydrogen) in the molecules increasing in proportion to the oxygen contained in the carboxylic acid radical. Surplus oxygen from an external source is thus needed to fully oxidise the VFA molecules into carbon dioxide and water. The contribution of VFA to the supernatant COD was derived by multiplying the values (Table 12.4) by the concentration of each individual compound. However, this method of estimating oxygen consumption was approximately 1% and 40% lower than the theoretical values in Trials 2 and 3 respectively (Table 12.3).

Table 12.3. Estimation of oxygen consumption (based on 1% TS).

Trial	CODw		CODs		CODs(VFA)[a]		Predicted COD[b]	
	kg	$kg.m^{-3}$	kg	$kg.m^{-3}$	kg	$kg.m^{-3}$	kg	$kg.m^{-3}$
2	3175[c]	2.04	3315	2.13	2510	1.6	2489	1.6
3	1980[d]	1.35	2334	1.98	3353	2.85	1970	1.67

Note: [a] Appendix J-Tables J8 and J9 [b] Appendix J Table J10

[c] Appendix J Table J2 [d] Appendix J Table J12

Table 12.4. Supernatant COD values of individual volatile fatty acids expressed as $gO_2.g^{-1}$ (Williams, 1981).

VFA component	Supernatant COD
Acetic acid	0.96
Propionic acid	1.4
I-butyric acid	1.67
N-butyric acid	1.7
I-valeric acid	1.8
N-valeric acid	1.87

The power consumption by the treatment plant during the monitoring periods is summarised in Table 12.2. Such a minimal aeration treatment will only give a limited the stability to slurry in terms of VFA reduction. A total energy of 3880 kWh was required to treat 455 m^3 of pig slurry to reach the target VFA level (500 $mg.l^{-1}$). The biggest component of the total energy was the power used by the slurry recirculation pump (71%), while the energy required for the blower was considerably less (13%). Both of these together accounted for 84% of the total energy consumption. The remainder of the energy was used for filling the reactor, emptying it, and for a mechanical foam breaker. The higher power consumption during the shorter residence time was mostly a reflection of the longer running time required by the blower. In Trial 2, the blower was run almost continuously with variable power for which, regardless of the redox value, the specific power was found to be 8.6 $kWh.m^{-3}$, in order to reach the target level of 1 day residence time with recycling through the reactor. This specific power was lower than that quoted by Sneath *et al.* (1992), who found that the specific power was 17 and 9 $kWh.m^{-3}$ of slurry when the blower was running for 30–60 and 70–100% of time during 2, and 1 day residence treatment times respectively.

Price of electricity varies widely depending on the tariffs and the amount was used. Normally, the cheap rate is 2.6p.kWh^{-1} for the period of 00:30 to 7:30 and 7.0 p.kWh^{-1} for the rest of the day (Pratt, 2000). As it was assumed that the energy consumed was the same in throughout the day. Therefore an average electricity cost per day was calculated to be 5.7 p.kWh^{-1} [(7*2.6p.kWh^{-1} + 17*7p.kWh^{-1})/24].

The cost of treatment per m^3 of slurry was £0.49 (Appendix J Table J11). Williams *et al.* (1989) found a range of £0.7 to £1.40 per pig produced. A complete estimate of the cost of treatment should also include a figure to cover capital depreciation and maintenance. This component of the cost is equivalent to 20 to 30% of the total energy cost (Sneath, 1988). However, the cost of maintenance is dependent on the individual farm.

12.3.1.2 Trial 3

The value of the CODw in the ML was greater than that in the feed slurry from the slurry storage tank. Thus, the use of the daily COD reduction for the calculation of oxygen consumption was not applicable. An alternative calculation method (Appendix J, Table J12) was to estimate the total amount of air entering the reactor vessel, and then to use the result from the SOTE (Chapter 8) to determine the amount of oxygen required for the treatment.

Using Figure 8.1 (oxygen uptake rate, OUR %) (Chapter 8), the oxygen transfer (utilisation) efficiency was estimated to be 25% for an airflow rate of 1.18 $m^3.min^{-1}$. The total mass of oxygen transferred was calculated to be 1980 kg, which was taken up by the biomass in the ML during the treatment of $455m^3$ slurry. This figure was very similar to the oxygen consumption, which was estimated using a different approach (Table 12.3). For example, the difference of 1970 kg between the CODw of the feed slurry and the predicted CODw of the ML was only 0.5% less than the actual one (1980 kg). In fact most of the oxygen would be expected to be consumed in the liquid fraction during the short residence time. Therefore, another approach was used to calculate the difference of supernatant COD from the feed slurry and the ML, and was found to be 2,334 kg (Table 12.3), about 18% greater than the measured value of the CODw (i.e. difference between the feed slurry and the ML). This amount of transferred oxygen required 1690 kWh of aeration energy (Table 12.2). The aeration efficiency was 1.2 kg $O_2.kWh^{-1}$. This figure was about 25% greater than that found in Trial 2. This could be explained by the amount of oxygen consumption being over-estimated, and the energy consumed being reduced, reflecting the more efficient aeration system.

Similarly, the sum of the daily VFA removal between the input slurry and the ML in Trial 3 was found to be 2560 kg over the whole period. The ratio of $kgO_2/kgVFA$ was approximately 0.77, the same as the theoretical oxygen consumption for VFA based on the difference between the feed slurry CODw and the predicted CODw of the ML.

The total energy required to achieve the target level of VFA (500 $mg.l^{-1}$) was 2150 kWh, given that the specific power was 4.7 $kWh.m^{-3}$. This was about 45% less than that found in Trial 2. As in Trial 2, the largest component of the energy consumed was for the slurry recirculation pump (venturi pump), 51%, which was 20% lower than in Trial 2. This difference shows that the energy consumption for aeration was reduced significantly. This was because the recirculation pump ran continuously in Trial 2 while in Trial 3 the recirculation pump ran only when there was a demand for oxygen (see Chapter 7.7 for control system). The blower and recirculation pump together therefore consumed only 79% of the total power consumption for Trial 3, 6 % lower than that in Trial 2. The cost of energy per m^3 of treated slurry was calculated to be £0.27 at this particular treatment condition for Trial 3.

The viability of the control strategy for Trials 1 and 2 has been demonstrated but there clearly remains scope for improvement. This could be achieved by a different approach to controlling the aeration system that would meet the same target criterion (i.e. the target level of VFA 500 $mg.l^{-1}$). Comparing Trials 2 and 3, the energy cost of the aeration was saved up to 45% in Trial 3 with a fixed airflow control as opposed to the Proportional Integrated Derivative (PID) control in Trial 2. The reason for this was that the PID control would probably supply excessive air for the treatment, also the blower became less efficient when it ran at different speeds during treatment (Pratt, 2000). Burton and Sneath (1995) found that a controlled system of variable treatment residence time saved 25% of the energy cost per tonne of pig slurry compared with an un-controlled (fixed residence time) system.

PART D: DISCUSSION AND CONCLUSION

13. GENERAL DISCUSSION AND CONCLUSION

The laboratory experimental studies reported in Chapters 4, 5 and 6 were conducted in order to provide a reliable basis for understanding the changes in slurry characteristics in relation to the oxygen requirement for the design of a full-scale treatment system. The major factors likely to influence treatment are the chemical characteristics of the slurry, and O'Callaghan *et al.* (1971) set out to characterise the treatment properties of waste. They found that the characteristics of livestock wastes were not easily predictable. For example, total solids contents varied from 5.6 to 9.5% (w/v); BOD_5 from 16 to 21 $g.l^{-1}$; and CODw from 44 to 84 $g.l^{-1}$. These factors depended on the feeding regime. Hobbs *et al.* (1997) reported that greater odour concentrations were produced from the slurry of pigs fed a stronger diet (water/dry feed; (3:1)) than from the slurry of pigs fed with a weaker diet (water/dry feed (4:1)).

Before designing a system for livestock slurry treatment, it is important to have a clear vision of the target that the treatment should achieve. Therefore, the experiments described here: anaerobic storage, single stage continuous flow aerobic treatment and continuous flow with recycling aerobic treatment were undertaken to show how certain operating conditions could be applied to reach the specific objective of odour offensiveness removal.

To minimise and prevent environmental pollution of the air, water and soil from modern agricultural practices, methods of slurry treatment and management and various regulations have been introduced (SOAEFD, 1997; MAFF, 1998a & 1998b; MAFF, 1995). There is a requirement stipulated in the PEPFAA Code (SOAEFD, 1997; MAFF, 1998a & 1998b) for farms to have a slurry storage capacity of 6 months in Scotland, and 4 months in England and Wales. Although prolonged storage of slurries is recommended, the anaerobic metabolism of slurry micro-organisms elevates the concentration of malodorous compounds in slurry during this storage period (Spoelstra, 1979; Williams & Evans, 1981; Hashimoto, 1983; Patni & Jui, 1985; Patni & Jui, 1987; Oleszkiewicz, 1986; Hill, 1988; Safley & Westerman, 1992). Thus, the length of the storage period and the storage temperature, can exacerbate the slurry odour, which contravenes the requirement for odour control (MAFF, 1998a).

The results (Chapter 4.3) of cattle (7.5% w/v DM), and pig (8.5% w/v DM), slurry storage experiments were similar, and showed that the rate of odour generation increased, in terms of concentrations of VFA, TOA and TIP, with an increase in both temperature and storage time. The general trends of these odour indicators in both cattle and pig slurry were similar at three temperatures (Chapter 4), increasing from the initial concentrations to a peak level and remaining constant at this level until the end of the storage period. The odour indicators did not increase significantly at a storage temperature of 5 ^{o}C.

At 15 ^{o}C, TIP of both cattle and pig slurry increased, from the initial value to a peak concentration after approximately 15 weeks of storage, from 210 to 300 mg.l^{-1} for cattle slurry, and 70 to 80 mg.l^{-1} for pig slurry. The VFA concentration of cattle and pig slurry increased from 3.9 to 8.9 g.l^{-1} (by 130%) and 8.4 to 20.6 g.l^{-1} (by 145%) after 18 weeks of storage, respectively. The highest VFA generation rates, approximately 0.8 g.l^{-1}.week^{-1} for cattle slurry, and 1 g.l^{-1}.week^{-1} for pig slurry, occurred during the first 10 to 12 weeks of storage. These VFA figures show that although the pig slurry was much stronger than the cattle slurry, and that both of the slurries reached the peak level after a similar storage period. Relating these VFA concentrations to odour, the odour offensiveness rating increased from 6.4 to 7.9 for cattle slurry, and from 7.8 to 9.5 for pig slurry, on the scale defined by equation 2.1 (Chapter 4) (Williams, 1984). Also the ratings of odour offensiveness for both cattle and pig slurry were above the maximum value of the scale "5" when the TOA starting value was applied to equation 10.1 (Chapter 10) (Thacker and Evans 1986). These calculated odour offensiveness ratings (5.5 - 8) were much higher than the maximum rating of 5. This was because the equation for the odour offensiveness rating was only derived for diluted and pre-treated pig slurry. Both raw cattle and pig slurry were used for this anaerobic storage experiment (Chapter 4). They were not diluted and these raw slurries were also very strong initially. Therefore, the indication of odour offensiveness by these equations, 2.1 and 10.1, was not strictly applicable. However, they indicated in general that the odour increased from the level "very strongly offensive" to an even higher level after prolonged storage. Williams (1984) found that pig slurry containing a VFA concentration of greater than 0.7 g.l^{-1}, could confidently be expected to be unacceptably offensive in odour. The odour

offensiveness of both cattle and pig slurry reached their peak levels after about 20 weeks of storage period, which was within the same range as the storage capacity periods (6 months for Scotland , and 4 months for England & Wales) specified by legislation (SOAEFD, 1997; MAFF, 1995). The study of anaerobic storage experiment can thus provide an indication of the level of odour offensiveness expected for a particular period of time during storage at particular concentrations of slurry characteristics.

Continuous aerobic treatment can effectively control slurry odour offensiveness in terms of odorous compound (i.e. VFA, TOA, TIP and BODs) concentration reduction, and also reduce the water pollution parameters (BODw and CODw), as has been demonstrated in this report (Chapters 5, 6, 9, 10 & 11). Concentrations of both VFA and TIP were reduced by more than 95%, while TOA and BODs were reduced by approximately 80% under a continuous steady state process consisting of two passes through a single-stage reactor at 15 °C with maintained minimal aeration. Similar findings for pig slurry have also been reported elsewhere (Thacker & Evans, 1986; Williams *et al.*, 1989; Sneath *et al.*, 1992; Svoboda & Sym, 1997; Burton & Sneath, 1995; Burton *et al.*, 1998; Burton & Farrent, 1998).

The degree of correlation between a theoretical model (Evans *et al.*, 1983), and the laboratory experimental data, for pig slurry (Chapter 5) was found to be in good agreement in terms of TS, TSS and CODw at 15 °C, with a 1 day residence time. The treatment system comprised a steady state process with two passes through a single stage reactor, therefore the slurry was actually treated twice over (i.e. Treatments 1 and 2) as described in Chapter 5. The percentage differences between the predicted (i.e. by the model of Evans *et al.*, 1983) and the actual observed mean value of TS, TSS and CODw of pig and cattle slurry in Treatments 1 and 2 are shown in Table 13.1. Although these models were initially derived for pig slurry, they have also been found to fit well for TS, TSS and CODw of cattle slurry.

Table 13.1. Values of predicted TS, TSS and CODw of pig and cattle slurry in Treatment 1 and 2 (at 15°C and 1 day residence time) compared with observed values.

	Pig slurry		Cattle slurry	
Parameter	Treatment 1	Treatment 2	Treatment 1	Treatment 2
	%	%	%	%
TS	0	-1	-2	2
TSS	-1	-2	14	-14
CODw	-1	4	-1	6

In effect, the overall treatment residence time should be considered as being effectively 2 days, because the slurry was treated twice over, each pass with a 1 day residence time (i.e. "1+1" day residence time for two passes). As a result, the percentage difference between the predicted and the final observed values (after Treatments 1 and 2) of TS, TSS, CODw, and BOD_5w were -4, 2, -2, and -20% for pig slurry and -3, 11, -4 and -63% for cattle slurry respectively. These results show that the predicted values were also in good agreement with the mathematical models derived from Evans *et al.* (1983) for a 2 day residence time. These predicted values were also close to the observed values (Chapter 5). This demonstrates no great difference between the two process configurations (i.e. 2 day and "1+1" day residence time). The treated ML was thus actually only affected by the overall treatment residence time, and not by the process configuration. The reduction of predicted BOD_5w of both pig and cattle slurry was much greater than the observed value (Tables 5.8 and 5.13). This could be explained if the predicted BOD_5w was mainly affected by the residence time for such a low concentration BOD of feed slurry as was used, when applying equation 2.5. Evans *et al.* (1979) found that the observed BOD was 147% greater than the predicted value for a 1 day residence time and 15 °C.

Predicted and observed CODw values of pig and cattle slurry were very close, with the CODw concentration reduction being an indication of the overall oxygen consumption by the treatment. From this, the oxygen requirement for a large-scale treatment process could be estimated more confidently for given particular slurry characteristics, with a given residence time and a temperature range. For instance, the amount of oxygen consumed was estimated to be 4.9 kg $O_2.m^{-3}$ for cattle slurry with 2.25% TS (w/v), and 6 kg $O_2.m^{-3}$ for pig slurry with 2.6% TS (w/v) with two passes

through a single-stage treatments of 1 day residence time each at 15°C (Chapter 5). These observed figures were only 5% different from the model predicted values. However, the solids concentration changed little due to the use of such a short residence time and minimal aeration. Also, nitrification did not occur during treatment, although some losses of ammoniacal-nitrogen were observed by stripping, as by 30 and 18% for Treatments 1 and 2 of pig slurry respectively, and 25 and 18% for Treatments 1 and 2 of cattle slurry respectively. Similar findings that little nitrogen loss occurred at short residence times (less than 3 days)– a fact also observed by Evans *et al.* (1985 & 1986) and Burton & Farrent (1998)), and at very low aeration levels (Sneath, 1988).

The stability of treated slurry, in terms of the levels of odorous compounds developed during a subsequent period of anaerobic storage, increased with either residence time (i.e. 1 and 2 day) or with overall treatment period as demonstrated here (Chapters 5, 9, 10 and 11). Although the odour was reduced to an acceptable level (below 230 $mg.l^{-1}$ of VFA) by the treatment (Chapter 5), it started to become offensive (above 230 $mg.l^{-1}$ VFA) after 10 days for cattle slurry, and after 15 days for pig slurry during a subsequent period of anaerobic storage. This indicates that pig slurry is stronger (greater concentration of organic matter) than cattle slurry in general, although the rate of regeneration of VFA was also proportional to the solids concentration in either pig or cattle slurry.

The original proposal for this project was to design a treatment system to cope with continuous slurry production and the inevitable variation in feed composition. This is often to be expected to be the case for real treatment practices on the farm. The process of laboratory Study 1, as described in Chapter 5, required a higher capital cost because a larger foot print area and additional equipment, such as an extra storage tank, were required for the treatment plant. Therefore, another laboratory experiment (Study 2, Chapter 6) was set up and the process configuration of laboratory Study 1 (Chapter 5) was modified to include recycling. This process is another option for continuous aeration, but without intermittent storage. The effect of this treatment process on odour level, as indicated by the VFA concentration of the feed slurry, was to cause a slow decrease with time in the feed storage tank during treatment. Although the concentration of VFA in the ML, between 10 and 180 $mg.l^{-1}$, indicated

that the odour offensiveness was reduced to below the acceptable level (230 $mg.l^{-1}$ of VFA) after treatment, the generation of odorous compounds in the feed slurry in the storage tank was still significant after mixing the treated ML with the partially untreated slurry (see results and discussion of Chapter 6). In this case, the concentration of the feed slurry into the reactor vessel was varying (decreasing continuously) and causing the microbial activity to be in an unstable state of flux in response to the changing availability concentration of substrate (Williams, 1981; Williams *et al.,* 1984). Over the course of the experiment, the VFA concentration in the feed slurry only decreased from 3.25 to 1.3 $g.l^{-1}$, indicating a decrease in odour offensiveness rating from 5.9 to 4.4, i.e. "very strongly offensive" to "strongly offensive", by equation 2.1 (Chapter 2). The concentration of VFA in the feed storage tank remained high after treatment. This was could be due to a number of reasons:- (1) The feed slurry was stored under anaerobic conditions, hence anaerobic microbial activity in the feed slurry regenerated a large VFA concentration; (2) The actual net daily degradation by the aerobic treatment was only slightly greater than the VFA regenerated by anaerobic microbial activity; (3) The daily addition of treated slurry, a volume of approximately 1 litre, was relatively insignificant when compared with the volume (approximately 45 litres) of the feed slurry storage tank. (4) A low residence time (1 day) was being used for such a concentrated slurry (3% TS (w/v)). Inadequate mixing also occurred in the slurry storage tank, and this was one of the major problems with this recycling process (as described in Chapter 6). Although mixing was not adequate for this type of process in laboratory Study 2, this is often also the case in the farm practice. Therefore, to make a treatment system work effectively, an additional energy input to ensure adequate mixing is required, although there is then an increase in the operating cost of the treatment process.

In practice, it can be difficult to supply the optimal amount of oxygen to a continually changing aerobic culture environment, unlike a steady state process (experience of which was gained from Study 1 (Chapter 5)) where a constant oxygen supply was matched with a constant supply of substrate. Oxygen uptake is thus more efficient in a continuous steady state process. The variation in the feed slurry composition to be expected on many farms can be reduced by good mixing of the total contents of the slurry in the storage tank, and by keeping the temperature low to limit the activity of the anaerobic microbial population, mainly by acetogenic bacteria. In reality, there is

an advantage in increasing the methanogenic bacterial activity during anaerobic storage. Methanogenic bacteria can reduce the organic acid concentration by converting them into methane and carbon dioxide (Loehr, 1984). The results of the anaerobic storage experiment (Chapter 4) proved that the regeneration of VFA was a function both of time and temperature during slurry storage period.

The oxygen requirement for the farm scale treatment system was estimated and based on the laboratory experimental findings (Chapter 5), along with the mathematical model prediction. The method of introducing air into the system greatly affects the quantity of oxygen transferred into the mixed liquor within the reactor. The large amount of energy consumed selects against certain types of aeration devices being employed on individual working farms. Unlike in the sewage treatment industry, the choice of aeration devices suitable for use in the agricultural sector is more limited. The selection of an aerator is difficult, since it requires an understanding of the characteristics of the slurry (Chapter 2.2) to be treated in order to:- a) reduce the possibility of mechanical problems with the aerator and the dynamics of the slurry; b) maintain a constant mixing and to prevent settling. A venturi aerator was chosen for this farm scale treatment study. It was chosen because of its ease of handling and maintenance, with good mixing characteristics and high oxygen transfer efficiency (as described in Chapters 2.5 and 7), as compared to other types of aerator (such as fine bubble diffusers or mechanical surface aerators).

From the investigations of the venturi aeration system in the farm scale treatment Trials 1, 2 and 3 (Chapters 9, 10 and 11), odour offensiveness, as indicated by odorous compound concentrations, was also found to be reduced significantly after treatment. The treatment conditions of these trials was with a 1 day residence time, at an average of 15 ^{o}C and with low redox control (approximately –150 mVE_{cal}) similar to the laboratory treatment. The odour indicators of the feed slurry in terms of VFA, TOA and TIP were decreased logarithmically with time during treatment. Attainment of the target VFA level (500 $mg.l^{-1}$), indicates that an acceptably low level of odour offensiveness of the feed slurry was reached after only two passes (two cycles) through the aeration vessel. This meant that the target VFA level was achieved readily by a treatment with a two passes a single stage process.

As expected, the pattern of change in odorous indicators (VFA, TOA, TIP, BOD_5s) and the supernatant COD concentration of the feed slurry during farm scale treatments (i.e. Trials 1, 2 and 3) were similar to the laboratory findings for cattle slurry (Chapter 6). This shows that the trends for odorous compounds in pig and cattle slurries had closely associated characteristics and relationships under similar treatment process configurations. Although all of these parameters could act as good indicators of odour offensiveness, Williams (1984) & Thacker & Evans (1986) found that the BOD_5s was the best overall indicator of odour offensiveness. The similarity trends in these odorous indicators show that the treatment occurred in, and affected mainly the liquid fraction (soluble material) of the slurry, rather than the whole slurry. This can be mostly attributed to the short residence time, low temperature and the minimal aeration regime. Therefore, the biological oxidation was dominant in the soluble carbonaceous compounds mainly. The pH values of ML and feed slurry were greater than 7 indicating that low acid concentrations were present, whilst the nitrogen content was conserved as a result of the low level of dissolved oxygen maintained.

There was a problem with mixing the feed slurry in the storage tank during the laboratory trials, mainly in Study 2 with the cattle slurry (Chapter 6). Inadequate mixing was likely due to the less suitable mixing apparatus available here for such a relatively high solids concentration. This problem unfortunately led to inadequate odour control, because of the formation of dead zones which were never treated, and resulted in increased regeneration of odour by anaerobic degradation of the slurry within the feed slurry storage tank. The mixing problem was also suspected in the farm scale treatment system; The CODw, Kj-N and solids concentrations were higher in the reactor vessel than those in the slurry storage tank, although the supernatant concentrations of these samples remained as expected. This could be due to a number of reasons:

1) More solids may have been pumped into the reactor, since slurry was pumped from the bottom of the storage tank where higher concentrations of solids may have settled.
2) Samples for analysis were taken with a bucket from the top part of the storage tank where a lower concentration of solids may have been present.

3) The whole reactor volume could be high in suspended matter i.e. TSS and VSS, due to the input slurry being fed from the bottom of the storage tank, and these solids could have been broken down by high shear forces when they circulated through the venturi.
4) Mixing in the reactor may not have been adequate, more solids may have been deposited at the bottom part of the reactor, or slurry may have been recirculating radially in the same region all the time due to localised effects of the high injecting force from the venturi aerator.
5) Solids may have accumulated after each trial, due to the ML not being completely discharged.

Burton & Farrent (1998) also found that the suspended solid particles settled out preferentially due to relatively low levels of mixing (per unit volume) in a long treatment residence time reactor (5000 litres) pilot plant causing erroneous results for TKN, CODw, and TS, VSS and TSS. Hence, the accuracy of experimental results in this farm-scale treatment plant could be improved by: (a) a better design of mixing mechanism in the feed slurry storage tank; (b) slurry for analyses should be sampled from the discharge and filling slurry pipeline.

Low concentrations of VFA were regenerated in both the feed slurry and ML after aerobic treatment when they were subsequently stored anaerobically for 10 or 20 days at 10 °C after farm scale treatment Trials 2 and 3 (Chapters 10 and 11). Only a small VFA increase was measured because very diluted pig slurry, less than 1% TS (w/v), was used and therefore less substrate was initially available for VFA production. Williams *et al.* (1984) found that diluted pig slurries with less than 1.5 %TS were stable for at least a year after aerobic treatment, while slurries with 3 to 4.5% TS were stable for 10 to 75 days after the same period of aeration. Also, the activity of the VFA-producing microbial population was restricted at low temperatures. However, VFA levels in slurries stored for 20 days were slightly greater than in those stored for 10 days in both the feed slurry and the ML for every sampling day throughout the trial. On farms where aerobically-treated slurries must be stored for a long period without odour nuisance regeneration, there is thus a requirement for a low solids concentration and a low temperature.

A major concern of this project was to design a high performance aeration system for odour removal. The resulting improvement in treated slurry characteristics, as discussed previously (Chapters 5, 6, 9, 10 and 11) clearly showed that continuous aerobic treatment performed well in terms of odorous compound reduction. However, aerobic treatment requires an input of high-grade energy and is consequently expensive to operate. The operation cost was mainly attributed to the energy used for aeration. The biggest component of the total energy consumption was the venturi pump and a blower, together requiring approximately 84 and 79% of the total electrical power required in Trials 2 and 3 respectively. This value was similar to the findings of Sneath *et al.* (1992), who quotes approximately 90% of total power consumption being required for aeration. The oxygen transfer and aeration efficiency of the farm scale treatment were 30% and 0.96 kg $O_2.kWh^{-1}$ for Trial 2; and 25% and 1.2 kg $O_2.kWh^{-1}$ for Trial 3 respectively. These findings compare well with the standard SOTE test (Chapter 8) as well as with Allen (1996), who found that the oxygen transfer and aeration efficiency were 26–35% and 0.74–1.0 kg $O_2.kWh^{-1}$ respectively. The daily energy consumption declined with an increase in treatment duration, due to the continuously decreasing oxygen demand of the input slurry in the recycling process configuration. However, energy consumption during Trial 2 (3940 kWh for 49 days treatment) was around 45% greater than in Trial 3 (2150 kWh for 37 days treatment) to achieve the same target VFA level (500 $mg.l^{-1}$). This comparison is very difficult to explain since the energy consumption varied with the concentration of the feed raw slurry (10.1 g TS $.l^{-1}$ and 12.1 g CODw $.l^{-1}$ in Trial 2, and 9.6 g TS $.l^{-1}$ and 13.2 g CODw $.l^{-1}$ for Trial 3).

The power consumption can be reduced by optimising the aeration control strategy (i.e. PID used for Trial 2 and fixed airflow rate used for Trial 3) as described in Chapter 7. The specific powers of Trials 2 and 3 in the reactor were 2.1 and 1.1 $kWh.m^{-3}$, respectively. It was assumed that the energy consumed was constant throughout the day and the average electricity cost was found to be 5.7 $p.kWh^{-1}$. The cost of treatment (only running energy costs) per m^3 of slurry (i.e. feed slurry was treated to reach the target VFA level 500 $mg.l^{-1}$) in Trial 2 and 3, was thus calculated to be £0.49 per m^3 and £0.27 per m^3 respectively.

In the present farm scale trials, there were two different ways used to automate control the aeration system, as described in Chapter 7. Firstly, the strategy of Proportional Integrated Derivatives (PID) control was chosen in the first two trials, because it should have given a much more accurate and stable control of the DO level and therefore the greatest level of treatment possible. Unfortunately, it was not possible to optimise the settings to cope with the delay in response of redox to aeration. No airflow occurred until the speed of the compressor reached 715 rpm. Although it would be possible to develop a control system to avoid this problem, additional costs would be required. The fact that the compressor ran at variable speed, meant that it was rarely operating at its most efficient level. Therefore, the energy of aeration cost per m^3 of air would have been greater than if a more appropriately sized fixed compressor had been available. Hence, the control of the aeration for Trial 3 was optimised by experiences from Trial 2. Therefore the aeration control system for Trial 3 used a fixed speed compressor operation, which had a number of advantages:

1) more efficient operating point for the compressor;
2) simpler control;
3) lower capital cost – no inverter drive involved;
4) lower aeration energy consumption – less running time of the compressor and venturi pump.

Against the advantages stated above is the fact that the DO level could be expected to vary more widely giving reduced oxygen transfer rates at the higher DO levels thus counteracting the increased efficiency of running the compressor at a more efficient speed level. Also the effect on the activity of the microbial population could have been negative due to the more widely varying oxygen levels in the mixed liquor. The latter does not appear to have been true because a high level of treatment was achieved, as shown by the results for the treated slurry. Certainly, optimal control of the aeration process can be used to reduce the inefficiency in energy usage. However, complete optimisation would involve ensuring that the effect of the interactions between the process and the biochemical characteristics of the slurry were also minimised. These farm-scale trials demonstrated that energy saving could be increased by optimising the control of the aeration, although the saving would also be

dependent on the initial concentration of the raw feed slurry if all of the slurry has to be treated to meet the treatment criterion of a target VFA level of 500 $mg.l^{-1}$. Two aeration strategies of PID and fixed airflow rate controls were carried out using similar starting concentrations of pig slurry. An energy cost saving of approximately 45% was achieved with a fixed airflow control system compared with the PID system using varying airflow rates.

Finally, the increased demand for long term storage of slurries as required by new legislation and regulations can be met by continuous aerobic treatment with recycling. It would be a good option for controlling the odour offensiveness of slurry. Although this process requires frequent supervision of the reactor vessel, pumps, timers and frequent analysis of the treated slurry effluent, livestock slurries can be effectively treated continuously once passed through a reactor vessel with an established stable microbial population. Therefore, the storage time of these treated slurries can be increased while keeping the smell "sweet" before spreading on the land. Besides, the quantity pathogen were decreased by reducing of the substrate after treatment, so that the risk of spread of diseases could be reduced when the treated slurry disposed on the land field.

13.1. Recommendations for further work

It is believed that this study presents sufficient evidence to support the scope of work and consequently the promotion of the proposed process with slurry recycling and continuous minimal aeration treatment for odour removal. However, in order to improve the performance of the treatment plant, the following recommendations and suggestions need to be considered in further research:

1. The effect of mixing on the solids characteristics in the reactor vessel should be studied by sampling at various positions and depths in the reactor vessel.

2. Improvement of the aeration control system by adding an additional redox probe at another depth in the reactor vessel, and using the average value from these redox values as a control point.

3. Trials with higher solids concentration of pig and cattle slurry, in order to extend the odour offensiveness and the slurry characteristics data in general.

4. Improvement in the experimental data accuracy by taking more frequent samples at different points of the pipeline.

5. From the experience gained by this study, it was found that the blower was oversized for all the experiments. Another more suitably sized blower (for similar of diluted slurries) should replace the existing one, thus improving the capital and energy costs.

6. Perform different aeration systems (fine bubble aeration and vertical venturi injection) studies and using in similar slurry characteristics to investigate on the aspect and efficiency of odour removal.

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Appendices

Appendix A A1 Slurry production from the average farm size of 200 sows.

A2 Volume of slurry from cattle (100 dairy) and pig (200 sows) farm.

A3 Volatile compound identified as being associated with fresh and decomposing swine wastes.

Appendix B Analytical data of anaerobic storage experiment
Cattle slurry data: Tables B1-B7.
Pig slurry data: Table B8-B14.

Appendix C Analytical data of laboratory Study 1
Cattle slurry data: Tables C1-C18.
Pig slurry data: Tables C19-C36.

Appendix D Analytical data of laboratory Study 2.

Appendix E Design of full scale reactor.

Appendix F Figures of log dissolved oxygen deficit (Cs-C) against time with airflow rates in water and pig slurry.

Appendix G Analytical data of farm scale treatment Trial 1.

Appendix H Analytical data of farm scale treatment Trial 2.

Appendix I Analytical data of farm scale treatment Trial 3.

Appendix J Capital and operating cost
Table J1 Total capital purchase cost
Tables J2-J13 Estimate of energy and oxygen requirement for Trials 2 and 3.

Appendix A1

Slurry production from the average farm size of 200 sows

Housing required /Sow

Farrowing	0.18
Dry sow	0.904
Boar	0.051
Weaner (14 kg)	1.72
Grower (36kg)	2.72
Finisher (100kg)	6.01

Average farm size 200 sows
Therefore

	place/sow		for 200sows
Farrowing	0.18	*200	---> 36
Dry sow	0.904		--> 181
Boar	0.051		--> 10.2
Weaner (14 kg)	1.72		--> 344
Grower (36kg)	2.72		--> 544
Finisher (100kg)	6.01		--> 1202

Daily slurry Production

	litre/day/sow	Total
Farrowing	14.9*36	=536.4
Dry sow	4.0*181	=724
Boars	4.0*10.2	=40.8
Weaners	2.0*344	=688
Grower	3.0*544	=1632
Finisher	4.5*1202	=7041
	Total	= 10662.2 litre.d^{-1}
		= 10.6 $m^3.d^{-1}$

Appendix A1 (*continuous*)

Washing water

Assumed that 3 pans takes 18 litres of water to cleaned out

18 litre /10 pigs

Farrowing

52 woals - each pan washed out after 4 woals

52/4*36 = 468/3 =156 litres

Dry sows

each sow moves 2.2 turns to the farrowing house

therefore 2.2 washing / sow each year

200 sows *2.2 =440/10 *18 =792 litres

Boars

Weaners

Cleaned out at 4 woals

52/4 *304 =3952/10 *18 =7113 litres

Grower

Cleaned out after 7 woals

52/7 *480 =3566/10 *18 =6149 litres

Finisher

Cleaned out after 14 woals

52/14 *1064 =3952/10 *18 =7114 litres

Total wash water =21324 litres.d^{-1}
=21 $m^3.d^{-1}$

Appendix A2

Volumes of slurry from cattle (100 dairy) and pig (200 sows) farm.

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)			
SEMI-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	1460

Outside silage clamp $1000m^3$ (area of 18m x 30m, annual rainfall 1m, winter collection 70% of annual) 540

TOTAL ANNUAL **$3294m^3$**

Slurry spreading	Jan, Feb	silage, grazing
	May, June	silage - first cut
	Mid July	silage - second cut

Slurry accumulation

August till October (Dry cattle outside)	15% of 100x0.052x3x30	$70m^3$
November till January	100x0.052x30x3	468
	30x0.035x30x3	95
Wash water	100x0.04x30x3	360
Rain	18x30x0.5	270

TOTAL **$1193m^3$**

This is 3 months storage (90 days)

PIGS

Unit with 200 sows

The estimate will be based on the three piggeries with smaller nos. of sows.

1. 22 sows; 10 + 12 dry

Farm has 120 places i.e. 120 weaners, 120 growers, 120 fatteners

For 200 sows
200/22x360=3270

2. 30 sows
6 farrowing/month=48pigs/month
Altogether 520 places
For 200 sows
200/30x520=3400

SIGNET calculations
30 sows would produce 679 pigs per year
for 200 sows
200/30x676=4500

3. Production of 60 sow unit is $1m^3$ of FYM per day
Need to provide 3x280 places = 840 places
For 200 sows
200/60x840=2800

4. For 90 sows there is a requirement for 3x 500 places = 1500 places
For 200 sows
200/90x1500=3300

200 sows
Total 17200/5=3400 places
3400/3=1100 weaners, 1100 growing pigs, 1100 fatteners

For 1100 litter with 8 litter for a sow, there will be 138 sows with litter at any one time.

Production of slurry (all animals on slurry)

138 sows and litter		@14.9L.d^{-1*}	2.06m^3 d^{-1}
64 dry sows		@4 L.d^{-1*}	FYM
1100 weaners	up to 40kg	@2 L.d^{-1++}	2.2m^3 d^{-1}
1100 growers	20-40kg	@3L.d^{-1++}	3.3m^3 d^{-1}
1100 fatteners	40 - 100kg	@4.5 L.d^{-1++}	4.95m^3 d^{-1}
Total	**(approx.10%DM)**		**12.51m^3.d^{-1}**

Note: (*) data from PEPFAA code (SOAEFD, 1997),

(++) data from (MAFF, 1998b)

Appendix A3

Volatile compound identified as being associated with fresh and decomposing swine wastes (Ritter, 1989).

Methanol	Methanal	
Ethanol	Ethanal	Ammonia
1-Propanol	Propanal	Methylamine
2-Propanol	Butanal	Ethylamine
1-Butanol	Pentanal	Trimethylamine
2-Butanol	Hexanal	Triethylamine
2-Methyl-1-Propanol	Heptanal	
3-Methyl-1-butanol	Octanal	
2-Ethoxy-1-Propanol	Decanal	
2-Methyl-2-pentanol	2-Methyl-1-propanal	
2,3-Butanediol	Ethylacetate	
	Methanoic acid	Carbonylsulphide
	Ethanoic acid	Hydrogen sulphide
3-Hydroxy-2-butanone	Propanoic acid	Methanethiol
Propanone	Butanoic acid	Dimethylsulphide
2-Butanone	2-Methylpropanoic acid	Dimethyldisulphide
3-Pentanone	Pentanoic acid	Diethyltrisulphide
Cyclopentanone	3-Methylbutanoic acid	Propanethiol
1-Octanone	Hexanoic acid	Butanethiol
2,3-Butanidione	4-Methylpentanoic acid	Dipropldisulphide
	Heptanoic acid	2-Methylthiophene
	Octanoic acid	Propylprop-1-enyldisulphide
Phenol	Nonanoic acid	2,4-Dimethylthiophene
4-Methylphenol	Phenylacetic acid	2-Methylfuran
4-Ethylphenol	2-Phenylpropanoic acid	
Toluene		
Xylene		
Indone		
Benzaldehyde		
Benzoic acid		
Methylphthalene		
Indole		
Skatole		
Acetophenone		
o-Aminoacetophenone		
Aneline		

Table B1. Analytical data of ammoniacal nitrogen, COD whole, Supernatant COD and pH in cattle slurry

Date	NH_4^+-N ($mg.l^{-1}$)			COD Whole ($g.l^{-1}$)			COD Supernatant ($g.l^{-1}$)			pH		
	5°C	10°C	15°C	5°C	10°C	15°C	5°C	10°C	15°C	5°C	10°C	15°C
23/02/1998	3003	3003	3003	92	92	92	34.3	34.3	34.3	8.8	8.8	8.8
16/03/1998	3010	3080	3570	82.7	86.7	91.4	39.2	39	38	8.8	8.7	8.5
07/04/1998	3650	3430	3460	94.1	86.6	80.8	35.1	33.3	33.1	8.7	8.6	8.4
28/04/1998	3220	3514	3619	94.2	99.3	96	37.4	38.5	36.3	8.6	8.4	8.3
18/05/1998	3510	3110	3440	125	132	106.3	40.2	41.2	36.5	8.6	8.4	8.3
08/06/1998	3020	3000	3280	88	97.6	93.8	41.5	38.7	38.7	8.5	8.3	8.1
29/06/1998	3050	3200	3340	90	93	93.2	39	40	38	8.5	8.3	8.0
21/07/1998	3730	3200	3490	97.8	105.2	101.3	40.4	38.9	35.7	8.5	8.2	8.0
10/08/1998	3402	3080	3950	99	90.4	104.9	40.1	36	35.2	8.5	8.3	8.0
31/08/1998	3600	3550	4020	117	110	110	41.5	39.6	37.4	8.5	8.4	8.2

Table B2. Analytical data of individual VFA at 5°C in cattle slurry

Date	Acetic $mg.l^{-1}$	Propionic $mg.l^{-1}$	I-Butyric $mg.l^{-1}$	N-Butyric $mg.l^{-1}$	I-Valeric $mg.l^{-1}$	N-Valeric $mg.l^{-1}$	Total VFA $g.l^{-1}$
23/02/1998	3149	388	51	237	59	43	3.93
16/03/1998	3019	207	63	99	54	18	3.46
06/04/1998	4094	366	81	136	60	25	4.76
27/04/1998	5433	615	121	311	104	51	6.63
18/05/1998	7532	814	137	303	102	34	8.92
08/06/1998	5210	613	122	258	84	33	6.32
29/06/1998	5586	654	108	272	89	31	6.74
21/07/1998	5958	793	128	336	111	44	7.37
10/08/1998	5968	683	115	241	90	31	7.13
31/08/1998	5915	687	114	246	94	28	7.08

Table B3. Analytical data of individual VFA at 10°C in cattle slurry

Date	Acetic $mg.l^{-1}$	Propionic $mg.l^{-1}$	I-Butyric $mg.l^{-1}$	N-Butyric $mg.l^{-1}$	I-Valeric $mg.l^{-1}$	N-Valeric $mg.l^{-1}$	Total VFA $g.l^{-1}$
23/02/1998	3149	388	51	237	59	43	3.93
16/03/1998	3273	269	69	90	57	15	3.77
06/04/1998	4918	422	83	135	66	17	5.64
27/04/1998	5773	645	119	281	96	39	6.95
18/05/1998	5799	654	124	295	102	31	7
08/06/1998	5879	643	134	294	89	32	7.07
29/06/1998	5669	680	111	319	89	40	6.91
21/07/1998	6789	825	127	385	106	34	8.27
10/08/1998	3308	471	91	205	62	22	4.16
31/08/1998	6888	798	121	332	99	34	8.27

Table B4. Anayltical data of individual VFA at 15°C in cattle slurry

Date	Acetic $mg.l^{-1}$	Propionic $mg.l^{-1}$	I-Butyric $mg.l^{-1}$	N-Butyric $mg.l^{-1}$	I-Valeric $mg.l^{-1}$	N-Valeric $mg.l^{-1}$	Total VFA $g.l^{-1}$
23/02/1998	3149	388	51	237	59	43	3.93
16/03/1998	4868	400	108	129	59	17	5.58
06/04/1998	4348	447	87	146	75	18	5.12
27/04/1998	6754	778	124	340	97	47	8.14
18/05/1998	7612	954	152	470	114	62	9.36
08/06/1998	6874	812	120	342	93	31	8.27
29/06/1998	7373	910	126	339	96	50	8.89
21/07/1998	6344	878	126	354	105	38	7.48
10/08/1998	4905	484	137	308	120	41	6.29
31/08/1998	7411	916	127	338	106	37	8.94

Table B5. Analytical data of individual indoles and phenols at 5°C in cattle slurry

Date	Phenol $mg.l^{-1}$	P-cresol $mg.l^{-1}$	O-ethyl-phenol $mg.l^{-1}$	Indole $mg.l^{-1}$	Skatole $mg.l^{-1}$	TIP $mg.l^{-1}$
23/02/1998	10.73	191.7	3.8	1.4	0	207.6
16/03/1998	31.5	233.5	4.8	2.8	0.0	272.6
06/04/1998	33.7	236.6	4.7	2.9	0	277.9
27/04/1998	51.1	227.7	4.9	3	0	286.7
18/05/1998	62.8	216.7	4.8	2.8	0	287.1
08/06/1998	61.9	203.9	5	2.9	0	273.7
29/06/1998	64.2	233	5	2.4	0.9	305.5
21/07/1998	64.1	232	4.9	2.3	0	303.3
10/08/1998	66.6	227.3	5.1	2.6	0	301.6
31/08/1998	55.1	189	4.1	1.58	0	249.78

Table B6. Analytical data of individual indoles and phenols at 10°C in cattle slurry

Date	Phenol $mg.l^{-1}$	P-cresol $mg.l^{-1}$	O-ethyl-phenol $mg.l^{-1}$	Indole $mg.l^{-1}$	Skatole $mg.l^{-1}$	TIP $mg.l^{-1}$
23/02/1998	10.73	191.7	3.8	1.4	0	207.6
16/03/1998	39.8	233.9	5	2.9	0	281.6
06/04/1998	60.5	230.9	4.6	2.7	0	298.7
27/04/1998	63.6	231.9	5	2.7	0	303.2
18/05/1998	54.8	224.1	4.7	0.6	1	285.2
08/06/1998	63.5	201	4.8	1.3	0	270.6
29/06/1998	60	231.7	4.9	0.9	0.7	298.2
21/07/1998	65.3	233.3	4.8	1.1	3.7	308.2
10/08/1998	104.2	198.4	4.5	0.9	4	312
31/08/1998	54.1	193.9	3.8	0.8	3.2	255.8

Table B7. Analytical data of individual indoles and phenols at 15°C in cattle slurry

Date	Phenol $mg.l^{-1}$	P-cresol $mg.l^{-1}$	O-ethyl-phenol $mg.l^{-1}$	Indole $mg.l^{-1}$	Skatole $mg.l^{-1}$	TIP $mg.l^{-1}$
23/02/1998	10.73	191.7	3.8	1.4	0	207.63
16/03/1998	62.3	232.4	4.7	3.2	0	302.6
06/04/1998	63.2	233.8	4.6	1.3	0	302.9
27/04/1998	65.9	232	4.9	0.7	3.1	306.6
18/05/1998	66.9	219.4	4.6	0.6	1.9	293.4
08/06/1998	66.8	200.2	4.8	0.7	1.2	273.7
29/06/1998	70.4	239.9	4.9	0	3.6	318.8
21/07/1998	66.3	229.3	4.7	0	0	300.3
10/08/1998	79.7	225	4.8	0	1	310.5
31/08/1998	53	189.8	3.7	0	1.9	248.4

Table B8. Analytical data of ammoniacal nitrogen,COD whole, Supernatant COD and pH in pig slurry.

Date	NH_4^+-N ($mg.l^{-1}$)			COD Whole ($g.l^{-1}$)			COD Supernatant ($g.l^{-1}$)			pH		
	5°C	10°C	15°C	5°C	10°C	15°C	5°C	10°C	15°C	5°C	10°C	15°C
23/02/1998	2650	2650	2650	117	117	117	19	19	19	6.8	6.8	6.8
16/03/1998	2520	2730	2800	118.3	115.6	107.1	22.9	25.4	27.7	6.8	6.7	6.6
07/04/1998	3220	2880	2880	109.6	101.5	104.9	23	24.2	25.4	6.7	6.6	6.6
28/04/1998	2786	2709	2828	106.7	107.2	115	26.2	25.4	33.1	6.7	6.6	6.5
18/05/1998	2940	3070	3190	113.1	150.4	114.3	31.2	28.1	33.7	6.7	6.8	6.7
08/06/1998	2810	2720	3070	117.5	113.4	128.2	30.7	28.9	34.6	6.6	6.9	6.5
29/06/1998	2910	2500	2700	126	107	117	32	28	34	6.6	7.0	6.5
21/07/1998	2670	2850	3170	117.6	105.6	119.6	30.1	25.8	34	6.6	7.0	6.5
10/08/1998	2912	2760	3045	119	105.6	116.4	32.4	24.7	33.7	6.6	7.3	6.5
31/08/1998	3080	2930	3560	128	114	132	30.6	27.9	36.2	6.8	7.4	6.9

Table B9. Analytical data of individual VFA at 5°C in pig slurry

Date	Acetic $mg.l^{-1}$	Propionic $mg.l^{-1}$	I-Butyric $mg.l^{-1}$	N-Butyric $mg.l^{-1}$	I-Valeric $mg.l^{-1}$	N-Valeric $mg.l^{-1}$	Total VFA $g.l^{-1}$
23/02/1998	5273	1652	214	873	252	146	8.14
16/03/1998	5753	1952	262	936	251	140	9.29
06/04/1998	6532	2476	274	1074	295	149	10.8
27/04/1998	8859	3394	398	1566	354	232	14.8
18/05/1998	10268	4653	650	2199	482	286	18.54
08/06/1998	9907	4245	445	1868	420	236	17.12
29/06/1998	8811	3975	413	1801	407	228	15.63
21/07/1998	9580	4442	469	2048	467	235	17.24
10/08/1998	9622	4612	469	2184	479	250	17.62
31/08/1998	9377	4063	405	1856	420	218	16.34

Table B10. Analytical data of individual VFA at 10°C in pig slurry

Date	Acetic $mg.l^{-1}$	Propionic $mg.l^{-1}$	I-Butyric $mg.l^{-1}$	N-Butyric $mg.l^{-1}$	I-Valeric $mg.l^{-1}$	N-Valeric $mg.l^{-1}$	Total VFA $g.l^{-1}$
23/02/1998	5273	1652	214	873	252	146	8.14
16/03/1998	6383	2579	289	1321	313	176	11.06
06/04/1998	7470	3156	322	1354	326	184	12.81
27/04/1998	9150	4581	502	2200	480	286	17.2
18/05/1998	8575	3825	408	1861	379	234	15.28
08/06/1998	10785	5516	735	3050	558	267	20.91
29/06/1998	7524	3393	530	1783	408	233	13.87
21/07/1998	4900	2357	341	1322	321	150	9.39
10/08/1998	4517	2215	255	1045	236	135	8.4
31/08/1998	8967	3830	520	2227	523	277	16.35

Table B11. Analytical data of individual VFA at 15°C in pig slurry

Date	Acetic $mg.l^{-1}$	Propionic $mg.l^{-1}$	I-Butyric $mg.l^{-1}$	N-Butyric $mg.l^{-1}$	I-Valeric $mg.l^{-1}$	N-Valeric $mg.l^{-1}$	Total VFA $g.l^{-1}$
23/02/1998	5273	1652	214	873	252	146	8.14
16/03/1998	6313	2764	297	1251	312	173	11.11
06/04/1998	8252	3182	340	1324	305	150	13.55
27/04/1998	9447	5088	606	2691	543	281	18.66
18/05/1998	9151	4398	629	2380	469	243	17.27
08/06/1998	7083	3354	426	1827	374	232	13.3
29/06/1998	10183	4963	650	2591	502	252	19.14
21/07/1998	10714	5484	674	2893	565	265	20.59
10/08/1998	10313	4780	543	2434	487	255	18.81
31/08/1998	9747	4464	582	2495	565	275	18.13

Table B12. Analytical data of individual indoles and phenols at 5°C in pig slurry

Date	Phenol $mg.l^{-1}$	P-cresol $mg.l^{-1}$	O-ethyl-phenol $mg.l^{-1}$	Indole $mg.l^{-1}$	Skatole $mg.l^{-1}$	TIP $mg.l^{-1}$
23/02/1998	17.4	47.3	3.6	1	0.8	70.1
16/03/1998	34.5	76.9	5	2.2	2.3	120.9
06/04/1998	39.3	84.4	5.2	1.3	3.7	133.9
27/04/1998	42.8	79.7	5.1	1.1	4.2	132.9
18/05/1998	44	91.2	5.3	1.3	4.8	146.6
08/06/1998	45.7	94.3	5.4	1.4	5.1	151.9
29/06/1998	49.4	96.2	5.3	1.6	5.1	157.6
21/07/1998	45.5	94.4	4.9	1.6	4.4	150.8
10/08/1998	48.2	99.7	5.4	1.6	5.2	160.1
31/08/1998	42.1	79.8	4.4	1.3	3.7	131.3

Table B13. Analytical data of individual indoles and phenols at 10°C in pig slurry

Date	Phenol $mg.l^{-1}$	P-cresol $mg.l^{-1}$	O-ethyl-phenol $mg.l^{-1}$	Indole $mg.l^{-1}$	Skatole $mg.l^{-1}$	TIP $mg.l^{-1}$
23/02/1998	17.4	47.3	3.6	1	0.8	70.1
16/03/1998	30.5	82	5.2	0	4.7	122.4
06/04/1998	31.8	95.1	5.5	0	6	138.4
27/04/1998	31.7	98.2	5.3	0.6	5.8	141.6
18/05/1998	33	99.9	5	0.7	4.9	143.5
08/06/1998	40.9	84.2	5	0.6	5.1	135.8
29/06/1998	55.1	86.7	5.3	0	4.4	151.5
21/07/1998	35.7	79.5	4.5	0	4.4	124.1
10/08/1998	29.9	71.5	4	0	4	109.4
31/08/1998	46.8	75.5	4.2	0	2.5	129

Table B14. Analytical data of individual indoles and phenols at 15°C in pig slurry

Date	Phenol $mg.l^{-1}$	P-cresol $mg.l^{-1}$	O-ethyl-phenol $mg.l^{-1}$	Indole $mg.l^{-1}$	Skatole $mg.l^{-1}$	TIP $mg.l^{-1}$
23/02/1998	17.4	47.3	3.6	1	0.8	70.1
16/03/1998	29.2	90.9	5.3	0	5.5	130.9
06/04/1998	29.5	105.7	5.6	0	5.4	146.2
27/04/1998	29.3	113.3	5.5	0	6.6	154.7
18/05/1998	29.3	122.6	5.4	0	6.6	163.9
08/06/1998	29.7	130.9	5.8	0	6.4	172.8
29/06/1998	29.9	135.1	5.6	0	4.6	175.2
21/07/1998	29.1	132	5.3	0	3.8	170.2
10/08/1998	30.3	131.4	5.4	0	1.8	168.9
31/08/1998	23.6	114.2	4.3	0	1.4	143.5

Tables C1-C3. Analytical data of feed cattle slurry during Treatment 1 (Study 1).

Table C1

Date	TS	TSS	VS	VSS	CODw	BODw	Kj- N	NH_4^+-N	Resp-rate	TS	VS	CODs	BODs	VFA	TIP	TOA	NO_3	NO_2	pH	Stripped NH_3-N
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mgO_2 l^{-1} hr^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$			(in eactor)	$mgNH_3 l^{-1} hr^{-1}$
07/05/1998	23.2	11.2	11.9	10.5	31.6	6	1610	890	88	11.3	6.1	14	4.5	1.71	54.9	4.4	nd	nd	8.7	5.7
12/05/1998	20.6	7.7	14.7	7.5	28.8	5.3	1600	900	98	11	6.2	13.7	4.8	2	54.5	4.6	nd	nd	8.9	4.3
22/05/1998	24.7	11.3	18.3	10.2	36	5.5	1660	900	140	10.4	5.9	13	3.7	1.93	46.1	4.2	nd	nd	8.6	-
29/05/1998	22.4	8.2	16.6	7.8	35	4.6	1490	840	106	11.8	7	12.3	3.4	2.03	47.0	4.2	nd	nd	8.6	0.9
05/06/1998	23.6	10.4	17.5	10.2	33	6.5	1590	900	130	11.1	6	13.2	4.4	1.63	48.5	4.1	nd	nd	8.5	2.5
16/06/1998	20.5	8.6	14.8	8.5	30	4.7	1510	840	80	10.9	6	12.9	3.2	1.96	39.8	3.6	nd	nd	8.5	
Average	**22.5**	**9.6**	**15.6**	**9.1**	**32.4**	**5.4**	**1576.7**	**878.3**	**107.0**	**11.1**	**6.2**	**13.2**	**4.0**	**1.9**	**48.5**	**4.2**	-	-	**8.6**	
STDEV	**1.7**	**1.6**	**2.3**	**1.3**	**2.8**	**0.7**	**64.39**	**29.9**	**23.6**	**0.5**	**0.4**	**0.6**	**0.7**	**0.2**	**5.7**	**0.3**	-	-	**0.2**	

Table C2

	Individual VFA						
Date	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
07/05/1998	1203	277	53	109	44	24	1710
12/05/1998	1387	340	61	133	50	28	1999
22/05/1998	1335	330	60	133	45	26	1929
29/05/1998	1340	377	70	154	59	30	2030
05/06/1998	1097	307	53	111	40	22	1630
16/06/1998	1265	378	57	175	52	31	1958
Average	**1271.2**	**334.8**	**59.0**	**135.8**	**48.3**	**26.8**	**1876.0**
STDEV	**107.0**	**39.5**	**6.4**	**25.4**	**6.8**	**3.5**	**165.2**

Table C3

	Individual indoles and phenols					
Date	Phenol	P-cresol	O-ethyl-ph	Indole	Skatole	TIP
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
07/05/1998	20.4	31.5	2	1	0	54.9
12/05/1998	21.1	30.4	1.9	1.1	0	54.5
22/05/1998	22	15.6	1.5	7	0	46.1
29/05/1998	23.5	20.6	1.8	1.1	0	47.0
05/06/1998	23.4	22.3	1.8	1	0	48.5
16/06/1998	16.4	21.1	1.5	0.8	0	39.8
Average	**21.1**	**23.6**	**1.8**	**2.0**	**0.0**	**48.5**
STDEV	**2.6**	**6.2**	**0.2**	**2.5**	**0.0**	**5.7**

Note : Ac = Acetic acid Pro = Propionic acid I-Bu = I-butyric acid
N-Bu = N-butyric acid I-Val = I-valeric acid N-Val = N-valeric acid

STDEV = standard deviation

Tables C4-C6. Analytical data of treated (ML) cattle slurry during Treatment 1 (Study 1)

Table C4

Date	TS	TSS	VS	VSS	CODw	BODw	Kj- N	NH_4^+-N	Resp-rate	TS	VS	CODs	BODs	VFA	TIP	TOA	NO_3	NO_2	pH
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mgO_2.l^{-1}hr^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$			(in eactor)
07/05/1998	22.3	11	16	10.3	27.1	3.4	1550	680	360	10.3	5.5	6.3	1.1	0.11	0	1.4	nd	nd	9.1
12/05/1998	19.2	9.8	13.4	9	23.9	3.7	1500	595	370	9.7	5.2	9.1	1.5	0.08	1.2	1.2	nd	nd	9
15/05/1998	22	9.5	15.7	8.6	29.1	2.9	1590	630	300	9.5	5.1	10	0.95	0.09	0	1.1	nd	nd	9
22/05/1998	25.8	16	19	13.8	34	3.5	1690	670	640	8.8	4.6	8	0.66	0.13	0	1.2	nd	nd	9
26/05/1998	23.6	13	17.3	11.6	31.9	3.1	1620	660	270	9.4	5	9.4	0.65	0.09	0	1.4	nd	nd	8.9
29/05/1998	20.9	9.7	15.3	9	30.5	2.2	1430	640	330	9.3	5.3	8.6	0.39	0.07	0	1.3	nd	nd	8.9
01/06/1998	20.3	10.4	14.4	9.8	24.5	2.8	1400	660	200	9.1	4.9	8.8	0.59	0.11	0	1.4	nd	nd	8.9
05/06/1998	22.2	12.3	15.8	11.5	27.3	3.1	1590	690	290	9	4.9	8	0.65	0.08	0	1.4	nd	nd	8.9
12/06/1998	21.2	10.6	15	10.2	25.5	2.6	1400	640	190	8.8	4.6	8.1	0.58	0.09	0	1.5	nd	nd	9
16/06/1998	18.1	8.5	12.4	8.3	21.5	2	1370	660	360	8.7	4.5	7.3	0.41	0.14	0	1.3	nd	nd	8.9
19/06/1998	23.1	11.6	17	11.4	27	2	1490	580	400	10.5	6.2	11.1	0.46	0.1	0	1.6			8.9
Average	**21.7**	**11.1**	**15.6**	**10.3**	**27.5**	**2.8**	**1511.8**	**645.9**	**337.3**	**9.4**	**5.1**	**8.6**	**0.7**	**0.1**	**0.1**	**1.3**	-	-	**9.0**
STDEV	**2.1**	**2.1**	**1.8**	**1.6**	**3.7**	**0.6**	**104.7**	**34.0**	**121.0**	**0.6**	**0.5**	**1.3**	**0.3**	**0.02**	**0.4**	**0.1**	-	-	**0.1**

Table C5

Date	Individual VFA						
	Ac $mg.l^{-1}$	Pro $mg.l^{-1}$	I-Bu $mg.l^{-1}$	N-Bu $mg.l^{-1}$	I-Val $mg.l^{-1}$	N-Val $mg.l^{-1}$	Total $mg.l^{-1}$
07/05/1998	69	21	4	12	4	1	111
12/05/1998	52	14	2	6	2	0	76
15/05/1998	57	16	2	8	3	0	86
22/05/1998	83	26	3	13	3	1	129
26/05/1998	56	17	3	12	3	0	91
29/05/1998	44	15	2	11	3	0	75
01/06/1998	70	22	5	12	4	1	114
05/06/1998	49	15	2	6	2	1	75
12/06/1998	61	16	2	6	2	1	88
16/06/1998	67	30	3	32	6	1	139
19/06/1998	57	22	2	18	4	1	104
Average	**60.45**	**19.45**	**2.73**	**12.36**	**3.27**	**0.64**	**98.91**
STDEV	**11.10**	**5.18**	**1.01**	**7.49**	**1.19**	**0.50**	**22.20**

Note : Ac = Acetic acid Pro = Propionic acid I-Bu = I-butyric acid
N-Bu = N-butyric acid I-Val = I-valeric acid N-Val = N-valeric acid

STDEV = standard deviation

Table C6

Date	Individual indoles and phenols					
	Phenol $mg.l^{-1}$	P-cresol $mg.l^{-1}$	O-ethyl-ph $mg.l^{-1}$	Indole $mg.l^{-1}$	Skatole $mg.l^{-1}$	TIP $mg.l^{-1}$
07/05/1998	0	0	0	0	0	0
12/05/1998	1.2	0	0	0	0	1.2
15/05/1998	0	0	0	0	0	0
22/05/1998	1	0	0	0	0	1
26/05/1998	0	0	0	0	0	0
29/05/1998	0	0	0	0	0	0
01/06/1998	1.1	0	0	0	0	1.1
05/06/1998	1.8	0	0	0	0	1.8
12/06/1998	0	0	0	0	0	0
16/06/1998	0	0	0	0	0	0
19/06/1998	0	0	0	0	0	0
average	**0.5**	**0.0**	**0.0**	**0.0**	**0.0**	**0.5**
STDEV	**0.7**	**0.0**	**0.0**	**0.0**	**0.0**	**0.7**

Tables C7-C9. Analytical data of stored cattle slurry after Treatment 1 (Study 1).

Table C7

Date	TS	TSS	VS	VSS	COD	BOD	Kj-N	NH_4^+-N	Resp-rate	TS	VS	COD	BOD	VFA	TIP	TOA	NO_3	NO_2	pH
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mgO_2.l^{-1}.hr^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$			(in eactor)
15/05/1998	21.8	10.3	15.5	9.2	28.1	3.5	1490	630	260	9.1	4.4	11.1	0.96	0.14	2.1	2.4	nd	nd	8.9
26/05/1998	21.4	11	17.2	9.3	27.9	2.8	1470	660	220	9.7	5.1	10.1	1.3	0.66	3.3	2.6	nd	nd	8.5
01/06/1998	19.2	7.8	13.4	7.4	23.5	3	1400	740	190	10.1	5.4	11.1	1.3	0.98	9.1	2.9	nd	nd	8.2
12/06/1998	21	8.7	14.9	8.5	28.2	3	1490	780	230	10	5.4	10.7	1.5	1.02	11.1	2.6	nd	nd	8.2
19/06/1998	21.2	9.2	15.2	9.1	27.7	2.6	1510	760	270	10.2	5.5	11	1.4	1.21	12.6	2.7	nd	nd	8
Average	**20.9**	**9.4**	**15.2**	**8.7**	**27.1**	**3.0**	**1472.0**	**714.0**	**234.0**	**9.8**	**5.2**	**10.8**	**1.3**	**0.8**	**7.6**	**2.6**	-	-	**8.4**
STDEV	**1.01**	**1.27**	**1.36**	**0.79**	**2.01**	**0.33**	**42.66**	**65.42**	**32.09**	**0.44**	**0.45**	**0.42**	**0.20**	**0.42**	**4.70**	**0.18**	-	-	**0.35**

Table C8

	Individual VFA						
Date	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
15/05/1998	89	30	4	11	5	1	140
26/05/1998	390	155	29	46	32	6	658
01/06/1998	567	226	50	69	57	12	981
12/06/1998	597	228	53	68	58	12	1016
19/06/1998	703	268	60	93	69	15	1208

Note : Ac = Acetic acid Pro = Propionic acid I-Bu = I-butyric acid
N-Bu = N-butyric acid I-Val = I-valeric acid N-Val = N-valeric acid

Table C9

	Individual indoles and phenols					
Date	Phenol	P-cresol	O-ethyl-ph	Indole	Skatole	TIP
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
15/05/1998	2.1	0	0	0	0	2.1
26/05/1998	3.3	0	0	0	0	3.3
01/06/1998	4.2	4.1	0	0.8	0	9.1
12/06/1998	3.9	6	0	1.2	0	11.1
19/06/1998	4.2	7.5	0	0.9	0	12.6

Tables C10-C12. Analytical data of feed cattle slurry during Treatment 2 (Study 1).

Table C10

Date	TS w	VS w	TSS w	VSS w	CODw	BODw	Kj-N	NH_4^+-N	Resp-rate	TS s	VS s	CODs	BODs	VFA	TIP	TOA	NO_2	NO_3	pH	resp rate	pH	Stripped NH_3-N
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mgO_2.l^{-1}.hr^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$				$mg\ O_2.l^{-1}.hr^{-1}$	(in eactor)	$mgNH_3.l^{-1}.hr^{-1}$
25/06/1998	18.1	12.6	15.6	14.5	23.3	2.63	1390	810	120	10	5.6	10.7	1.77	1.38	17.2	3.6	nd	nd	8.2	99	9	1.1
03/07/1998	18.4	12.3	13.3	13	33.4	2.3	1437	809	130	10.6	5.5	11.1	1.75	1.43	11.3	3.2	nd	nd	8.7	86	0	0.6
10/07/1998	22.5	16.3	9.6	9.5	27.4	2.49	-	800	150	10	5.3	10.4	1.43	1.39	11.2	3.2	nd	nd	8.6	80	8.9	1.8
17/07/1998	22.3	16.1	9.9	9.7	29.5	2.46	1517	872	250	10	5.4	10.9	1.3	1.38	12.2	3.6	nd	nd	8.7	81	9	2.6
24/07/1998	23.2	16.8	10.4	10.3	26.4	2.25	1540	849	156	9.6	4.7	10.4	1.8	1.1	9.6	3.2	nd	nd	8.3	140	9	0
Average	20.9	14.8	11.8	11.4	28.0	2.4	1471	826.2	161.2	10.0	5.3	10.7	1.6	1.3	12.3	3.4	-	-	8.5	97.2	7.2	1.2
STDEV	2.4	2.2	2.6	2.2	3.8	0.2	69.7	29.7	51.7	0.4	0.4	0.3	0.2	0.1	2.9	0.2	-	-	0.2	25.1	4.0	1.0

Table C11

Date	Individual VFA						
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
25/06/1998	835	287	62	107	70	18	1379
03/07/1998	889	265	55	134	69	18	1430
10/07/1998	865	267	60	107	73	14	1386
17/07/1998	814	253	47	199	59	10	1382
24/07/1998	671	216	51	91	59	10	1098
Average	814.8	257.6	55.0	127.6	66.0	14.0	1335.0
STDEV	85.3	26.3	6.2	42.8	6.6	4.0	134.1

Note : Ac = Acetic acid Pro = Propionic acid I-Bu = I-butyric acid
N-Bu = N-butyric acid I-Val = I-valeric acid N-Val = N-valeric acid

STDEV = standard deviation

Table C12

Date	Individual indoles and phenols					
	Phenol	P-cresol	O-ethyl-ph	Indole	Skatols	TIP
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
25/06/1998	5.4	10.3	0	1.5	0	17.2
03/07/1998	4.8	5.4	0	1.1	0	11.3
10/07/1998	4.4	4.9	0.9	1	0	11.2
17/07/1998	4.3	7	0	0.9	0	12.2
24/07/1998	3.7	5.9	0	0	0	9.6
Average	4.5	6.7	0.2	0.9	0.0	12.3
STDEV	0.6	2.2	0.4	0.6	0.0	2.9

Tables C13-C15. Analytical data of treated (ML) cattle slurry during Treatment 2 (Study 1)

Table C13

Date	TS w	VS w	TSS w	VSS w	CODw	BODw	Kj- N	NH_4^+-N	Resp-rate	TS s	VS s	CODs	BODs	VFA	TIP	TOA	NO_3	NO_2	pH
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mgO_2.l^{-1}.hr^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$			(in eactor)
25/06/1998	21.8	15.7	12.4	11.3	25.7	1.74	1400	640	200	10.9	6.5	10.6	0.35	0.03	0	1.6	nd	nd	8.9
01/07/1998	19.3	13.6	7.9	0	22.3	1.75	1290	655	210	8.7	4.6	7.9	0.33	0.03	1.2	1.3	nd	nd	8.9
03/07/1998	23.5	17.7	12.1	11.9	28.9	1.41	1330	665	74	10.2	5.7	10.1	0.46	0.05	0	1.4	nd	nd	9
07/07/1998	19.3	13.4	8.2	8	23.6	1.49	1340	646	63	9.2	5	10.6	0.46	0.02	0	1.4	nd	nd	9
10/07/1998	21.6	15.4	11.4	11.2	25.6	1.6	-	680	74	8.5	4.8	7.5	0.27	0.02	2.4	1.5	nd	nd	8.9
15/07/1998	19.4	13.3	8.9	8.4	23.8	1.04	1430	670	73	9	4.4	7.8	0.22	0.09	2.3	1.5	nd	nd	9
17/07/1998	20.8	14.7	11.4	11	26.4	1.48	1419	705	98	9.5	5.3	8.7	0.44	0.05	1.4	1.5	nd	nd	9
22/07/1998	21.9	15.6	12	11.6	26	1.85	1400	707	-	8.8	4.2	7.6	0.38	0.04	0	1.3	nd	nd	9
24/07/1998	22.1	15.7	11.5	7	26.3	1.43	1433	683	108	9.4	4.8	8.6	0.32	0.03	0	1.4	nd	nd	9
27/07/1998	20.5	14.4	8.1	7.9	26	1.97	1339	672	100	9.1	5.1	9.3	0.57	0.02	0	1.3	nd	nd	9
Average	**21.0**	**15.0**	**10.4**	**8.8**	**25.5**	**1.6**	**1375.7**	**672.3**	**111.1**	**9.3**	**5.0**	**8.9**	**0.4**	**0.04**	**0.7**	**1.4**	-	-	**9.0**
STDEV	**1.4**	**1.4**	**1.9**	**3.6**	**1.8**	**0.3**	**51.7**	**22.5**	**55.3**	**0.7**	**0.7**	**1.2**	**0.1**	**0.02**	**1.0**	**0.1**	-	-	**0.0**

Table C14

Date	Individual VFA						
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
25/06/1998	11	5	0	9	2	0	27
01/07/1998	15	3	0	6	0	0	24
03/07/1998	32	6	0	6	1	0	45
07/07/1998	15	4	0	0	0	0	19
10/07/1998	17	2	0	0	0	0	19
15/07/1998	39	20	2	26	4	2	93
17/07/1998	20	9	0	16	2	2	49
22/07/1998	19	7	0	12	1	1	40
24/07/1998	24	6	0	0	1	1	32
27/07/1998	16	3	0	0	0	1	20
Average	**20.80**	**6.50**	**0.20**	**7.50**	**1.10**	**0.70**	**36.80**
STDEV	**8.64**	**5.19**	**0.63**	**8.61**	**1.29**	**0.82**	**22.57**

Note : Ac = Acetic acid Pro = Propionic acid I-Bu = I-butyric acid
N-Bu = N-butyric acid I-Val = I-valeric acid N-Val = N-valeric acid

STDEV = standard deviation

Table C15

Date	Individual indoles and phenols					
	Phenol	P-cresol	O-ethyl-ph	Indole	Skatole	TIP
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
25/06/1998	0	0	0	0	0	0
01/07/1998	1.2	0	0	0	0	1.2
03/07/1998	0	0	0	0	0	0
07/07/1998	0	0	0	0	0	0
10/07/1998	2.4	0	0	0	0	2.4
15/07/1998	2.3	0	0	0	0	2.3
17/07/1998	1.4	0	0	0	0	1.4
22/07/1998	0	0	0	0	0	0
24/07/1998	0	0	0	0	0	0
27/07/1998	0	0	0	0	0	0
Average	**0.7**	**0.0**	**0.0**	**0.0**	**0.0**	**0.7**
STDEV	**1.0**	**0.0**	**0.0**	**0.0**	**0.0**	**1.0**

Tables C16-C18. Analytical data of stored cattle slurry after Treatment 2 (Study 1).

Table C16

Date	TS w	VS w	TSS w	VSS w	CODw	BODw	Kj-N	NH_4^+-N	Resp-rate	TS s	VS s	CODs	BODs	VFA	TIP	TOA	NO_3	NO_2	pH
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mgO_2.l^{-1}.hr^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$			(in reactor)
01/07/1998	19.6	13.9	8.7	0	28	1.55	1335	667	240	9.5	5.4	9.3	0.59	0.27	0	2	nd	nd	9.1
07/07/1998	18.4	12.8	7.2	7.1	21.7	1.53	1260	648	240	8.9	4.8	10.4	0.61	0.35	4.8	2.1	nd	nd	8.8
15/07/1998	19.5	13.5	8.8	8.4	24.8	1.04	1330	680	240	9.3	4.4	8.5	0.51	0.41	2.3	2	nd	nd	8.8
22/07/1998	18.8	13	9.5	9.4	22.5	1.58	1400	688	-	8.8	4.1	8.1	0.67	0.45	2.9	2.1	nd	nd	8.7
27/07/1998	19.6	14.8	7.3	7.1	20	1.35	1127	648	162	8.7	4.5	9.8	0.78	0.47	3.3	2.48	nd	nd	8.7
Average	**19.2**	**13.6**	**8.3**	**6.4**	**23.4**	**1.4**	**1290.4**	**666.2**	**220.5**	**9.0**	**4.6**	**9.2**	**0.6**	**0.4**	**2.7**	**2.1**	-	-	**8.8**
STDEV	**0.5**	**0.8**	**1.0**	**3.7**	**3.1**	**0.2**	**103.9**	**18.2**	**39.0**	**0.3**	**0.5**	**0.9**	**0.1**	**0.1**	**1.8**	**0.2**	-	-	**0.2**

Table C17

	Individual VFA						
Date	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
01/07/1998	159	56	13	22	16	1	267
07/07/1998	210	77	17	24	22	1	351
15/07/1998	237	93	17	43	22	3	415
22/07/1998	274	96	17	34	21	2	444
27/07/1998	299	100	20	28	25	0	472

Note : Ac = Acetic acid Pro = Propionic acid I-Bu = I-butyric acid
N-Bu = N-butyric acid I-Val = I-valeric acid N-Val = N-valeric acid

STDEV = standard deviation

Table C18

	Individual indoles and phenols					
Date	Phenol	P-cresol	O-ethyl-ph	Indole	Skatole	TIP
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
01/07/1998	0	0	0	0	0	0
07/07/1998	3.9	0.9	0	0	0	4.8
15/07/1998	1.4	0.9	0	0	0	2.3
22/07/1998	1.2	1.7	0	0	0	2.9
27/07/1998	1.4	1.9	0	0	0	3.3

Tables C19-C21. Analytical data of feed pig slurry during Treatment 1 (Study 1).

Table C19

Date	TS	TSS	VS	VSS	CODw	BODw	Kj-N	NH_4^+-N	pH	Resp-rate	TSs	VSs	CODs	BODs	VFA	TIP	TOA	NO_3	NO_2	pH	Stripped NH_3-N
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$		$mgO_2.l^{-1}.hr^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$			(in eactor)	$mgNH_3.l^{-1}.hr^{-1}$
08/09/1998	32.7	16.6	24.3	14.3	41	9.3	2847	1911	8.2	366	7.8	3.3	9.7	4.1	3.51	24.5	6.6	nd	nd	9	11.59
15/09/1998	24.3	15.7	18.5	14.6	35	7.8	2389	1894	8.9	440	6.9	2.6	8.1	4.2	2.82	25.5	7	nd	nd	9.2	13
23/09/1998	34.1	17.5	25.3	15.2	41.8	10	2931	1953	8.6	255	6.8	3.4	7.8	4.8	2.36	26.8	6.6	nd	nd	9.2	-
29/09/1998	21.4	11.4	14.7	10.1	31	7	2361	1845	8.6	180	6.5	2.6	8.1	3.5	2.72	29.0	6.8	nd	nd	9.2	11.81
05/10/1998	24.6	13.7	18.1	13	36	7.7	2610	1866	8.7	-	7	3.3	10	5.9	2.86	32.7	7	nd	nd	9.2	14
13/10/1998	38.7	24.7	29.3	21.3	40	4.7	2537	2075	8.6	400	6.4	2.8	9	3.2	3.15	35.7	6.7	nd	nd	9.2	15
19/10/1998	28.1	13.5	20.6	12.2	37.4	7.1	2464	1741	9	-	7	3.1	8.2	4.4	3.09	39.5	6.8				
Average	29.1	16.2	21.5	14.4	37.5	7.7	2591.3	1897.9	8.7	328.2	6.9	3.0	8.7	4.3	2.9	30.5	6.8	-	-	9.2	13.1
STDEV	6.2	4.3	5.0	3.5	3.8	1.7	221.5	102.5	0.3	107.7	0.5	0.3	0.9	0.9	0.4	5.6	0.2	-	-	0.1	1.4

Table C20

Date	Individual VFA						
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
08/09/1998	2679	492	83	127	92	34	3507
15/09/1998	2111	404	77	116	86	25	2819
23/09/1998	1745	326	95	71	104	22	2363
29/09/1998	1989	430	87	94	95	24	2719
05/10/1998	2060	481	96	98	106	24	2865
13/10/1998	2238	544	113	107	121	23	3146
19/10/1998	2179	570	97	108	107	25	3086
Average	2161.4	485.3	93.0	104.0	101.9	25.1	2970.6
STDEV	269.0	98.7	10.9	16.8	10.8	3.7	355.0

Table C21

Date	Individual indoles and phenols					
	Phenol	P-cresol	O-ethyl-ph	Indole	Skatole	TIP
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
08/09/1998	4.7	17.8	2	0	0	24.5
15/09/1998	6.4	17.3	1.8	0	0	25.5
23/09/1998	8.8	16.2	1.8	0	0	26.8
29/09/1998	6.8	18.9	1.9	0	1.4	29.0
05/10/1998	7.3	21.3	2.1	0.7	1.3	32.7
13/10/1998	8.9	22.1	2.1	0.8	1.8	35.7
19/10/1998	8.4	25.7	2.4	1	2	39.5
Averages	7.3	19.9	2.0	0.4	0.9	30.5
STDEV	1.5	3.3	0.2	0.5	0.9	5.6

Note : Ac = Acetic acid Pro = Propionic acid I-Bu = I-butyric acid
N-Bu = N-butyric acid I-Val = I-valeric acid N-Val = N-valeric acid

STDEV = standard deviation

Tables C22-C24. Analytical data of treated (ML) pig slurry during Treatment 1 (Study 1).

Table C22

Date	TS	TSS	VS	VSS	CODw	BODw	Kj-N	NH_4^+-N	pH	Resp-rate	TSs	VSs	CODs	BODs	VFA	TIP	TOA	NO_3	NO_2
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$		$mgO_2.l^{-1}.hr^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$		
08/09/1998	21.8	13	14.8	11.2	24.9	4.8	2305	1299	9.1	380	6.4	2.6	4.5	0.79	0.09	0	2.5	nd	nd
11/09/1998	27.8	16.3	19.6	14	25.8	4.4	2399	1299	9.3	550	7.1	3.3	5.9	0.89	0.05	0	2.1	nd	nd
15/09/1998	23.1	13.4	16.3	12.9	25.9	4.9	2128	1022	9.2	380	6.5	2.6	5.1	1.8	0.05	0	2.5	nd	nd
17/09/1998	23.8	13.8	16.9	12.4	27.6	4.2	2231	1260	9.2	520	7.1	3.2	4.9	1.1	0.03	0	2.5	nd	nd
23/09/1998	35.3	21.3	25.9	17.8	38	6.7	2660	1433	9.1	816	7.1	3	5.1	1.7	0.13	0	2.9	nd	nd
25/09/1998	29.8	18.6	21.6	16.1	35.2	5.3	2688	1365	9	560	7.2	3.3	4.7	1.1	0.04	2.2	2.4	nd	nd
29/09/1998	21.5	12	14.9	10.3	25.1	4	2147	1313	9.1	350	5.7	2	4	0.7	0.11	0	2.5	nd	nd
02/10/1998	24.3	12.3	17.7	11.6	25.1	4.7	2193.0	1180.0	9.2	320.0	6.1	2.5	3.9	1.6	0.04	0.0	2.5	nd	nd
05/10/1998	31.1	19.4	22.6	17.6	29.0	6.6	2450.0	1370.0	9.2	-	6.0	2.4	4.5	1.1	0.1	0.0	2.3	nd	nd
08/10/1998	26	14.2	17.9	12.8	29.3	4.8	2333	1218	9.4	620	6.1	2.3	3.8	1.6	0.04	0	2	nd	nd
13/10/1998	40.7	22.5	30.6	19	45	7.6	2987	1470	9.1	700	6.9	3	5.6	2.7	0.08	0	1.9	nd	nd
15/10/1998	39	20.3	30	18.2	45.2	6.6	2585	1428	9.3	460	7.3	3.6	6.5	1.5	0.09	0	2.3	nd	nd
19/10/1998	26	14	18.8	12.4	30.7	4.8	2497	1106	9.2		6.2	2.4	4.6	0.9	0.01	0	2.4	nd	nd
22/10/1998	31.9	15.8	23.6	14.1	34	4.8	2473	1334	9.3	1200	7.2	3.3	5.8	0.7	0.14	0.9	2.4	nd	nd
Average	**28.7**	**16.2**	**20.8**	**14.3**	**31.5**	**5.3**	**2434.0**	**1292.6**	**9.2**	**571.3**	**6.6**	**2.8**	**4.9**	**1.3**	**0.07**	**0.3**	**2.4**	-	-
STDEV	**6.2**	**3.6**	**5.2**	**2.9**	**7.1**	**1.1**	**240.7**	**127.2**	**0.1**	**247.7**	**0.5**	**0.5**	**0.8**	**0.6**	**0.04**	**0.6**	**0.2**	-	-

Table C23

Date	Individual VFA						
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
08/09/1998	62	15	2	4	4	0	87
11/09/1998	39	12	0	0	5	0	56
15/09/1998	35	10	3	2	4	0	54
17/09/1998	19	8	1	0	2	0	30
23/09/1998	86	23	6	6	6	3	130
25/09/1998	28	10	2	2	2	0	44
29/09/1998	57	22	2	19	4	0	104
02/10/1998	27	10	1	4	2	0	44
05/10/1998	27	13	3	2	3	0	48
08/10/1998	23	10	1	3	2	0	39
13/10/1998	53	14	6	7	4	0	84
15/10/1998	58	15	3	6	3	0	85
19/10/1998	48	3	0	0	1	0	52
22/10/1998	83	29	4	13	5	3	137
Average	**47.1**	**14.3**	**2.5**	**4.8**	**3.4**	**0.4**	**72.5**
STDEV	**21.1**	**6.8**	**1.8**	**5.2**	**1.4**	**1.1**	**33.3**

Note : Ac = Acetic acid Pro = Propionic acid I-Bu = I-butyric acid
N-Bu = N-butyric acid I-Val = I-valeric acid N-Val = N-valeric acid

STDEV = standard deviation

Table C24

Date	Individual indoles and phenols					
	Phenol	P-cresol	O-ethyl-ph	Indole	Skatole	TIP
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
08/09/1998	0	0	0	0	0	0
11/09/1998	0	0	0	0	0	0
15/09/1998	0	0	0	0	0	0
17/09/1998	0	0	0	0	0	0
23/09/1998	0	0	0	0	0	0
25/09/1998	2.2	0	0	0	0	2.2
29/09/1998	0	0	0	0	0	0
02/10/1998	0	0	0	0	0	0
05/10/1998	0	0	0	0	0	0
08/10/1998	0	0	0	0	0	0
13/10/1998	0	0	0	0	0	0
15/10/1998	0	0	0	0	0	0
19/10/1998	0	0	0	0	0	0
22/10/1998	0.7	0.2	0	0	0	0.9
Average	**0.2**	**0.0**	**0.0**	**0.0**	**0.0**	**0.2**
STDEV	**0.6**	**0.1**	**0.0**	**0.0**	**0.0**	**0.6**

Tables C25-C27. Analytical data of stored pig slurry after Treatment 1 (Study 1).

Table C25

Date	TS	TSS	VS	VSS	CODw	BODw	Kj-N	NH_4^+-N	pH	Resp-rate	TSs	VSs	CODs	BODs	VFA	TIP	TOA	NO_3	NO_2
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$		$mgO_2.l^{-1}.hr^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$		
11/09/1998	22.2	13.9	15.1	11.9	27.5	3.6	2016	1162	9.3	516	6.2	2.6	4.6	0.57	-	0	2.8	nd	nd
17/09/1998	24.6	12	17.1	10.6	28.6	3.9	2296	1337	9.2	510	6.7	2.6	4.6	0.99	0.31	0	3	nd	nd
25/09/1998	27	16.4	19.2	10.1	32	4.3	2394	1295	9.3	550	6.5	2.4	4.2	1	0.47	0	3.3	nd	nd
02/10/1998	24.8	13.4	17.6	12.4	28.7	3.5	2160	1215	9	400	6.4	2.5	4.5	1.4	0.58	5.1	3.5	nd	nd
08/10/1998	23.4	12.6	16.3	11.4	26.5	3.7	2240	1264	9.1	570	6.1	2.5	4.8	1.1	0.69	7	3.3	nd	nd
15/10/1998	24.8	14.7	17.5	12.8	31.7	4.9	2203	1397	9	440	6.6	2.7	5.5	1.3	0.81	7.9	3.4	nd	nd
22/10/1998	26.6	15.8	18.8	14.4	33	4.7	2613	1405	8.9	820	6.8	2.7	6.4	1.5	0.82	9.9	4	nd	nd
Average	**24.8**	**14.1**	**17.4**	**11.9**	**29.7**	**4.1**	**2274.6**	**1296.4**	**9.1**	**543.7**	**6.5**	**2.6**	**4.9**	**1.1**	**0.6**	**4.3**	**3.3**	-	-
STDEV	**1.7**	**1.6**	**1.4**	**1.4**	**2.5**	**0.6**	**189.5**	**90.6**	**0.2**	**135.6**	**0.3**	**0.1**	**0.8**	**0.3**	**0.2**	**4.2**	**0.4**	-	-

Table C26

Date	Individual VFA						
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
11/09/1998	73	22	3	0	5	0	103
17/09/1998	188	58	11	34	12	6	309
25/09/1998	325	82	17	24	17	1	466
02/10/1998	401	109	21	24	23	2	580
08/10/1998	472	134	27	27	27	2	689
15/10/1998	552	164	33	30	34	2	815
22/10/1998	546	168	36	27	38	2	817
Average	**365.3**	**105.3**	**21.1**	**23.7**	**22.3**	**2.1**	**539.9**
STDEV	**182.0**	**54.7**	**11.9**	**11.0**	**11.8**	**1.9**	**266.4**

Note : Ac = Acetic acid Pro = Propionic acid I-Bu = I-butyric acid
N-Bu = N-butyric acid I-Val = I-valeric acid N-Val = N-valeric acid

STDEV = standard deviation

Table C27

Date	Individual indoles and phenols					
	Phenol	P-cresol	O-ethyl-ph	Indole	Skatole	TIP
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
11/09/1998	0	0	0	0	0	0.0
17/09/1998	0	0	0	0	0	0.0
25/09/1998	0	0	0	0	0	0.0
02/10/1998	2.8	2.3	0	0	0	5.1
08/10/1998	3.6	3.4	0	0	0	7.0
15/10/1998	3.9	4	0	0	0	7.9
22/10/1998	4.9	5	0	0	0	9.9
Average	**2.2**	**2.1**	**0.0**	**0.0**	**0.0**	**4.3**
STDEV	**2.1**	**2.1**	**0.0**	**0.0**	**0.0**	**4.2**

Tables C28-C30. Analytical data feed pig slurry during Treatment 2 (Study 1).

Table C28

Date	TS	TSS	VS	VSS	CODw	BODw	Kj-N	NH_4^+-N	pH	Resp-rate	TSs	VSs	CODs	BODs	VFA	TIP	TOA	NO_3	NO_2	pH	Stripped NH_3-N
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$		$mgO_2.l^{-1}.hr^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$			(in reactor)	$mgNH_3.l^{-1}.hr^{-1}$
30/10/1998	25.7	14.7	18.4	13.2	36.4	3.1	2287	1400	8.9	470	7.1	3.5	6.4	2	1.24	15.6	3.8	nd	nd	9.2	7.5
05/11/1998	25.9	13.4	18.8	11.7	32.3	4.24	2455	1419	8.9	400	6.8	3.6	6.7	1.5	0.99	14.4	3.7	nd	nd	9.1	8.1
13/11/1998	27	15.5	19.4	13.5	32.5	3.65	2287	1435	8.8	350	6.8	3.3	6.6	0.84	1.17	17.7	4	nd	nd	9.3	11.4
20/11/1998	29.3	17.3	21.5	15.2	33.5	3.1	2333	1446	8.8	350	7.2	3.6	5.7	1.03	1.25	11.6	4.1	nd	nd	9.2	9
25/11/1998	28.6	16.6	20.9	14.6	33.7	2.94	2357	1479	8.8	310	6.8	3.1	5.5	1.23	1.2	14.2	3.8	nd	nd	9.2	5
Average	27	16	20	14	34	3	2344	1436	9	376	7	3	6	1	1.17	15	3.9	-	-	9	8
STDEV	1.6	1.5	1.3	1.4	1.6	0.5	69.1	29.7	0.1	61.5	0.2	0.2	0.5	0.5	0.1	2.1	0.2	-	-	0.1	2.3

Table C29

Date	Individual VFA						
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
30/10/1998	824	246	54	48	59	7	1238
05/11/1998	646	197	51	42	56	2	994
13/11/1998	763	216	66	49	73	3	1170
20/11/1998	809	228	89	41	80	0	1247
25/11/1998	737	192	99	47	115	0	1190
Average	755.8	215.8	71.8	45.4	76.6	2.4	1167.8
STDEV	70.6	22.3	21.3	3.6	23.6	2.9	102.4

Table C30

Date	Individual indoles and phenols					
	Phenol	P-cresol	O-ethyl-ph	Indole	Skatole	TIP
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
30/10/1998	7.3	7	0	1.3	0	15.6
05/11/1998	6.3	6.8	0	1.3	0	14.4
13/11/1998	7.6	8.6	0.3	1.2	0	17.7
20/11/1998	5.6	5.3	0	0.7	0	11.6
25/11/1998	7.6	5.8	0	0.8	0	14.2
Average	6.9	6.7	0.1	1.1	0.0	14.7
STDEV	0.9	1.3	0.1	0.3	0.0	2.2

Note : Ac = Acetic acid Pro = Propionic acid I-Bu = I-butyric acid
N-Bu = N-butyric acid I-Val = I-valeric acid N-Val = N-valeric acid

STDEV = standard deviation

Tables C31-C33. Analytical data of treated (ML) pig slurry duirng Treatment 2 (Study 1).

Table C31

Date	TS	TSS	VS	VSS	CODw	BODw	Kj-N	NH_4^+-N	pH	Resp-rate	TSs	VSs	CODs	BODs	VFA	TIP	TOA	NO_3	NO_2
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$		$mgO_2.l^{-1}.hr^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$		
30/10/1998	29.8	16.1	21.8	14.4	30.6	2.9	2277	1155	9.2	190	6.5	2.9	5	0.39	0.015	1.2	2.1	nd	nd
02/11/1998	23.1	12.7	16.2	11.4	26.7	2.42	2053	1087	9.3	162	6.5	2.8	4.9	0.26	0.016	0	2.2	nd	nd
05/11/1998	27.2	16.1	19.6	13.7	30.2	3.4	2485	1300	9.2	200	7.4	3.6	6.5	0.41	0.015	0	1.4	nd	nd
09/11/1998	23.2	12.6	16.2	11.1	26.4	2.6	1988	1325	9.1	300	6.3	2.7	4.6	0.2	0.014	2.5	1.5	nd	nd
13/11/1998	25.8	16.1	18.1	13.9	28	1.37	2147	1085	9.5	150	6.6	2.9	5.6	0.13	0.028	0	1.5	nd	nd
16/11/1998	26.5	13.3	18.6	12.2	29.3	3.1	2413	1087	9.4	130	6.8	2.9	5.8	0.37	0.031	0	2.2	nd	nd
20/11/1998	29.7	17.3	21.8	15.2	30.5	2	2240	1223	9.3	300	7.2	3.6	4.9	0.21	0.037	0.8	2.1	nd	nd
23/11/1998	28.7	16.4	20.4	13.8	27.8	2.7	2431	1141	9.3	250	6.9	3.1	4.8	0.1	0.026	0.0	2.3	nd	nd
25/11/1998	27.9	17.9	19.6	15.6	28.9	1.9	2249	1243	9.4	150	7.3	3.3	5.2	0.2	0.025	0.0	2.0	nd	nd
27/11/1998	26.2	14.8	18.3	13.2	27.9	2.5	2254	1108	9.1	130	6.5	2.7	5.8	0.2	0.019	0	2	nd	nd
Average	**26.8**	**15.3**	**19.1**	**13.5**	**28.6**	**2.5**	**2253.7**	**1175.4**	**9.3**	**196.2**	**6.8**	**3.1**	**5.3**	**0.2**	**0.023**	**0.5**	**1.9**	-	-
STDEV	**2.4**	**1.9**	**2.0**	**1.5**	**1.5**	**0.6**	**161.0**	**91.1**	**0.1**	**65.6**	**0.4**	**0.3**	**0.6**	**0.1**	**0.008**	**0.8**	**0.3**	-	-

Table C32

Date	Individual VFA						
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
30/10/1998	10	4	0	0	1	0	15
02/11/1998	11	4	0	0	1	0	16
05/11/1998	10	4	0	0	1	0	15
09/11/1998	10	3	0	0	1	0	14
13/11/1998	19	8	0	0	1	0	28
16/11/1998	18	10	1	0	2	0	31
20/11/1998	21	15	0	0	1	0	37
23/11/1998	13	10	2	0	1	0	26
25/11/1998	15	8	0	0	2	0	25
27/11/1998	12	6	0	0	1	0	19
Average	**13.9**	**7.2**	**0.3**	**0.0**	**1.2**	**0.0**	**22.6**
STDEV	**4.1**	**3.8**	**0.7**	**0.0**	**0.4**	**0.0**	**8.0**

Note : Ac = Acetic acid Pro = Propionic acid I-Bu = I-butyric acid
N-Bu = N-butyric acid I-Val = I-valeric acid N-Val = N-valeric acid

STDEV = standard deviation

Table C33

Date	Individual indoles and phenols					
	Phenol	P-cresol	O-ethyl-ph	Indole	Skatole	TIP
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
30/10/1998	1.2	0	0	0	0	1.2
02/11/1998	0	0	0	0	0	0.0
05/11/1998	0	0	0	0	0	0.0
09/11/1998	1.1	0.4	1	0	0	2.5
13/11/1998	0	0	0	0	0	0.0
16/11/1998	0	0	0	0	0	0.0
20/11/1998	0.6	0	0.2	0	0	0.8
23/11/1998	0	0	0	0	0	0.0
25/11/1998	0	0	0	0	0	0.0
27/11/1998	0	0	0	0	0	0.0
Average	**0.3**	**0.0**	**0.1**	**0.0**	**0.0**	**0.5**
STDEV	**0.5**	**0.1**	**0.3**	**0.0**	**0.0**	**0.8**

Tables C34-C36. Analytical data of stored pig slurry after Treatment 2 (Study 1).

Table C34

Date	TS	TSS	VS	VSS	CODw	BODw	Kj-N	NH_4^+-N	pH	Resp-rate	TSs	VSs	CODs	BODs	VFA	TIP	TOA	NO_3	NO_2
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$		$mgO_2.l^{-1}.hr^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$		
02/11/1998	27.6	13.2	20.3	12.9	33	2.7	2053	1057	9.2	468	6.4	2.9	4.9	0.38	0.19	0	3	nd	nd
09/11/1998	25.3	13	18.1	11.3	30.4	3	2053	1127	9	530	6.5	2.7	5.2	0.51	0.41	2.7	3.1	nd	nd
16/11/1998	24.7	14.5	17.2	13.2	26.5	2.4	2137	1188	9.2	360	6.7	2.7	5.2	0.51	0.4	4.9	3.1	nd	nd
23/11/1998	24.8	13.4	17.5	11.4	28.4	2.1	2007	1243	9.2	390	6.7	2.9	5.2	0.59	0.66	5.9	3.2	nd	nd
27/11/1998	24.9	14.6	17.5	13.2	28	1.5	2324	1223	8.9	350	6.4	2.8	5	0.75	0.7	6.3	3.6	nd	nd
Average	**25.5**	**13.7**	**18.1**	**12.4**	**29.3**	**2.3**	**2114.8**	**1167.6**	**9.1**	**419.6**	**6.5**	**2.8**	**5.1**	**0.5**	**0.5**	**4.0**	**3.2**	-	-
STDEV	**1.2**	**0.8**	**1.3**	**1.0**	**2.5**	**0.6**	**126.0**	**75.9**	**0.1**	**77.1**	**0.2**	**0.1**	**0.1**	**0.1**	**0.2**	**2.6**	**0.2**	-	-

Table C35

Date	Individual VFA						
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
02/11/1998	135	35	6	4	7	4	191
09/11/1998	274	82	15	8	20	8	407
16/11/1998	279	70	14	12	17	6	398
23/11/1998	469	135	12	10	21	10	657
27/11/1998	521	126	14	14	17	10	702
Average	**335.6**	**89.6**	**12.2**	**9.6**	**16.4**	**7.6**	**471.0**
STDEV	**157.6**	**41.3**	**3.6**	**3.8**	**5.5**	**2.6**	**209.6**

Note : Ac = Acetic acid Pro = Propionic acid I-Bu = I-butyric acid
N-Bu = N-butyric acid I-Val = I-valeric acid N-Val = N-valeric acid

STDEV = standard deviation

Table C36

Date	Individual indoles and phenols					
	Phenol	P-cresol	O-ethyl-ph	Indole	Skatole	TIP
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
02/11/1998	0	0	0	0	0	0.0
09/11/1998	2	0.7	0	0	0	2.7
16/11/1998	2.8	1.5	0.3	0.3	0	4.9
23/11/1998	3.2	1.8	0.6	0.3	0	5.9
27/11/1998	3.2	2.4	0.4	0.3	0	6.3
Average	2.2	1.3	0.3	0.2	0.0	4.0
STDEV	1.3	0.9	0.3	0.2	0.0	2.6

Tables D1 & D2. Analytical data of feed1 of laboratory Study 2.

Table D1

Date	TS	TSS	VS	VSS	CODw	BODw	Kj-N	NH_4^+-N	pH	TSs	VSs	CODs	BODs	VFA	TIP	TOA
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$		$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$
02/02/2000	26.3	-	20.4	-	45.3	8100	2370	1060	7.5	10.6	6.7	20.4	5000	3250	79.4	3.5
04/02/2000	25.7	-	20.2	-	42.6	6000	1980	1000	7.8	11.5	7.4	19.4	4300	3140	71.4	3.2
09/02/2000	25.6	-	20.0	-	39.0	5200	1900	1070	7.9	10.3	6.7	16.7	3800	2520	57.6	2.7
12/02/2000	26.0	-	21.0	-	37.8	-	-	1010	8	11.4	7.5	15.9	-	1740	48.4	2.2
15/02/2000	25.4	-	20.0	-	35.9	6600	2000	990	8.2	11.5	7.9	16.5	4000	1300	33.0	2.0
19/02/2000	25.0	-	19.6	-	34.8	-	-	990	8.2	11.1	6.9	14.9	-	1300	34.4	1.5
22/02/2000	24.7	-	19.5	-	34.1	5000	2100	990	8.2	11.2	7.2	14.9	3300	1290	31.7	1.7

Table D2

Date	VFA							Indoles and phenols					
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total	Phenol	P-cresol	O-et-ph	Indole	Skatole	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
01/02/2000	1980	700	160	210	140	60	3250	16.2	58	4.6	0.2	0.4	79.4
04/02/2000	1890	720	130	240	110	50	3140	24.6	41.6	4.4	0.4	0.4	71.4
09/02/2000	1430	710	120	150	110	0	2520	37.4	15.8	3.6	0.4	0.4	57.6
12/02/2000	1020	450	110	80	80	0	1740	38.4	6.8	2.8	0.2	0.2	48.4
15/02/2000	740	360	90	40	70	0	1300	30	1	1.8	0.2	0	33.0
19/02/2000	780	350	80	20	70	0	1300	32	0.4	1.8	0.2	0	34.4
22/02/2000	780	350	80	10	70	0	1290	30	0.2	1.4	0.1	0	31.7

Note : Ac = Acetic acid Pro = Propionic acid I-Bu = I-butyric acid
N-Bu = N-butyric acid I-Val = I-valeric acid N-Val = N-valeric acid

Tables D3 & D4. Analytical data of ML1 of laboratory Study 2.

Table D3

Date	TS	TSS	VS	VSS	CODw	BODw	Kj-N	NH_4^+-N	pH	TSs	VSs	CODs	BODs	VFA	TIP	TOA
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$		$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$
04/02/2000	25.9	ND	20.5	ND	40.2	4800	1820	750	8.7	11.7	8.4	16.2	2600	180	0.8	0.7
09/02/2000	25.3	ND	20.1	ND	38.9	3100	1850	830	8.6	11.2	8.1	11.2	1600	110	0.6	0.7
12/02/2000	24.9	ND	19.5	ND	33	ND	ND	790	8.8	9.1	7.5	10.6	ND	90	0.6	0.7
15/02/2000	25	ND	19.7	ND	32	4200	1880	830	8.8	9.1	6	9.7	1020	90	0.4	0.7
19/02/2000	23.9	ND	18.7	ND	31.4	ND	ND	850	8.7	8.9	5.7	9.5	ND	100	0.6	0.8
22/02/2000	23.6	11.3	19.5	10.5	30.9	3400	1890	860	8.8	8.9	5.8	9.7	810	40	0.2	0.4

Table D4

Date	VFA							Indoles and phenols					
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total	Phenol	P-cresol	O-et-ph	Indole	Skatole	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
04/02/2000	150	30	0	0	0	0	180	0.6	0.2	0	0	0	0.8
09/02/2000	90	20	0	0	0	0	110	0.5	0.1	0	0	0	0.6
12/02/2000	70	20	0	0	0	0	90	0.6	0	0	0	0	0.6
15/02/2000	80	10	0	0	0	0	90	0.4	0	0	0	0	0.4
19/02/2000	80	20	0	0	0	0	100	0.6	0	0	0	0	0.6
22/02/2000	30	10	0	0	0	0	40	0.2	0	0	0	0	0.2

Note : Ac = Acetic acid Pro = Propionic acid I-Bu = I-butyric acid
N-Bu = N-butyric acid I-Val = I-valeric acid N-Val = N-valeric acid

Table D5. Analytial data of feed2 of laboratory Study 2.

Table D5

Date	TS	TSS	VS	VSS	CODw	BODw	Kj-N	NH_4^+-N	pH	TSs	VSs	CODs	BODs	VFA	TIP	TOA
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$		$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$
31/03/2000	25.2	18.6	19.7	16.8	35.8	6414	2006	1102	8.1	11	7.5	14.6	4140	3440	66.1	4.124
03/04/2000	24.9	13.7	19.3	12.5	34.5	6086	1979	1078	8.1	11.6	7.4	14.7	4100	3190	65.9	3.168
07/04/2000	24.8	11.2	18.6	10.3	36.3	8840	1941	1089	8.1	11.1	6.3	15.8	5196	2920	55.5	2.8964
10/04/2000	33.9	20.3	26.5	18.3	35.9	8190	2000	1104	8.3	11.4	7.8	15.3	4627	2590	26.5	2.8776
13/04/2000	24.9	11	19.1	10.2	33.7	ND	1904	1033	8.4	11.4	7.9	15.9	ND	2820	53.1	2.8644
17/04/2000	24.5	10.8	18.9	9.7	35.9	4350	1941	1099	8.4	11.5	7.9	14.4	2867	2200	48.9	2.6082
20/04/2000	24.4	10.2	18.9	9.8	34.9	6500	1876	1057	8.5	11.5	7.4	14.1	4500	2180	54.5	2.583
25/04/2000	23.9	11.2	18.6	9.5	33.1	ND	1923	994	8.5	11.4	7.4	16.6	ND	3341	54.9	3.564
01/05/2000	23.2	10.5	17.8	8.2	32.4	6400	1829	896	8.5	10.9	7	15.1	3917	2990	41.3	2.953
05/05/2000	22.9	11.2	17.8	10	32.6	4500	1755	872	8.5	8.8	5.7	15.2	3184	2870	32.8	3.012
09/05/2000	25	12.5	19.5	11.3	34.9	4800	1820	917	8.8	11	6.8	14.7	2884	2550	35.6	2.9123
12/05/2000	22.9	9.5	17.8	8.5	32.8	5175	1615	872	8.7	11.3	7.3	15.2	3467	2340	31.8	2.5016
15/05/2000	22.8	8.7	17.6	7	31.2	5325	1783	928	8.6	11	7.3	14.1	3365	2200	30.6	1.9656
18/05/2000	22.6	10.7	17.6	9.6	30.5	4400	1783	956	8.8	10.8	7	16	3350	2350	24.7	2.4891
22/05/2000	22.9	9.2	17.7	8.3	31.5	4500	1820	875	8.8	10.6	6.9	14.3	3050	1980	23.1	2.1305
26/05/2000	22.6	8.3	17.5	7.7	29.8	ND	1661	780	8.8	10.7	6.6	14.8	ND	1840	22.1	1.6384
30/05/2000	23.1	9.5	17.7	8.3	28.2	4300	1743	882	8.8	11	7.3	11.9	2660	1790	17.4	1.8108
06/06/2000	22.3	11.6	17.2	10.3	30.8	3070	1736	878	8.9	11	7.4	14.5	2080	1460	15.6	1.5104
12/06/2000	22.5	9.2	17.6	8.3	30.5	3000	1736	837	8.9	10.7	7.1	14	1900	1380	12.0	1.4501
26/06/2000	-	-	-	-	-	-	-	continue storage anaerobically without treatment								
02/07/2000	-	-	-	-	-	-	-	-	-	-	-	-	-	1040	-	-
10/07/2000	-	-	-	-	-	-	-	-	-	-	-	-	-	710	-	-
17/07/2000	-	-	-	-	-	-	-	-	-	-	-	-	-	920	-	-
24/07/2000	-	-	-	-	-	-	-	-	-	-	-	-	-	920	-	-
														960	-	-

Note: ND = Not Detected

Table D6. Analytical data of feed2 of laboratory Study 2.

Table D6

Date	VFA							Indoles and phenols					
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total	Phenol	P-cresol	O-et-ph	Indole	Skatole	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
31/03/2000	1900	960	140	250	120	70	3440	26.8	35.0	3.5	0	0.8	66.1
03/04/2000	1770	910	130	240	110	30	3190	26.2	35.1	3.2	0.6	0.8	65.9
07/04/2000	1560	980	120	150	110	0	2920	26.0	26.5	2.5	0.5	0	55.5
10/04/2000	1480	710	140	140	120	0	2590	13.0	12.5	1.0	0	0	26.5
13/04/2000	1680	750	140	130	120	0	2820	28.2	21.2	2.5	0.6	0.6	53.1
17/04/2000	1290	580	120	80	130	0	2200	32.5	13.0	2.2	0.6	0.6	48.9
20/04/2000	1250	600	120	90	120	0	2180	34.5	16.2	2.4	0.7	0.7	54.5
25/04/2000	2101	820	160	110	150	0	3341	35.6	15.3	2.7	0.7	0.6	54.9
01/05/2000	1910	740	140	60	140	0	2990	32.6	6.4	1.6	0.5	0.2	41.3
05/05/2000	1890	650	140	40	150	0	2870	28.4	2.8	1.3	0.3	0	32.8
09/05/2000	1600	630	130	40	150	0	2550	30.4	3.1	1.6	0.5	0	35.6
12/05/2000	1550	520	110	20	140	0	2340	26.4	3.3	1.6	0.5	0	31.8
15/05/2000	1400	510	110	30	150	0	2200	25.6	3.9	1.1	0	0	30.6
18/05/2000	1500	560	120	20	150	0	2350	20.4	3.0	1.0	0.3	0	24.7
22/05/2000	1250	490	110	20	110	0	1980	18.4	3.6	0.8	0.3	0	23.1
26/05/2000	1200	440	90	10	100	0	1840	17.0	4.0	0.8	0.3	0	22.1
30/05/2000	1150	440	90	20	90	0	1790	14.2	2.6	0.6	0	0	17.4
05/06/2000	900	370	90	10	90	0	1460	12.4	2.6	0.6	0	0	15.6
12/06/2000	880	340	70	10	80	0	1380	9.6	2.0	0.4	0	0	12.0
	continue storage anaerobically without treatment							-	-	-	-	-	-
26/06/2000	610	260	70	20	80	0	1040	-	-	-	-	-	-
02/07/2000	430	170	40	20	50	0	710	-	-	-	-	-	-
10/07/2000	520	280	40	30	50	0	920	-	-	-	-	-	-
17/07/2000	500	290	50	40	40	0	920	-	-	-	-	-	-
24/07/2000	550	290	50	40	30	0	70	-	-	-	-	-	-

Note : Ac = Acetic acid Pro = Propionic acid I-Bu = I-butyric acid
N-Bu = N-butyric acid I-Val = I-valeric acid N-Val = N-valeric acid

Table D7. Analytical data of ML2 of laboratory Study 2.

Table D7

Date	TS	TSS	VS	VSS	CODw	BODw	Kj-N	NH_4^+-N	pH	TSs	VSs	CODs	BODs	VFA	TIP	TOA
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$		$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$
31/03/2000	24.9	11.2	18.9	10	31.7	4325	1923	882	8.8	8.9	5.6	8.9	886	180	17.5	3.0096
03/04/2000	24.3	15.8	18.6	14.2	30.3	5808	1820	805	8.8	9.5	6.2	9.7	1495	110	6.5	1.112
07/04/2000	26.8	12.3	21.2	11.3	37.7	7944	1923	847	8.4	11.3	7.8	14.6	4186	100	0.5	0.792
10/04/2000	26.9	12.2	21.2	11.5	36.5	5787	1950	805	8.4	9.7	6.4	10.5	1808	110	0	0.6204
13/04/2000	25.1	13	19.4	11	30.2	-	1880	810	8.6	9.2	6	10.5	-	70	0	0.5292
17/04/2000	25.8	12	20.2	10.7	34.7	4050	1820	854	8.5	10.7	7.5	13.7	1300	60	0	0.4662
20/04/2000	25.8	12.5	20.2	11.2	34.3	5134	1736	812	8.7	9.6	6.4	11.5	1462	80	0	0.567
25/04/2000	24.1	12.5	18.7	10.8	33.5	-	1820	980	8.6	9.6	6.6	17.6	-	130	5.3	0.4536
01/05/2000	23.9	14.8	18.6	13.5	32.7	4784	1661	746	8.6	9.6	6.6	11.8	2425	160	3.3	0.63
05/05/2000	22.2	12.3	17.2	11	30.8	3151	1643	613	8.7	10.9	7.1	10	1075	20	0	0.5414
09/05/2000	25.8	11.3	20.7	10.2	36.6	2984	1633	627	8.9	11	7.8	15.4	1150	100	0	0.6678
12/05/2000	23.2	10	18	9.3	30.3	3864	1633	676	8.7	9.5	6.2	11.5	1450	50	0	0.7308
15/05/2000	21.6	7.6	16.6	6.7	28.3	2650	1587	648	8.6	9.1	5.9	9.8	2138	40	0	0.504
18/05/2000	21.7	9	17.6	8.5	29.2	3300	1568	728	8.8	9.2	6	10.3	1150	60	0	0.4736
22/05/2000	20.6	8.7	15.8	8.2	27	3250	1568	690	8.9	8.9	5.7	9.9	1010	50	0	0.6016
25/05/2000	25.5	13	17.5	12.3	33.9	-	1650	658	8.8	9.1	5.8	10.9	-	0	0	0.5888
30/05/2000	21.8	10.7	16.8	9.7	25.7	2920	1700	660	8.7	9.4	6.1	7.8	1100	10	0	0.5632
06/06/2000	21.8	10.7	16.8	9.5	28.5	2220	1620	660	8.7	9.6	6.3	11.3	900	5	0	0.5376
12/06/2000	22.1	9.2	16.9	8.3	28.3	2100	1670	675	8.8	9.7	6.5	11.1	870	5	0	0.5296

Table D8. Analytical data of ML2 of laboratory Study 2.

Table D8

Date	VFA							Indoles and phenols					
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total	Phenol	P-cresol	O-et-ph	Indole	Skatole	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
31/03/2000	130	20	0	0	0	0	150	5	12	0.5	0	0	17.5
03/04/2000	100	10	0	0	0	0	110	1.5	5	0	0	0	6.5
07/04/2000	80	20	0	0	0	0	100	0	0.5	0	0	0	0.5
10/04/2000	80	30	0	0	0	0	110	0	0	0	0	0	0
13/04/2000	50	20	0	0	0	0	70	0	0	0	0	0	0
17/04/2000	50	10	0	0	0	0	60	0	0	0	0	0	0
20/04/2000	60	20	0	0	0	0	80	0	0	0	0	0	0
25/04/2000	90	40	0	0	0	0	130	0.5	4.8	0	0	0	5.3
01/05/2000	130	30	0	0	0	0	160	1	2.3	0	0	0	3.3
05/05/2000	20	0	0	0	0	0	20	0	0	0	0	0	0
09/05/2000	80	20	0	0	0	0	100	0	0	0	0	0	0
12/05/2000	50	0	0	0	0	0	50	0	0	0	0	0	0
15/05/2000	40	0	0	0	0	0	40	0	0	0	0	0	0
18/05/2000	60	0	0	0	0	0	60	0	0	0	0	0	0
22/05/2000	50	0	0	0	0	0	50	0	0	0	0	0	0
26/05/2000	0	0	0	0	0	0	0	0	0	0	0	0	0
30/05/2000	10	0	0	0	0	0	10	0	0	0	0	0	0
05/06/2000	5	0	0	0	0	0	5	0	0	0	0	0	0

Note : Ac = Acetic acid Pro = Propionic acid I-Bu = I-butyric acid
N-Bu = N-butyric acid I-Val = I-valeric acid N-Val = N-valeric acid

Table E1 & E2 Calculation of oxygen requirement for the full scale reactor

Table E1

Bold & italic = Velocity head - m

Basis : Solid conc. 2 - 6%
Cylindrical

For pig, the TS 2.7 - 7 % => Delt COD : 5 - 13 kg.m^{-3}
For cattle, the TS 2.25 - 6% => Delt COD : 4.9 - 13.1 kg.m^{-3}

Treatment period		*30*	*days*
Feed-rate		*30*	*m^3.d^{-1}*
Residence time		*1*	*day*
reactor-volume		*30*	*m^3*
diff COD	*TS:2.7%*	*5*	*kg.m^3*
O_2 density		*1.4*	*kg.m^3*
Utilization of O_2	10%	**0.1**	
Air requirement		**5102.0**	m^3.d^{-1}
		212.6	m^3.h^{-1}
Each m^3 of slurry needs		**170.1**	m^3 of air

Size of the aerator

At least 30 % to allow for variation

Output of aerator	**276.4**	m^3.h^{-1}
The aeration capacity	**6.3**	kgO_2.h^{-1}
(Feed rate*diff COD)		
The aeration intensity	**0.2**	kgO_2.h^{-1}.m^3 of reactor volume
Typical aerator efficiency	**1.0**	kgO_2.kWh^{-1}
Power required	**6.3**	kW
Electricity cost:	**7.0**	p.kWh^{-1}
Cost/m^3 of slurry	**35.0**	p.m^{-3} of slurry

Table E2

Preliminary design of Reactor

Basis : Solid conc. 2 - 6%
Cylindrical

For pig, the TS 2.7 - 7 % => Delt COD : 5 - 13 kg.m^{-3}
For cattle, the TS 2.25 - 6% => Delt COD : 4.9 - 13.1 kg.m^{-3}

Treatment period		*30*	*days*
Feed-rate		*30*	*m^3.d^{-1}*
Residence time		*1*	*day*
reactor-volume		*30*	*m^3*
diff COD	*TS:7%*	*13*	*kg.m^3*
O_2 density		*1.4*	*kg.m^3*
Utilization of O_2	*10%*	*0.1*	
Air requirement		*13265.3*	*m^3.d^{-1}*
		552.7	m^3.h^{-1}
Each m^3 of slurry needs		**442.2**	m^3 of air

Size of the aerator

At least 30 % to allow for variation

Output of aerator	**718.5**	m^3.h^{-1}
The aeration capacity	**16.3**	kgO_2.h^{-1}
(Feed rate*diff COD)		
The aeration intensity	**0.5**	kgO_2.h^{-1}.m^3 of reactor volume
Typical aerator efficiency	**1.0**	kgO_2.kWh^{-1}
Power required	**16.3**	kW
Electricity cost:	**7.0**	p.kWh^{-1}
Cost/m^3 of slurry	**91.0**	p.m^{-3} of slurry

Note:

a) diff COD is the difference between input and output COD

b) The final specification of an aerator for treatment system will be depended on liquid volume, power used air fowrate and the intensity of aeration.

c) Additional consideration:
1) O_2 transfer efficiency
2) mechanical mixing
3) type of aerator
4) hydrostatic pressure (liquid head)

Tables E3 & E4. Specification of aeration system.

Table E3. Specification of slurry re-circulation pump

Re-circulation pump		
		units
Pump type	Monoblock Screw Centrifgal	
Pump Duty	10	Litre.sec^{-1}
Max. efficiency	66	%
Max. head	14.2	m
Suction flange Size	65/16	mm/PN
Delivery flange Size	65/16	mm/PN
Pump motor:		
Motor type	IP55 TEFV	
Motor rating	2.2	kW
Type of starting	Dol	
Full Load current	6.5	amps
Starting Current	45	amps
Supply Voltage	400/3/50	watt
Pump weight	58 (approx.)	kg

Table E4. Specification of venturi aerator system

Venturi Aerator			
			units
Model		Hydrostal monobloc	
No. of Ejectors		1	
Pump Employed		3	phase
Pump Power consumption		2.6	kW
Pumping capacity		11	Litre.sec^{-1}
Compressor Power consumption		Max. 9.6	kW
Total pump consumption		Max. 12.2	kW
Nozzle size		35	mm
Barrel size	I.D.	70	mm
	Long	700	mm

Table E6. Venturi calculation

Bold & italic = Velocity head - m

$m^3.h^{-1}$	litre.sec^{-1}	Nozzle /pipe dia/mm														
		20	*25*	*30*	*35*	*40*	*45*	*50*	*55*	*60*	*65*	*70*	*75*	*80*	*85*	*90*
36	*10*	***51.64***	***21.15***	***10.20***	***5.51***	***3.23***	***2.01***	***1.32***	***0.90***	***0.64***	***0.46***	***0.34***	***0.26***	***0.20***	***0.16***	***0.13***
43.2	*12*	***74.36***	***30.46***	***14.69***	***7.93***	***4.65***	***2.90***	***1.90***	***1.30***	***0.92***	***0.67***	***0.50***	***0.38***	***0.29***	***0.23***	***0.18***
50.4	*14*	***101.22***	***41.46***	***19.99***	***10.79***	***6.33***	***3.95***	***2.59***	***1.77***	***1.25***	***0.91***	***0.67***	***0.51***	***0.40***	***0.31***	***0.25***
57.6	*16*	***132.20***	***54.15***	***26.11***	***14.10***	***8.26***	***5.16***	***3.38***	***2.31***	***1.63***	***1.18***	***0.88***	***0.67***	***0.52***	***0.41***	***0.32***
64.8	*18*	***167.32***	***68.53***	***33.05***	***17.84***	***10.46***	***6.53***	***4.28***	***2.93***	***2.07***	***1.50***	***1.11***	***0.85***	***0.65***	***0.51***	***0.41***
72	*20*	***206.57***	***84.61***	***40.80***	***22.02***	***12.91***	***8.06***	***5.29***	***3.61***	***2.55***	***1.85***	***1.38***	***1.04***	***0.81***	***0.63***	***0.50***
79.2	*22*	***249.95***	***102.38***	***49.37***	***26.65***	***15.62***	***9.75***	***6.40***	***4.37***	***3.09***	***2.24***	***1.67***	***1.26***	***0.98***	***0.77***	***0.61***
86.4	*24*	***297.46***	***121.84***	***58.76***	***31.72***	***18.59***	***11.61***	***7.61***	***5.20***	***3.67***	***2.67***	***1.98***	***1.50***	***1.16***	***0.91***	***0.73***
93.6	*26*	***349.10***	***142.99***	***68.96***	***37.22***	***21.82***	***13.62***	***8.94***	***6.10***	***4.31***	***3.13***	***2.33***	***1.77***	***1.36***	***1.07***	***0.85***
100.8	*28*	***404.87***	***165.84***	***79.97***	***43.17***	***25.30***	***15.80***	***10.36***	***7.08***	***5.00***	***3.63***	***2.70***	***2.05***	***1.58***	***1.24***	***0.99***
108	*30*	***464.78***	***190.37***	***91.81***	***49.56***	***29.05***	***18.13***	***11.90***	***8.13***	***5.74***	***4.17***	***3.10***	***2.35***	***1.82***	***1.42***	***1.13***

Figure E3. Relationships of velocity head, flow rate and venturi nozzle size

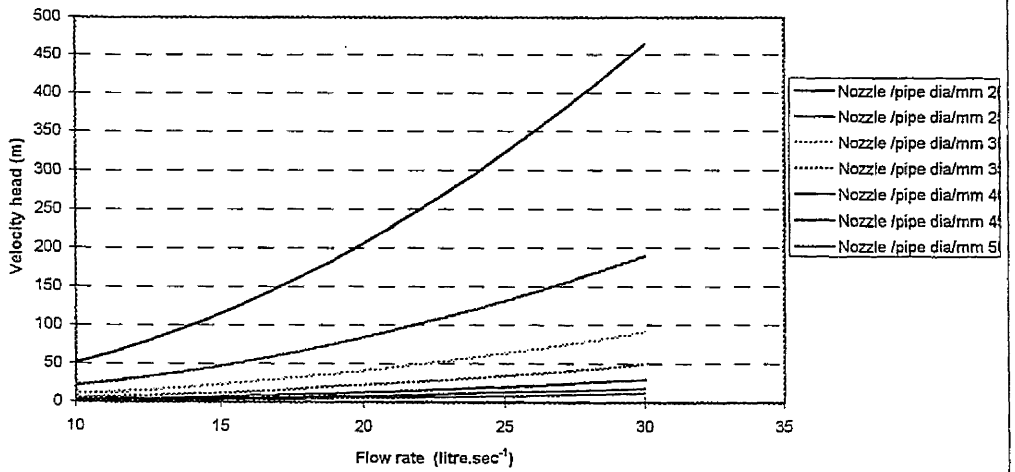


Table E5. Calculation of Nozzle pressure loss - m

Bold Italic = calculated pressure loss - in m

Italic = Velocity head - m			Flow-rate/ litre.sec^{-1}										
Nozzle dia/mm	Area/m^2	Cd	10	12	14	16	18	20	22	24	26	28	30
20	0.0003142	1	***51.64***	***74.36***	***101.22***	***132.20***	***167.32***	***206.57***	***249.95***	***297.46***	***349.10***	***404.87***	***464.78***
25	0.0004909	1	***21.15***	***30.46***	***41.46***	***54.15***	***68.53***	***84.61***	***102.38***	***121.84***	***142.99***	***165.84***	***190.37***
30	0.0007069	1	***10.20***	***14.69***	***19.99***	***26.11***	***33.05***	***40.80***	***49.37***	***58.76***	***68.96***	***79.97***	***91.81***
35	0.0009621	1	***5.51***	***7.93***	***10.79***	***14.10***	***17.84***	***22.02***	***26.65***	***31.72***	***37.22***	***43.17***	***49.56***
40	0.0012566	1	***3.23***	***4.65***	***6.33***	***8.26***	***10.46***	***12.91***	***15.62***	***18.59***	***21.82***	***25.30***	***29.05***
45	0.0015904	1	***2.01***	***2.90***	***3.95***	***5.16***	***6.53***	***8.06***	***9.75***	***11.61***	***13.62***	***15.80***	***18.13***
50	0.0019635	1	***1.32***	***1.90***	***2.59***	***3.38***	***4.28***	***5.29***	***6.40***	***7.61***	***8.94***	***10.36***	***11.90***
55	0.0023758	1	***0.90***	***1.30***	***1.77***	***2.31***	***2.93***	***3.61***	***4.37***	***5.20***	***6.10***	***7.08***	***8.13***
60	0.0028274	1	***0.64***	***0.92***	***1.25***	***1.63***	***2.07***	***2.55***	***3.09***	***3.67***	***4.31***	***5.00***	***5.74***
65	0.0033183	1	***0.46***	***0.67***	***0.91***	***1.18***	***1.50***	***1.85***	***2.24***	***2.67***	***3.13***	***3.63***	***4.17***
70	0.0038485	1	***0.34***	***0.50***	***0.67***	***0.88***	***1.11***	***1.38***	***1.67***	***1.98***	***2.33***	***2.70***	***3.10***
75	0.0044179	1	***0.26***	***0.38***	***0.51***	***0.67***	***0.85***	***1.04***	***1.26***	***1.50***	***1.77***	***2.05***	***2.35***
80	0.0050265	1	***0.20***	***0.29***	***0.40***	***0.52***	***0.65***	***0.81***	***0.98***	***1.16***	***1.36***	***1.58***	***1.82***
85	0.0056745	1	***0.16***	***0.23***	***0.31***	***0.41***	***0.51***	***0.63***	***0.77***	***0.91***	***1.07***	***1.24***	***1.42***
90	0.0063617	1	***0.13***	***0.18***	***0.25***	***0.32***	***0.41***	***0.50***	***0.61***	***0.73***	***0.85***	***0.99***	***1.13***
95	0.0070882	1	***0.10***	***0.15***	***0.20***	***0.26***	***0.33***	***0.41***	***0.49***	***0.58***	***0.69***	***0.80***	***0.91***
100	0.007854	1	***0.08***	***0.12***	***0.16***	***0.21***	***0.27***	***0.33***	***0.40***	***0.48***	***0.56***	***0.65***	***0.74***

Note: Air flowrate (Q) was based on the Benoulli's equation below:

$Q = Cd*a*(2gh)^{0.5}$ Q = flowrate, m^3.sec^{-1} Cd = nozzle coefficier a = Cross section area of nozzle, m^2

g = gravity, m.sec^{-1} h = static head, m (liquid level to the discharge point)

Bernoulli's equation (Coulson and Richardson, 1993)

Consider a tank with a small hole at the side of the wall. The liquid is accelerated by causing it to flow through a constriction, the kinetic energy is thereby increased and the pressure energy therefore decrases. In considering the energy balance by applying Bernoulli's equation :

$h_1 + P_1/pg + V_1^2/2g = h_2 + P_2/pg + V_2^2/2g +$ losses

With $P_1 = P_2$ (both atmospheric pressure).
$h_2 = 0$ datum value
Assuming $V_1 = 0$ comparing the V_2
and assuming the the energy losses is negligible

Then the Bernoulli's equation become

$h_1 = V_2^2/2g$
or $V_2 = (2gh)^{0.5}$ Torricelli's theorem and the velocity is called the theoretical velocity.

The velocity coefficient have to be considered in order to figure out the actual velocity

Cv = actual velocity/ theoretical velocity

then the actual velocity $V_2 = Cv(2gh)^{0.5}$

The jet area is much less than the area of the nozzle due to contraction and the corresponding coefficient of contraction is defined as :

Cc = area of jet / area of nozzle

The velocity of the fluid is gradually increased and the contours are so designed that almost frictionless flow takes place in the converging portion; the outlet corresponds to the vena contracta on the orifice. The nozzle has a constant high coefficient of discharge (ca 0.99) over a wide range of condition because the coefficient of contraction is unity. (C&R, chapter 6. vol1) The velocity is normal to the cross-section of the jet and hence the discharge can be written:

Q = area of jet * velocity of jet
$= Ca*a*Cv*(2gh)^{0.5}$
$= Cd * a * (2gh)^{0.5}$

Where Cd is the coefficient of discharge and defined as :
Cd = actual discharge / theoretical discharge, a $(2gh)^{0.5}$
= CcCv

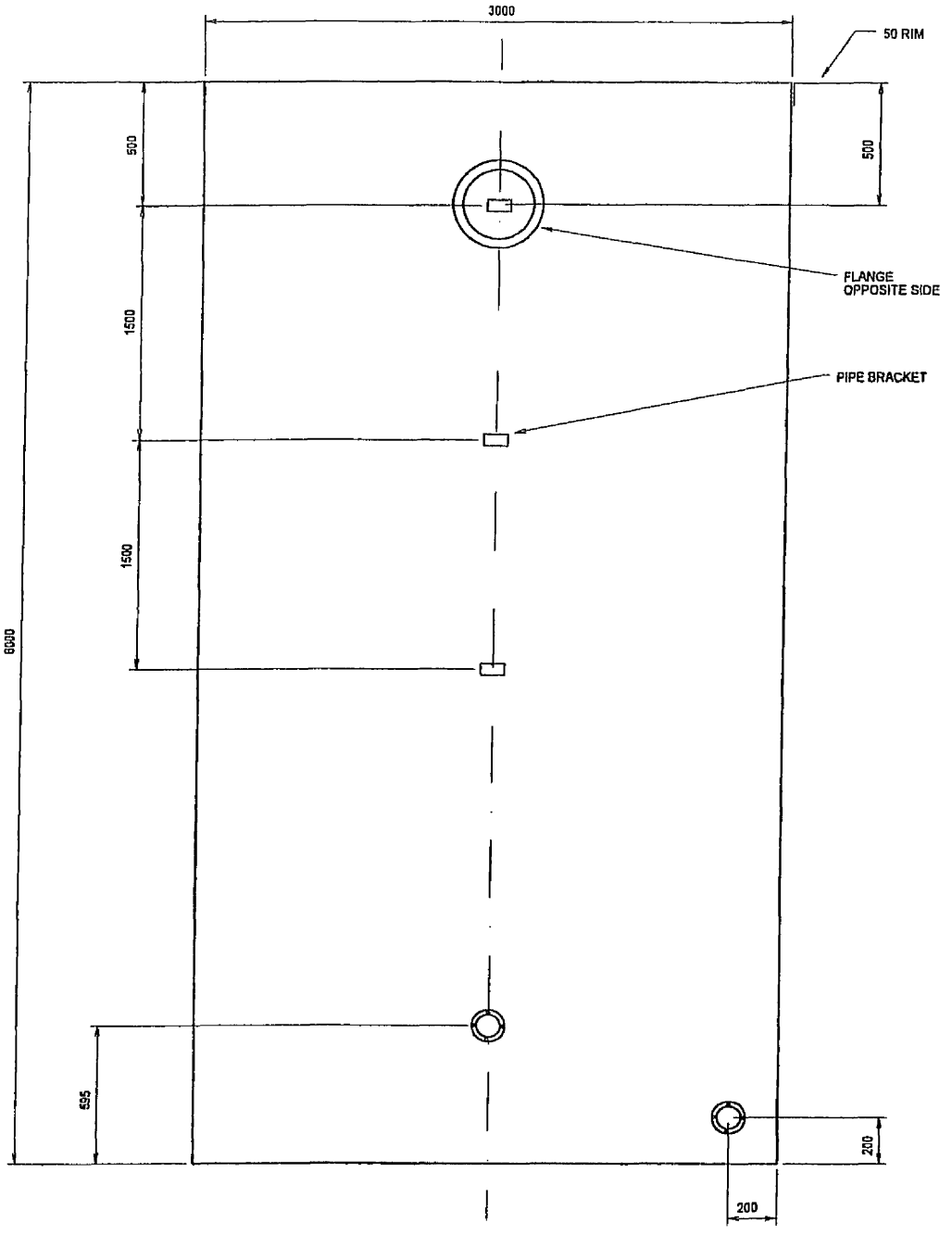


Figure E1 Front elevation of reactor vessel dimensions in mm

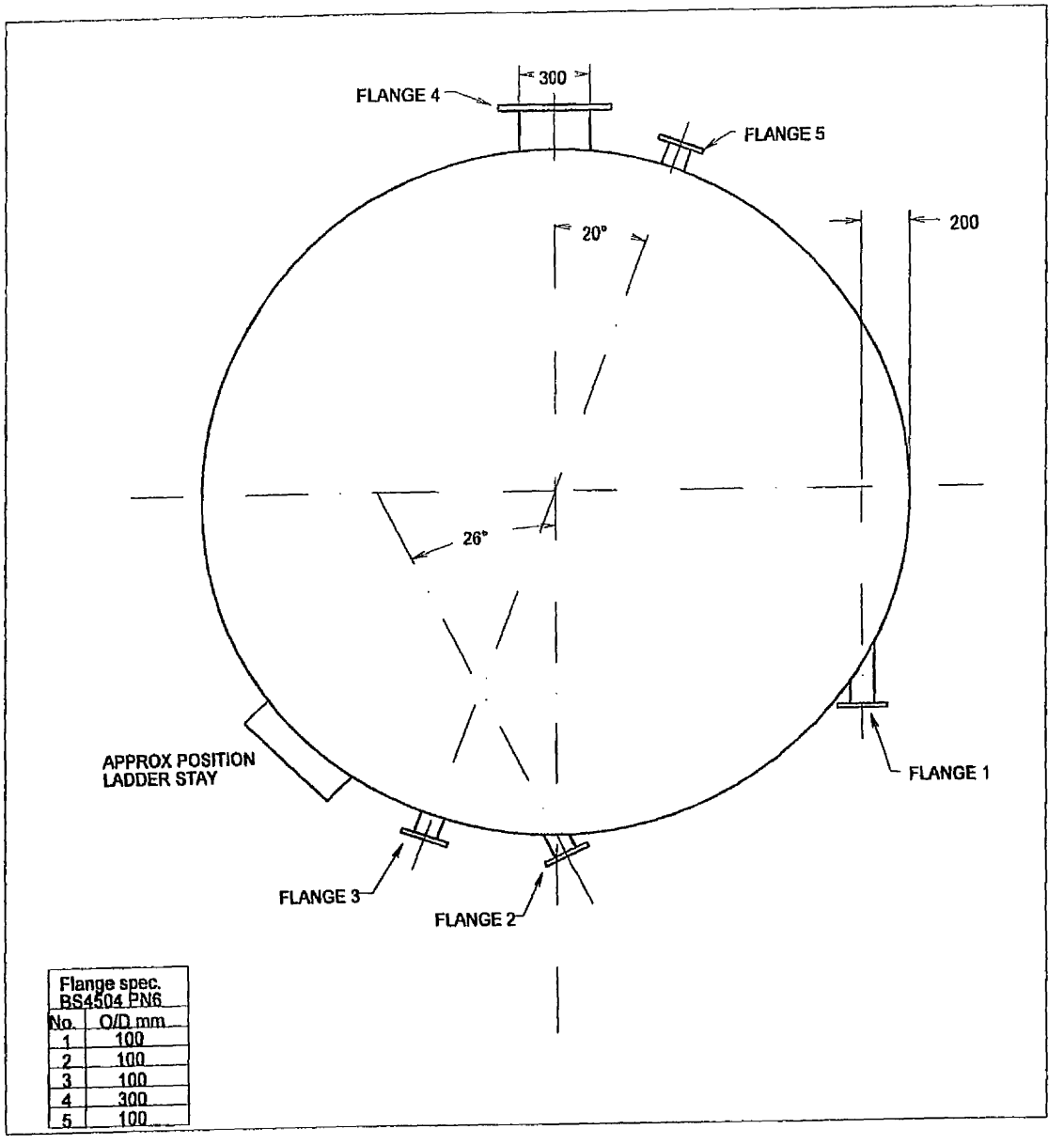


Figure E2. Top elevation of reactor vessel dimensions in mm

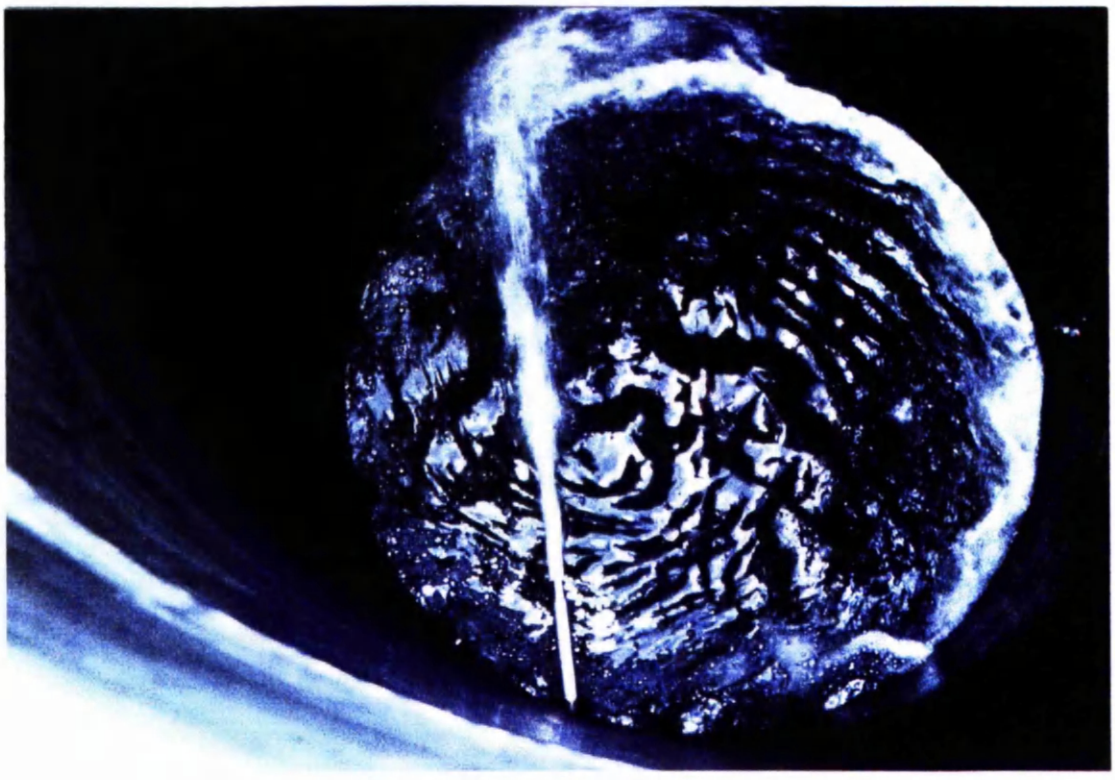


Figure E3. Venturi barrel and phenomena of liquid jet

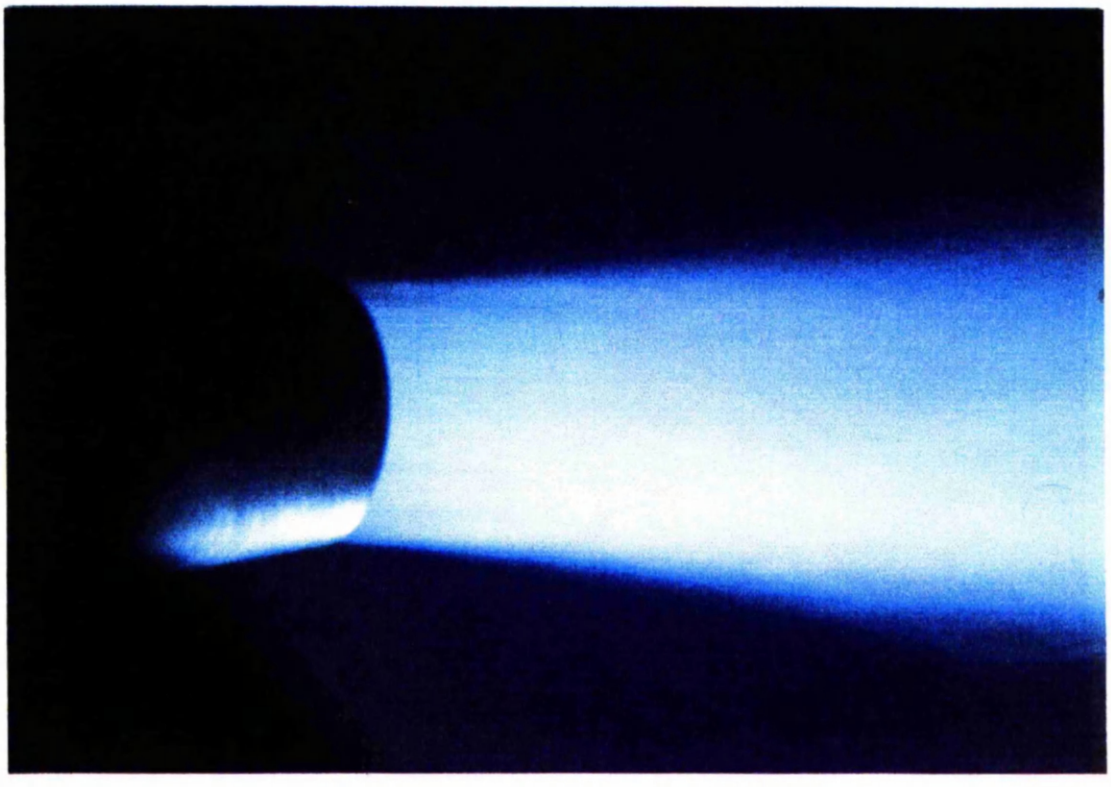
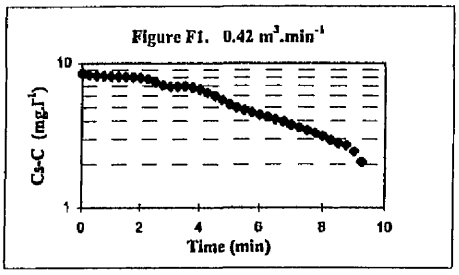
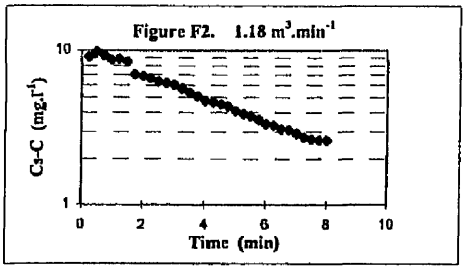
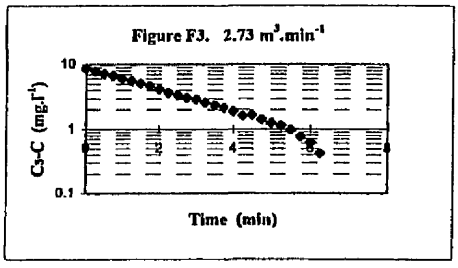
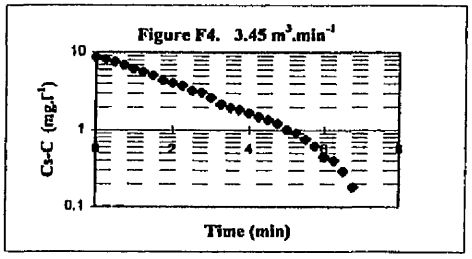


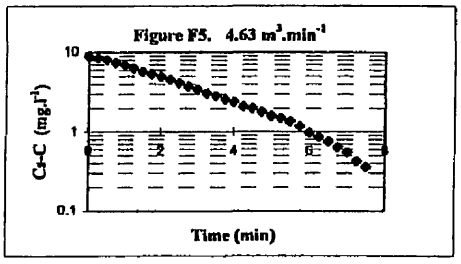
Figure E4. Venturi jet

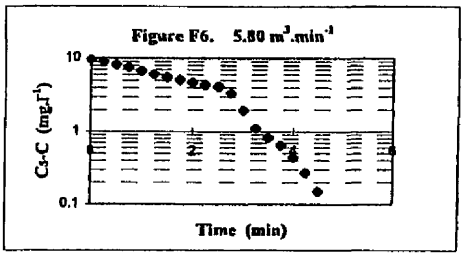












Figures F1 - F6 Dissolved oxygen deficit (Cs-C) (logarithmic) vs time with air flow rate 0.42, 2.73, 3.35, 4.63, 5.8 $m^3.min^{-1}$ in water and 1.18 $m^3.min^{-1}$ in pig slurry

Tables G1-G3. Analytical data of feed slurry during farm scale treatment Trial 1

Table G1

Date	TS	TSS	VS	VSS	CODw	BODw	Kj-N	NH_4^+-N	pH	TSs	VSs	CODs	BODs	VFA	TIP	TOA
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$		$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$
18/01/2000	8.7	-	4.3	-	22.4	3800	1895	1544	8.1	6.1	2.7	10.5	2500	3390	42.4	2.9
21/01/2000	8.3	-	4	-	10.5	4060	2044	1690	8.2	6.6	2.6	7.5	2900	5060	25.6	3.5
02/02/2000	9.6	-	5.4	-	10.9	-	-	1640	8.2	6.7	3.6	5.3	-	3030	19.4	-
04/02/2000	9.9	-	5.7	-	11.8	-	-	1840	8.1	6.6	2.8	6	-	2060	16.2	2
08/02/2000	8.5	-	3.8	-	8	2470	1930	1520	8.2	6.5	2.4	5.3	1690	1740	10	0.7
11/02/2000	8.2	-	3.8	-	7.3	-	-	1660	8.2	6.4	2.3	4.7	-	1660	10.8	1.5
15/02/2000	7.8	-	3.7	-	6.4	2600.0	1890.0	1620.0	8.2	6.1	2.4	4.2	1700.0	1450	11	1.5
18/02/2000	7.8	-	3.5	-	6.5	-	-	1580.0	8.2	6.1	2.1	4.1	-	1300	7.8	1.3
22/02/2000	7.6	-	3.5	-	6	1920	1910	1540	8.2	6.1	2.1	4.1	1250	1100	7	1.1
25/02/2000	7.4	1.5	3.1	1.3	5.1	1280	1910	1550	8.2	6.1	1.9	3.5	1200	1040	9.1	0.5

Table G2

Date	VFA						
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
18/01/2000	2100	750	140	210	130	60	3390
21/01/2000	3100	1050	370	280	170	90	5060
02/02/2000	1800	660	160	210	140	60	3030
04/02/2000	1140	450	130	160	130	50	2060
08/02/2000	960	370	120	130	110	50	1740
11/02/2000	920	350	110	120	110	50	1660
15/02/2000	820	310	90	110	90	30	1450
18/02/2000	720	280	90	100	80	30	1300
22/02/2000	640	240	70	80	70	0	1100
25/02/2000	610	230	70	70	60	0	1040

Table G3

Date	Indoles and phenols					
	Phenol	P-cresol	O-ethy-ph	Indole	Skatole	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
18/01/2000	2	35	4.1	0	1.3	42.4
21/01/2000	2.5	20	2.1	0	1	25.6
02/02/2000	7.5	9.8	1.5	0	0.6	19.4
04/02/2000	5.3	9.3	1.1	0	0.5	16.2
08/02/2000	6.3	2.1	1	0	0.6	10
11/02/2000	5	4.5	0.9	0	0.4	10.8
15/02/2000	5.2	4.7	0.7	0	0.4	11
18/02/2000	4.6	2.5	0.7	0	0	7.8
22/02/2000	4.4	2.1	0.5	0	0	7
25/02/2000	5.8	2.8	0.5	0	0	9.1

Tables G4-G6. Analytical data of ML during farm scale treatment Trial 1

Table G4

Date	TS	TSS	VS	VSS	CODw	BODw	Kj-N	NH_4^+-N	pH	TSs	VSs	CODs	BODs	VFA	TIP	TOA
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$		$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$
21/01/2000	8.6	-	4.2	-	10	3560	2000	1670	8.4	6.7	2.6	7.3	2710	3780	13.2	3.5
02/02/2000	7.9	-	2.8	-	5.8	-	-	1530	8.4	5.5	1.7	1.8	-	160	5	<0.5
04/02/2000	7.6	-	3.6	-	5.8	-	-	1460	8.2	5.5	1.7	2.7	-	80	3.1	<0.5
08/02/2000	7.6	-	3.4	-	5.6	640	1910	1310	8.2	5.5	1.4	2.3	95	50	8.1	<0.5
11/02/2000	7.8	-	3.6	-	5.3	-	-	1550	8.3	5.5	1.5	1.7	-	30	2	<0.5
15/02/2000	7.6	-	3.6	-	5.2	1300	1900	1550	8.3	5.4	1.5	2.1	160	30	0.4	<0.5
18/02/2000	7.6	-	3.4	-	4.8	-	-	1540	8.3	5.5	1.6	3.0	-	<10	1.6	<0.5
22/02/2000	7.6	-	3.5	-	5.0	920	1920	1520	8.3	5.4	1.5	2.1	120	<10	2	<0.5
25/02/2000	7.4	1.6	3.3	1.5	4.9	1000	1930	1530	8.2	5.6	1.6	1.9	200	30	1	<0.5

Table G5

Date	VFA						
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
21/01/2000	2350	830	150	230	150	70	3780
02/02/2000	130	30	0	0	0	0	160
04/02/2000	70	10	0	0	0	0	80
08/02/2000	50	0	0	0	0	0	50
11/02/2000	20	10	0	0	0	0	30
15/02/2000	30	0	0	0	0	0	30
18/02/2000	8	0	0	0	0	0	8
22/02/2000	7	0	0	0	0	0	7
25/02/2000	30	0	0	0	0	0	30

Table G6

Date	Indoles and phenols					
	Phenol	P-cresol	O-ethy-ph	Indole	Skatole	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
21/01/2000	1	11	1.2	0	0	13.2
02/02/2000	1	3.5	0.5	0	0	5
04/02/2000	0.8	1.3	1	0	0	3.1
08/02/2000	4	1.5	2	0	0.6	8.1
11/02/2000	2	0	0	0	0	2
15/02/2000	0.4	0	0	0	0	0.4
18/02/2000	1.6	0	0	0	0	1.6
22/02/2000	2	0	0	0	0	2
25/02/2000	1	0	0	0	0	1

Tables H1-H3. Analytical data of feed slurry during farm scale treatment Trial 2

Table H1

Date	TS	TSS	VS	VSS	CODw	BODw	Kj-N	NH_4^+-N	pH	TSs	VSs	CODs	BODs	VFA	TIP	TOA
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$		$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$
29/02/2000	10.1	1.1	5.2	1.0	12.1	4590	2410	2100	8.1	7.8	2.9	8.5	2770	4070	39.9	3950
03/03/2000	9.8	1.0	5.0	1.0	11.4	4680	2450	2100	8.1	7.4	2.9	8.1	2900	2650	33.0	3340
07/03/2000	14.0	2.7	8.8	2.5	15.7	5050	2700	2030	8.1	7.4	2.9	7	2560	2640	22.5	2532
10/03/2000	9.6	1.7	4.0	1.7	12.2	3780	2570	2030	8.3	7.4	2.4	6.2	2660	3290	18.8	3510
14/03/2000	11.6	5.2	6.7	4.9	11.7	3410	2560	1930	8.4	7.1	2.5	4.5	1880	1670	12.4	1980
17/03/2000	9.2	2.0	4.5	1.8	7.5	3030	2440	2020	8.3	7.1	2.7	4.1	1720	1450	11.7	1470
21/03/2000	9.0	1.9	4.3	1.4	7.4	2070	2410	1820	8.3	6.8	2.3	3.7	1190	1060	6.3	1358
24/03/2000	8.2	1.4	3.5	1.3	6.9	1300	2300	1930	8.3	6.6	2.1	3.8	830	760	2.6	952
27/03/2000	9.9	1.8	5.2	1.7	7.1	1870	2450	1930	8.4	6.3	1.9	2.3	770	930	3.5	1100
31/03/2000	8.0	1.6	3.3	1.5	5.3	875	2360	2020	8.4	6.4	1.9	3.4	560	490	3.5	420
04/04/2000	7.5	1.2	3.0	1.0	4.7	900	2240	1920	8.3	6.1	1.9	1.9	433	240	2.0	476
07/04/2000	7.5	1.3	3.0	1.2	4.5	875	2198	1883	8.5	6.1	1.8	1.7	362	120	1.5	358
11/04/2000	7.0	1.1	2.6	1.0	4.5	488	2133	1909	8.4	6	1.7	2.4	350	90	0.0	165
14/04/2000	7.2	1.1	2.7	1.0	4.2	310	2199	1908	8.5	6.1	1.7	2.3	150	140	0.0	253
17/04/2000	7.3	1.1	2.8	1.0	3.9	425	2063	1843	8.4	6	1.7	2	210	130	0.0	271

Table H2

Date	VFA						
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
29/02/2000	2310	970	210	270	220	90	4070
03/03/2000	1300	720	170	210	180	70	2650
07/03/2000	1500	640	140	170	140	50	2640
10/03/2000	1790	800	230	250	220	0	3290
14/03/2000	950	390	110	110	110	0	1670
17/03/2000	800	370	90	100	90	0	1450
21/03/2000	610	260	60	70	60	0	1060
24/03/2000	450	180	40	40	50	0	760
27/03/2000	550	230	50	50	50	0	930
31/03/2000	330	130	30	0	0	0	490
04/04/2000	160	70	10	0	0	0	240
07/04/2000	80	40	0	0	0	0	120
11/04/2000	60	30	0	0	0	0	90
14/04/2000	100	40	0	0	0	0	140
17/04/2000	90	40	0	0	0	0	130

Table H3

Date	Indoles and phenols					
	Phenol	P-cresol	O-ethy-ph	Indole	Skatole	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
29/02/2000	4.1	33	2.8	0	0	39.9
03/03/2000	3.8	26	2.2	0	1	33.0
07/03/2000	3.3	18	1.0	0	0	22.5
10/03/2000	2.8	15	1.0	0	0	18.8
14/03/2000	4.0	8	0.6	0	0	12.4
17/03/2000	3.2	8	0.8	0	0	11.7
21/03/2000	2.8	3	0.5	0	0	6.3
24/03/2000	2.6	0	0.0	0	0	2.6
27/03/2000	1.5	2	0.0	0	0	3.5
31/03/2000	3.5	0	0.0	0	0	3.5
04/04/2000	2.0	0	0.0	0	0	2.0
07/04/2000	1.5	0	0.0	0	0	1.5
11/04/2000	0.0	0	0.0	0	0	0.0
14/04/2000	0.0	0	0.0	0	0	0.0
17/04/2000	0.0	0	0.0	0	0	0.0

Tables H4-H6. Analytical data of ML during farm scale treatment Trial 2

Table H4

Date	TS	TSS	VS	VSS	CODw	BODw	Kj- N	NH_4^+-N	pH	TSs	VSs	CODs	BODs	VFA	TIP	TOA
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$		$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$
29/02/2000	8.1	1.1	3.9	1.0	7.0	1490	2170	1890	8.2	5.7	1.6	2.7	520	410	0.6	662
03/03/2000	9.3	1.4	4.7	1.3	7.5	1700	2320	1900	8.2	5.8	1.6	2.9	210	200	0.0	560
07/03/2000	11.5	2.6	6.5	2.4	10.4	2500	2750	1920	8.2	6.1	1.6	2.9	210	250	1.6	394
10/03/2000	12.2	2.5	7.1	2.5	9.8	2240	2680	1940	8.3	6.2	1.7	2.9	220	120	1.2	448
14/03/2000	11.8	2.0	6.7	1.9	10.5	2090	2640	1890	8.5	6.0	1.6	1.9	220	140	0.0	294
17/03/2000	10.5	2.0	5.8	1.7	8.0	1800	2560	1920	8.3	6.2	1.9	1.8	220	30	0.0	350
21/03/2000	10.1	1.9	5.2	1.8	8.0	1310	2690	1820	8.2	6.1	1.6	1.9	200	100	0.8	238
24/03/2000	10.1	1.7	5.4	1.6	8.0	850	2540	1960	8.2	6.1	1.7	2.2	100	40	0.0	364
27/03/2000	8.7	1.9	3.9	1.8	5.3	1000	2310	1960	8.5	5.9	1.5	1.3	90	10	0.6	574
31/03/2000	8.5	1.6	3.8	1.5	3.6	620	2400	1940	8.4	6.1	1.6	3.6	180	40	0.0	392
04/04/2000	8.8	1.7	4.3	1.6	5.9	583	2280	1940	8.2	5.9	1.7	1.5	170	30	0.0	294
07/04/2000	8.2	1.8	3.6	1.6	4.6	758	2324	1855	8.5	6.0	1.6	1.4	160	30	0.0	410
11/04/2000	7.7	1.4	3.1	1.3	4.9	490	2263	1906	8.4	5.9	1.5	2.1	120	20	0.0	120
14/04/2000	7.6	1.4	3.0	1.3	4.8	350	2263	1814	8.5	6.0	1.6	2.1	120	70	0.0	220
17/04/2000	7.3	1.2	2.7	1.0	2.9	392	2053	1785	8.3	5.9	1.5	1.9	120	40	0.0	250

Table H5

Date	VFA						
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
29/02/2000	250	110	30	20	0	0	410
03/03/2000	150	50	0	0	0	0	200
07/03/2000	200	50	<10	<10	0	0	250
10/03/2000	90	30	0	0	0	0	120
14/03/2000	110	30	0	0	0	0	140
17/03/2000	30	<10	0	0	0	0	30
21/03/2000	80	20	0	0	0	0	100
24/03/2000	40	<10	0	0	0	0	40
27/03/2000	10	0	0	0	0	0	10
31/03/2000	40	0	0	0	0	0	40
04/04/2000	30	<10	0	0	0	0	30
07/04/2000	30	0	0	0	0	0	30
11/04/2000	20	0	0	0	0	0	20
14/04/2000	50	20	0	0	0	0	70
17/04/2000	40	0	0	0	0	0	40

Table H6

Date	Indoles and phenols					
	Phenol	P-cresol	O-ethy-ph	Indole	Skatole	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
29/02/2000	0.6	0	0	0	0	0.6
03/03/2000	0	0	0	0	0	0
07/03/2000	1.6	0	0	0	0	1.6
10/03/2000	1.2	0	0	0	0	1.2
14/03/2000	0	0	0	0	0	0
17/03/2000	0	0	0	0	0	0
21/03/2000	0.8	0	0	0	0	0.8
24/03/2000	0	0	0	0	0	0
27/03/2000	0.6	0	0	0	0	0.6
31/03/2000	0	0	0	0	0	0
04/04/2000	0	0	0	0	0	0
07/04/2000	0	0	0	0	0	0
11/04/2000	0	0	0	0	0	0
14/04/2000	0	0	0	0	0	0
17/04/2000	0	0	0	0	0	0

Table H7. Analytical data of anaerobic storage during Farm scale treatment Trial 2.

day of treatment	Slurry storage		ML	
	sample1	sample2	sample1	sample2
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
0	5500	5140	750	870
3	3760	4110	480	900
8	4080	3020	390	930
11	3320	3200	300	810
15	2450	2940	460	680
18	1950	2340	290	650
22	2580	840	560	740
25	1300	1440	190	730
28	1370	1100	130	360
32	840	630	130	440
36	420	400	268	220
43	290	334	370	140
46	170	334	125	280
49	180	110	10	100

Note : sample 1 = slurry store for 10 days
sample 2 = slurry store for 20 days

Tables I1-I3. Analytical data of feed slurry during farm scale treatment Trial 3

Table I1

Date	TS	TSS	VS	VSS	CODw	BODw	Kj-N	NH_4^+-N	pH	TSs	VSs	CODs	BODs	VFA	TIP	TOA
	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$		$g.l^{-1}$	$g.l^{-1}$	$g.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$g.l^{-1}$
15/05/2000	9.6	2.6	5.5	2.4	13.2	6500	1920	1570	8	6.2	2.6	8.8	5350	6890	64	7.210
19/05/2000	9.5	2.2	5.3	2.0	12.7	5050	2120	1720	8.1	6.7	3	8.2	3650	6130	48	6.620
23/05/2000	9.0	2.3	4.9	1.8	10.3	3280	2040	1600	8.2	6.3	2.8	6.2	2720	4170	29.2	4.520
26/05/2000	9.0	2.7	4.9	2.1	9.9	2960	2010	1620	8.3	5.9	2.4	6.7	2530	3250	25.4	4.010
30/05/2000	8.3	2.7	4.3	2.0	8.2	1860	1940	1600	8.3	5.7	2.2	4.9	1500	2310	12.4	3.096
02/06/2000	8.9	2.8	4.8	2.6	8.7	1680	2060	1580	8.3	5.6	2.1	4.2	1270	400	10.6	1.242
06/06/2000	8.1	2.7	4.0	2.4	7.4	1040	1980	1590	8.2	5.3	1.9	1.9	840	1370	5.4	1.600
09/06/2000	7.8	2.2	3.8	2.0	6.6	1010	1927	1590	8.4	5.2	1.9	3.0	850	1210	2.4	1.800
13/06/2000	7.8	2.0	3.8	1.8	5.9	1025	1900	1550	8.3	5.9	2.1	3	710	680	0.6	0.779
16/06/2000	8.0	2.2	4.0	1.6	5.8	966	1910	1520	8.3	5.9	2.2	2.7	503	480	1	0.713
19/06/2000	7.8	2.8	3.5	2.5	5.3	585	1782	1421	8.3	5.1	1.6	1.7	346	450	0	0.528
22/06/2000	7.2	2.1	3.1	1.8	4.3	600	1910	1432	8.2	5	1.5	1.6	357	410	0	0.462

Table I2

Date	VFA						
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
15/05/2000	3100	2240	480	340	480	250	6890
19/05/2000	2910	1900	410	290	410	210	6130
23/05/2000	2580	1000	230	150	210	0	4170
26/05/2000	1680	920	220	130	220	80	3250
30/05/2000	1270	630	150	80	140	40	2310
02/06/2000	350	30	20	0	0	0	400
06/06/2000	810	340	80	40	80	0	1350
09/06/2000	750	240	70	20	50	0	1130
13/06/2000	490	120	40	10	20	0	680
16/06/2000	390	70	20	0	0	0	480
19/06/2000	400	30	20	0	0	0	450
22/06/2000	380	20	10	0	0	0	410

Table I3

Date	Indoles and phenols					
	Phenol	P-cresol	O-ethy-ph	Indole	Skatole	Total
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
15/05/2000	7.8	51.0	3.4	0.4	1.4	64.0
19/05/2000	6.2	38.4	2.4	0.2	0.8	48.0
23/05/2000	3.6	23.6	1.4	0.2	0.4	29.2
26/05/2000	2.8	21.4	1.0	0.2	0.0	25.4
30/05/2000	1.4	10.4	0.6	0.0	0.0	12.4
02/06/2000	1.0	9.2	0.4	0.0	0.0	10.6
06/06/2000	0.6	4.6	0.2	0.0	0.0	5.4
09/06/2000	0.4	1.8	0.2	0.0	0.0	2.4
13/06/2000	0.0	0.6	0.0	0.0	0.0	0.6
16/06/2000	0.0	1.0	0.0	0.0	0.0	1.0
19/06/2000	0.0	0.0	0.0	0.0	0.0	0.0
22/06/2000	0.0	0.0	0.0	0.0	0.0	0.0

Tables I4-I7. Analytical data of ML during farm scale treatment Trial 3

Table I4

Date	TS	TSS	VS	VSS	CODw	BODw	Kj-N	NH4-N	pHw	TSs	VSs	CODs	BODs	VFA	TIP	TOA
	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	mg.l^{-1}	mg.l^{-1}	mg.l^{-1}		g.l^{-1}	g.l^{-1}	g.l^{-1}	mg.l^{-1}	mg.l^{-1}	mg.l^{-1}	g.l^{-1}
15/05/2000	9.4	2.2	5.2	2	13.2	6950	2050	1680	8	5.8	2.3	8.2	5250	5730	59.2	7.120
19/05/2000	15.9	10.2	9.9	9.6	17.2	2400	2600	1520	8.2	5.5	1.8	3.5	200	100	0.4	0.397
23/05/2000	18.9	8.2	12.2	6.7	20.1	2000	2890	1700	8.4	5.2	1.7	2.9	300	40	0.2	0.384
26/05/2000	17.5	5.8	11.1	5.1	18.7	1810	2690	1580	8.4	4.7	1.3	2.5	185	40	0.2	0.486
30/05/2000	16.6	10.2	12.4	8.3	18	1540	2840	1540	8.3	4.8	1.3	2.3	190	40	0.1	0.256
02/06/2000	16.4	10.8	10.3	8.3	17.4	1350	2670	1570	8.3	4.8	1.3	2.3	180	40	0	0.243
06/06/2000	16.2	9.3	10.2	7.6	16.9	560	2600	1550	8.2	4.8	1.3	2.0	70	110	0	0.230
09/06/2000	16.6	7.8	10.5	6.6	16.5	1100	2630	1560	8.3	4.9	1.5	2.3	130	70	0	0.317
13/06/2000	17.4	7.6	11.1	5.8	16.8	1813	2610	1570	8.2	5.2	1.5	2.4	85	20	0	0.317
16/06/2000	16.8	5.9	10.6	4.8	15.2	1483	2530	1470	8.2	5.3	1.4	2.3	89	20	0	0.304
19/06/2000	17.4	4.9	11	4.1	16.6	1005	2497	1421	8.2	4.9	1.3	1.5	68	20	0	0.264
22/06/2000	22.3	3.6	14.7	3	14.5	1298	3024	1442	8.2	4.9	1.4	1.3	89	10	0	0.277

Table I5

Date	VFA						
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total
	mg.l^{-1}	mg.l^{-1}	mg.l^{-1}	mg.l^{-1}	mg.l^{-1}	mg.l^{-1}	mg.l^{-1}
15/05/2000	4180	2010	430	380	440	290	7730
19/05/2000	90	10	0	0	0	0	100
23/05/2000	30	10	0	0	0	0	40
26/05/2000	40	0	0	0	0	0	40
30/05/2000	30	10	0	0	0	0	40
02/06/2000	40	0	0	0	0	0	40
06/06/2000	80	30	0	0	0	0	110
09/06/2000	60	10	0	0	0	0	70
13/06/2000	20	0	0	0	0	0	20
16/06/2000	20	0	0	0	0	0	20
19/06/2000	20	0	0	0	0	0	20
22/06/2000	10	0	0	0	0	0	10

Table I6

Date	Indoles and phenols					
	Phenol	P-cresol	O-ethy-ph	Indole	Skatole	Total
	mg.l^{-1}	mg.l^{-1}	mg.l^{-1}	mg.l^{-1}	mg.l^{-1}	mg.l^{-1}
15/05/2000	8	46.8	3	0.4	1	59.2
19/05/2000	0	0.4	0	0	0	0.4
23/05/2000	0	0.2	0	0	0	0.2
26/05/2000	0	0.2	0	0	0	0.2
30/05/2000	0	0.1	0	0	0	0.1
02/06/2000	0	0	0	0	0	0
06/06/2000	0	0	0	0	0	0
09/06/2000	0	0	0	0	0	0
13/06/2000	0	0	0	0	0	0
16/06/2000	0	0	0	0	0	0
19/06/2000	0	0	0	0	0	0
22/06/2000	0	0	0	0	0	0

Anaerobic storage after the treatment

Table I7

Date	VFA						
	Ac	Pro	I-Bu	N-Bu	I-Val	N-Val	Total
	mg.L^{-1}	mg.L^{-1}	mg.L^{-1}	mg.L^{-1}	mg.L^{-1}	mg.L^{-1}	mg.L^{-1}
26/06/2000	100	0	0	0	0	0	100
03/07/2000	190	20	0	0	0	0	210
10/07/2000	210	50	5	0	0	0	265
17/07/2000	230	100	0	0	0	0	330
24/07/2000	260	140	0	0	0	0	400

Table I8. Analytical data of anaerobic storage during Farm scale treatment Trial 3.

day of treatment	Slurry storage		ML	
	sample1	sample2	sample1	sample2
	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$	$mg.l^{-1}$
0	6410	5850	8120	7610
4	5930	3970	250	310
8	3880	4180	330	550
11	3290	2950	360	560
15	2090	2420	100	220
18	1920	1700	70	140
22	1510	1380	90	70
25	1120	1090	100	113
29	660	650	100	110
32	590	590	40	96
35	360	261	-	-

Note : sample 1 = slurry store for 10 days
sample 2 = slurry store for 20 days

Table J1. Total capital purchase cost

Item	Cost (£)	%
Tank & Fixings		
Aeration Vessel	6876.00	48.2
Blower	2776.77	19.5
Venturi	1650.00	11.6
Piranha	680.00	4.8
Submersible pump	340.00	2.4
Hydrostal pump	1352.00	9.5
38 mm Suction hose	53.10	0.4
Hose Clamps	8.00	0.1
Tap & Bush	17.25	0.1
Solid Entrainment Pipe	467.32	3.3
Foam o/flow	34.60	0.2
sub-toal	**14255.04**	100.0
Supply & Control		
Float switches	26.08	0.5
Temperature Sensor	46.60	0.8
Signal cable	187.29	3.4
Logger connectors	116.98	2.1
Control Box	338.08	6.1
Inverter drive	927.50	16.6
Power cable	92.00	1.6
Power Isolators	41.85	0.8
Data Logger	2500.00	44.8
Redox Analyser	1301.30	23.3
sub-total	**5577.68**	100.0
Installation & Commisioning		
Base	800.00	77.2
Crane	235.75	22.8
sub-total	**1035.75**	100.0
Total £	**20868.47**	

Table J2. Oxygen and VFA removal after treatment Trial 2

method 1

day	CODin g.l^{-1}	CODout g.l^{-1}	vol litre	(CODin-CODout)*vol g	VFAin mg.l^{-1}	VFAout mg.l^{-1}	VFAin -VFA out mg.l^{-1}	VFA removed g
0	12.1	7	31800	162180	4070	410	3660	116328
1	11.9	7.2	31800	149460	3600	343	3257	103572.6
2	11.6	7.4	31800	133560	2650	270	2380	75684
3	11.4	7.5	31800	124020	2650	200	2450	77910
4	12.3	8.1	31800	133560	2650	210	2440	77592
5	13.1	8.6	31800	143100	2650	220	2430	77274
6	14	9.3	31800	149460	2650	230	2420	76956
7	14.8	9.8	31800	159000	2640	240	2400	76320
8	15.7	10.4	31800	168540	2850	250	2600	82680
9	14.5	10.2	31800	136740	3080	205	2875	91425
10	13.4	10	31800	108120	3290	165	3125	99375
11	12.2	9.8	31800	76320	2900	120	2780	88404
12	12.1	10	31800	66780	2490	125	2365	75207
13	12	10.1	31800	60420	2090	130	1960	62328
14	11.8	10.3	31800	47700	2090	130	1960	62328
15	11.7	10.5	31800	38160	1670	140	1530	48654
16	10.4	9.1	31800	41340	1600	105	1495	47541
17	9	7.9	31800	34980	1520	68	1452	46173.6
18	7.5	6.54	31800	30528	1450	30	1420	45156
19	7.5	6.4	31800	34980	1350	48	1302	41403.6
20	7.5	6.1	31800	44520	1250	65	1185	37683
21	7.4	6	31800	44520	1150	83	1067	33930.6
22	7.4	5.8	31800	50880	1060	100	960	30528
23	7.3	5.6	31800	54060	960	80	880	27984
24	7.1	5.4	31800	54060	870	60	810	25758
25	6.9	5.2	31800	54060	760	40	720	22896
26	7	5.3	31800	54060	820	30	790	25122
27	7	5.3	31800	54060	880	20	860	27348
28	7.1	5.3	31800	57240	930	10	920	29256
29	6.7	4.9	31800	57240	820	18	802	25503.6
30	6.2	4.5	31800	54060	710	23	687	21846.6
31	5.8	4	31800	57240	600	31	569	18094.2
32	5.3	3.6	31800	54060	490	40	450	14310
33	5.2	3.4	31800	57240	420	39	381	12115.8
34	5	3.3	31800	54060	380	35	345	10971
35	4.9	3.1	31800	57240	300	32	268	8522.4
36	4.7	2.97	31800	55014	240	30	210	6678
37	4.6	3.5	31800	34980	200	30	170	5406
38	4.6	4	31800	19080	250	30	220	6996
39	4.6	4.5	31800	3180	120	30	90	2862
40	4.5	4.5	31800	0	110	29	81	2575.8
41	4.5	4.3	31800	6360	100	25	75	2385
42	4.5	4	31800	15900	100	22	78	2480.4
43	4.5	3.84	31800	20988	90	20	70	2226
44	4.4	3.7	31800	22260	110	37	73	2321.4
45	4.3	3.5	31800	25440	120	53	67	2130.6
46	4.2	3.41	31800	25122	140	70	70	2226
47	4.1	3.3	31800	25440	140	60	80	2544
48	4	3	31800	31800	140	50	90	2862
49	3.9	2.9	31800	31800	130	40	90	2862
			total	3174912			total	1890796.2

Tables J3-J7 Energy and oxygen requirement for Trial 2

Table J3

from method 1			
total CODdiff over the treatment period	=	3174912	g
O_2 consumed		3175	kg
Energy consumed by aeration system	=	3316.32	kWh
aeration efficiency $kgO_2.kWh^{-1}$	=	0.96	

Table J4

Method 2			
Max O_2 consumption in Tin tank	=	MaxCOD - minCOD	
MaxCOD	15.7 g.l^{-1}		
minCOD	3.9 g.l^{-1}		
vol of tin tank		455 m^3	
		455000 l	
kgO_2 consumed	=	5369 kg	
aeration efficiency	=	1.36 $kgO_2.kWh^{-1}$	
$kWh.m^{-3}$ of aerated slurry	=	7.3	
Total energy consumption kWh		3936.4303	
$kWh.m^{-3}$ in feed slurry	=	8.7 $kWh.m^{-3}$	
		0.0087 $kWh.l^{-1}$	

Table J5

kgO2/kg VFA removed				
		reduction in feed slurry		
Mehtod 1		Method 2		
total O_2 consumed =	3174.9 kg		5369 kg	
		total VFA removed =		
total daily VFA removal		maxVFA =	4.07 g.l^{-1}	
	1890.7962 kg	minVFA =	0.1 g.l^{-1}	
		VFA removal	3.97 g.l^{-1}	
		VFA removed	1806350 g	
		VFA removed in kg	1806 kg	
therefore :				
$kgO_2/kgVFA$ removed =	1.7		3.0	

Table J6

Assuming average running speed was 10 Hz from actual running speed of 8 to 20 Hz		
at 12 Hz the air flow rate		54 $m^3.h^{-1}$
Blower running time was the total kWh		
of blower run / power consumption at 12 Hz		637.5 hr
Therefore total air		34425 m^3
total oxygen	volume	7229.25 m^3
	mass	10330.598 kg
total O_2 consumed (COD diff in and out)		3175 kg
% of O_2 transfer		31 %

Table J7

Power consumption				
empty pump, kW	1.42			
fill pump, kW	2.39			
Venturi pump, kW	2.64			
foam breaker.kW	0.5			
	runing time			
	29/02/2000	17/04/2000	diff./hr	kWh
empty pump	214.35	364.94	150.59	213.8
fill pump	323.78	471.53	147.75	353.1
venturi pump	1867	2930	1063	2806.3
foam breaker				53
			sub-total	3426.4
compressor, kWh	814	1324		510.0
			total	3936.4
compressor power consumption, kWh =		510		
Aeration power consumption.kWh =		3316.3		
(compressor +venturi pump)				

Table J8. Oxygen requirement for farm scale treatment Trial 2 supernatant COD and VFA relationships.

			VFA (in)						VFA(out)		CODin (VFAin)							CODout(VFAout)				
day	VFAin	VFAout	AC	Pro	I-Bu	N-Bu	I-Va	N-Va	AC	Pro	AC	Pro	I-Bu	N-Bu	I-Va	N-Va	total	AC	Pro	total	volume	Oxygen demand
	mg.l^{-1}	mg.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	litre	g
0	4070	410	2.442	1.0175	0.2035	0.407	0.2035	0.0814	0.3075	0.1025	2.34432	1.4245	0.339845	0.6919	0.3663	0.152218	5.319083	0.2952	0.1435	0.4387	31800	155196.1794
1	3600	343	2.16	0.9	0.18	0.36	0.18	0.072	0.25725	0.08575	2.0736	1.26	0.3006	0.612	0.324	0.13464	4.70484	0.24696	0.12005	0.36701	31800	137942.994
2	2650	270	1.59	0.6625	0.1325	0.265	0.1325	0.053	0.2025	0.0675	1.5264	0.9275	0.221275	0.4505	0.2385	0.09911	3.463285	0.1944	0.0945	0.2889	31800	100945.443
3	2650	200	1.59	0.6625	0.1325	0.265	0.1325	0.053	0.15	0.05	1.5264	0.9275	0.221275	0.4505	0.2385	0.09911	3.463285	0.144	0.07	0.214	31800	103327.263
4	2650	210	1.59	0.6625	0.1325	0.265	0.1325	0.053	0.1575	0.0525	1.5264	0.9275	0.221275	0.4505	0.2385	0.09911	3.463285	0.1512	0.0735	0.2247	31800	102987.003
5	2650	220	1.59	0.6625	0.1325	0.265	0.1325	0.053	0.165	0.055	1.5264	0.9275	0.221275	0.4505	0.2385	0.09911	3.463285	0.1584	0.077	0.2354	31800	102646.743
6	2650	230	1.59	0.6625	0.1325	0.265	0.1325	0.053	0.1725	0.0575	1.5264	0.9275	0.221275	0.4505	0.2385	0.09911	3.463285	0.1656	0.0805	0.2461	31800	102306.483
7	2640	240	1.584	0.66	0.132	0.264	0.132	0.0528	0.18	0.06	1.52064	0.924	0.22044	0.4488	0.2376	0.098736	3.450216	0.1728	0.084	0.2568	31800	101550.6288
8	2850	250	1.71	0.7125	0.1425	0.285	0.1425	0.057	0.1875	0.0625	1.6416	0.9975	0.237975	0.4845	0.2565	0.10659	3.724665	0.18	0.0875	0.2675	31800	109937.847
9	3080	205	1.848	0.77	0.154	0.308	0.154	0.0616	0.15375	0.05125	1.77408	1.078	0.25718	0.5236	0.2772	0.115192	4.025252	0.1476	0.07175	0.21935	31800	121027.6836
10	3290	165	1.974	0.8225	0.1645	0.329	0.1645	0.0658	0.12375	0.04125	1.89504	1.1515	0.274715	0.5593	0.2961	0.123046	4.299701	0.1188	0.05775	0.17655	31800	131116.2018
11	2900	120	1.74	0.725	0.145	0.29	0.145	0.058	0.09	0.03	1.6704	1.015	0.24215	0.493	0.261	0.10846	3.79001	0.0864	0.042	0.1284	31800	116439.198
12	2490	125	1.494	0.6225	0.1245	0.249	0.1245	0.0498	0.09375	0.03125	1.43424	0.8715	0.207915	0.4233	0.2241	0.093126	3.254181	0.09	0.04375	0.13375	31800	99229.7058
13	2090	130	1.254	0.5225	0.1045	0.209	0.1045	0.0418	0.0975	0.0325	1.20384	0.7315	0.174515	0.3553	0.1881	0.078166	2.731421	0.0936	0.0455	0.1391	31800	82435.8078
14	2090	130	1.254	0.5225	0.1045	0.209	0.1045	0.0418	0.0975	0.0325	1.20384	0.7315	0.174515	0.3553	0.1881	0.078166	2.731421	0.0936	0.0455	0.1391	31800	82435.8078
15	1670	140	1.002	0.4175	0.0835	0.167	0.0835	0.0334	0.105	0.035	0.96192	0.5845	0.139445	0.2839	0.1503	0.062458	2.182523	0.1008	0.049	0.1498	31800	64640.5914
16	1600	105	0.96	0.4	0.08	0.16	0.08	0.032	0.07875	0.02625	0.9216	0.56	0.1336	0.272	0.144	0.05984	2.09104	0.0756	0.03675	0.11235	31800	62922.342
17	1520	68	0.912	0.38	0.076	0.152	0.076	0.0304	0.051	0.017	0.87552	0.532	0.12692	0.2584	0.1368	0.056848	1.986488	0.04896	0.0238	0.07276	31800	60856.5504
18	1450	30	0.87	0.3625	0.0725	0.145	0.0725	0.029	0.0225	0.0075	0.8352	0.5075	0.121075	0.2465	0.1305	0.05423	1.895005	0.0216	0.0105	0.0321	31800	59240.379
19	1350	48	0.81	0.3375	0.0675	0.135	0.0675	0.027	0.036	0.012	0.7776	0.4725	0.112725	0.2295	0.1215	0.05049	1.764315	0.03456	0.0168	0.05136	31800	54471.969
20	1250	65	0.75	0.3125	0.0625	0.125	0.0625	0.025	0.04875	0.01625	0.72	0.4375	0.104375	0.2125	0.1125	0.04675	1.633625	0.0468	0.02275	0.06955	31800	49737.585
21	1150	83	0.69	0.2875	0.0575	0.115	0.0575	0.023	0.06225	0.02075	0.6624	0.4025	0.096025	0.1955	0.1035	0.04301	1.502935	0.05976	0.02905	0.08881	31800	44969.175
22	1060	100	0.636	0.265	0.053	0.106	0.053	0.0212	0.075	0.025	0.61056	0.371	0.08851	0.1802	0.0954	0.039644	1.385314	0.072	0.035	0.107	31800	40650.3852
23	960	80	0.576	0.24	0.048	0.096	0.048	0.0192	0.06	0.02	0.55296	0.336	0.08016	0.1632	0.0864	0.035904	1.254624	0.0576	0.028	0.0856	31800	37174.9632
24	870	60	0.522	0.2175	0.0435	0.087	0.0435	0.0174	0.045	0.015	0.50112	0.3045	0.072645	0.1479	0.0783	0.032538	1.137003	0.0432	0.021	0.0642	31800	34115.1354
25	760	40	0.456	0.19	0.038	0.076	0.038	0.0152	0.03	0.01	0.43776	0.266	0.06346	0.1292	0.0684	0.028424	0.993244	0.0288	0.014	0.0428	31800	30224.1192
26	820	30	0.492	0.205	0.041	0.082	0.041	0.0164	0.03	0	0.47232	0.287	0.06847	0.1394	0.0738	0.030668	1.071658	0.0288	0	0.0288	31800	33162.8844
27	880	20	0.528	0.22	0.044	0.088	0.044	0.0176	0.02	0	0.50688	0.308	0.07348	0.1496	0.0792	0.032912	1.150072	0.0192	0	0.0192	31800	35961.7296
28	930	10	0.558	0.2325	0.0465	0.093	0.0465	0.0186	0.01	0	0.53568	0.3255	0.077655	0.1581	0.0837	0.034782	1.215417	0.0096	0	0.0096	31800	38344.9806
29	820	18	0.492	0.205	0.041	0.082	0.041	0.0164	0.018	0	0.47232	0.287	0.06847	0.1394	0.0738	0.030668	1.071658	0.01728	0	0.01728	31800	33529.2204
30	710	23	0.426	0.1775	0.0355	0.071	0.0355	0.0142	0.023	0	0.40896	0.2485	0.059285	0.1207	0.0639	0.026554	0.927899	0.02208	0	0.02208	31800	28805.0442
31	600	31	0.36	0.15	0.03	0.06	0.03	0.012	0.031	0	0.3456	0.21	0.0501	0.102	0.054	0.02244	0.78414	0.02976	0	0.02976	31800	23989.284
32	490	40	0.294	0.1225	0.0245	0.049	0.0245	0.0098	0.04	0	0.28224	0.1715	0.040915	0.0833	0.0441	0.018326	0.640381	0.0384	0	0.0384	31800	19142.9958
33	420	39	0.252	0.105	0.021	0.042	0.021	0.0084	0.039	0	0.24192	0.147	0.03507	0.0714	0.0378	0.015708	0.548898	0.03744	0	0.03744	31800	16264.3644
34	380	35	0.228	0.095	0.019	0.038	0.019	0.0076	0.035	0	0.21888	0.133	0.03173	0.0646	0.0342	0.014212	0.496622	0.0336	0	0.0336	31800	14724.0996
35	300	32	0.18	0.075	0.015	0.03	0.015	0.006	0.032	0	0.1728	0.105	0.02505	0.051	0.027	0.01122	0.39207	0.03072	0	0.03072	31800	11490.93
36	240	30	0.144	0.06	0.012	0.024	0.012	0.0048	0.03	0	0.13824	0.084	0.02004	0.0408	0.0216	0.008976	0.313656	0.0288	0	0.0288	31800	9058.4208
37	200	30	0.12	0.05	0.01	0.02	0.01	0.004	0.03	0	0.1152	0.07	0.0167	0.034	0.018	0.00748	0.26138	0.0288	0	0.0288	31800	7396.044
38	250	30	0.15	0.0625	0.0125	0.025	0.0125	0.005	0.03	0	0.144	0.0875	0.020875	0.0425	0.0225	0.00935	0.326725	0.0288	0	0.0288	31800	9474.015
39	120	30	0.072	0.03	0.006	0.012	0.006	0.0024	0.03	0	0.06912	0.042	0.01002	0.0204	0.0108	0.004488	0.156828	0.0288	0	0.0288	31800	4071.2904
40	110	29	0.066	0.0275	0.0055	0.011	0.0055	0.0022	0.029	0	0.06336	0.0385	0.009185	0.0187	0.0099	0.004114	0.143759	0.02784	0	0.02784	31800	3686.2242
41	100	25	0.06	0.025	0.005	0.01	0.005	0.002	0.03	0	0.0576	0.035	0.00835	0.017	0.009	0.00374	0.13069	0.03552	0	0.03552	31800	3026.406
42	100	22	0.06	0.025	0.005	0.01	0.005	0.002	0.022	0	0.0576	0.035	0.00835	0.017	0.009	0.00374	0.13069	0.02112	0	0.02112	31800	3484.326
43	90	20	0.054	0.0225	0.0045	0.009	0.0045	0.0018	0.02	0	0.05184	0.0315	0.007515	0.0153	0.0081	0.003366	0.117621	0.0192	0	0.0192	31800	3129.7878
44	110	37	0.066	0.0275	0.0055	0.011	0.0055	0.0022	0.037	0	0.06336	0.0385	0.009185	0.0187	0.0099	0.004114	0.143759	0.03552	0	0.03552	31800	3442.0002
45	120	53	0.072	0.03	0.006	0.012	0.006	0.0024	0.053	0	0.06912	0.042	0.01002	0.0204	0.0108	0.004488	0.156828	0.05088	0	0.05088	31800	3369.1464
46	140	70	0.084	0.035	0.007	0.014	0.007	0.0028	0.07	0	0.08064	0.049	0.01169	0.0238	0.0126	0.005236	0.182966	0.0672	0	0.0672	31800	3681.3588
47	140	60	0.084	0.035	0.007	0.014	0.007	0.0028	0.06	0	0.08064	0.049	0.01169	0.0238	0.0126	0.005236	0.182966	0.0576	0	0.0576	31800	3986.6388
48	140	50	0.084	0.035	0.007	0.014	0.007	0.0028	0.05	0	0.08064	0.049	0.01169	0.0238	0.0126	0.005236	0.182966	0.048	0	0.048	31800	4291 9188
49	130	40	0.078	0.0325	0.0065	0.013	0.0065	0.0026	0.04	0	0.07488	0.0455	0.010855	0.0221	0.0117	0.004862	0.169897	0.0384	0	0.0384	31800	4181.6046
																					total	2510222.899
																					kg	2510.222899

COD values of individual volatile fatty acids expressed as gO$_2$.g^{-1} (Williams, 1981)

VFA component	AC	Pro	I-Bu	N-Bu	I-Va	N-Va
CODs	0.96	1.4	1.67	1.7	1.8	1.87

Note : CODout(VFAout) = Amount of oxygen required to remove VFA
assume only acetic and propionic acids were left in ML after treatment

Table J9. oxygen requirement for farm scale treatment Trial 3 using supernatant COD and VFA relationships.

Daily VFA removal			VFA (in)							VFA (out)	COD in (VFAin)							CODout(VFAout)	COD(VFAin)-COD(VFAout)		
day	VFAin	VFAout	AC	Pro	I-Bu	N-Bu	I-Va	N-Va	total	AC	Ac	Pro	I-Bu	N-Bu	I-Va	N-Va	total	Ac		volume	Oxygen demand
	mg.l^{-1}	mg.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	g.l^{-1}	litres	g
0	6890	5730	3.445	2.067	0.3	0.3	0.4	0.3	6.89	5.73	3.3072	2.8938	0.575315	0.58565	0.74412	0.515372	8.621457	5.5008	3.120657	31800	99236.8926
1	6700	4350	3.35	2.01	0.3	0.3	0.4	0.3	6.7	4.35	3.216	2.814	0.55945	0.5695	0.7236	0.50116	8.38371	4.176	4.20771	31800	133805.178
2	6500	2930	3.25	1.95	0.3	0.3	0.4	0.3	6.5	2.93	3.12	2.73	0.54275	0.5525	0.702	0.4862	8.13345	2.8128	5.32065	31800	169196.67
3	6300	1550	3.15	1.89	0.3	0.3	0.4	0.3	6.3	1.55	3.024	2.646	0.52605	0.5355	0.6804	0.47124	7.88319	1.488	6.39519	31800	203367.042
4	6130	100	3.065	1.839	0.3	0.3	0.4	0.2	6.13	0.1	2.9424	2.5746	0.511855	0.52105	0.66204	0.458524	7.670469	0.096	7.574469	31800	240868.1142
5	5650	50	2.825	1.695	0.3	0.3	0.3	0.2	5.65	0.05	2.712	2.373	0.471775	0.48025	0.6102	0.42262	7.069845	0.048	7.021845	31800	223294.671
6	5150	50	2.575	1.545	0.3	0.3	0.3	0.2	5.15	0.05	2.472	2.163	0.430025	0.43775	0.5562	0.38522	6.444195	0.048	6.396195	31800	203399.001
7	4650	50	2.325	1.395	0.2	0.2	0.3	0.2	4.65	0.05	2.232	1.953	0.388275	0.39525	0.5022	0.34782	5.818545	0.048	5.770545	31800	183503.331
8	4170	50	2.085	1.251	0.2	0.2	0.3	0.2	4.17	0.05	2.0016	1.7514	0.348195	0.35445	0.45036	0.311916	5.217921	0.048	5.169921	31800	164403.4878
9	3850	50	1.925	1.155	0.2	0.2	0.2	0.2	3.85	0.05	1.848	1.617	0.321475	0.32725	0.4158	0.28798	4.817505	0.048	4.769505	31800	151670.259
10	3550	50	1.775	1.065	0.2	0.2	0.2	0.1	3.55	0.05	1.704	1.491	0.296425	0.30175	0.3834	0.26554	4.442115	0.048	4.394115	31800	139732.857
11	3250	50	1.625	0.975	0.2	0.2	0.2	0.1	3.25	0.05	1.56	1.365	0.271375	0.27625	0.351	0.2431	4.066725	0.048	4.018725	31800	127795.455
12	3000	50	1.5	0.9	0.2	0.2	0.2	0.1	3	0.05	1.44	1.26	0.2505	0.255	0.324	0.2244	3.7539	0.048	3.7059	31800	117847.62
13	2790	50	1.395	0.837	0.1	0.1	0.2	0.1	2.79	0.05	1.3392	1.1718	0.232965	0.23715	0.30132	0.208692	3.491127	0.048	3.443127	31800	109491.4386
14	2550	50	1.275	0.765	0.1	0.1	0.2	0.1	2.55	0.05	1.224	1.071	0.212925	0.21675	0.2754	0.19074	3.190815	0.048	3.142815	31800	99941.517
15	2310	50	1.155	0.693	0.1	0.1	0.1	0.1	2.31	0.05	1.1088	0.9702	0.192885	0.19635	0.24948	0.172788	2.890503	0.048	2.842503	31800	90391.5954
16	2150	50	1.075	0.645	0.1	0.1	0.1	0.1	2.15	0.05	1.032	0.903	0.179525	0.18275	0.2322	0.16082	2.690295	0.048	2.642295	31800	84024.981
17	2000	50	1	0.6	0.1	0.1	0.1	0.1	2	0.05	0.96	0.84	0.167	0.17	0.216	0.1496	2.5026	0.048	2.4546	31800	78056.28
18	1880	50	0.94	0.564	0.1	0.1	0.1	0.1	1.88	0.05	0.9024	0.7896	0.15698	0.1598	0.20304	0.140624	2.352444	0.048	2.304444	31800	73281.3192
19	1740	50	0.87	0.522	0.1	0.1	0.1	0.1	1.74	0.05	0.8352	0.7308	0.14529	0.1479	0.18792	0.130152	2.177262	0.048	2.129262	31800	67710.5316
20	1600	50	0.8	0.48	0.1	0.1	0.1	0.1	1.6	0.05	0.768	0.672	0.1336	0.136	0.1728	0.11968	2.00208	0.048	1.95408	31800	62139.744
21	1490	50	0.745	0.447	0.1	0.1	0.1	0.1	1.49	0.05	0.7152	0.6258	0.124415	0.12665	0.16092	0.111452	1.864437	0.048	1.816437	31800	57762.6966
22	1370	50	0.685	0.411	0.1	0.1	0.1	0.1	1.37	0.05	0.6576	0.5754	0.114395	0.11645	0.14796	0.102476	1.714281	0.048	1.666281	31800	52987.7358
23	1310	50	0.655	0.393	0.1	0.1	0.1	0.1	1.31	0.05	0.6288	0.5502	0.109385	0.11135	0.14148	0.097988	1.639203	0.048	1.591203	31800	50600.2554
24	1270	50	0.635	0.381	0.1	0.1	0.1	0.1	1.27	0.05	0.6096	0.5334	0.106045	0.10795	0.13716	0.094996	1.589151	0.048	1.541151	31800	49008.6018
25	1210	50	0.605	0.363	0.1	0.1	0.1	0.0	1.21	0.05	0.5808	0.5082	0.101035	0.10285	0.13068	0.090508	1.514073	0.048	1.466073	31800	46621.1214
26	1070	50	0.535	0.321	0.1	0.1	0.1	0.0	1.07	0.05	0.5136	0.4494	0.089345	0.09095	0.11556	0.080036	1.338891	0.048	1.290891	31800	41050.3338
27	940	50	0.47	0.282	0.0	0.0	0.1	0.0	0.94	0.05	0.4512	0.3948	0.07849	0.0799	0.10152	0.070312	1.176222	0.048	1.128222	31800	35877.4596
28	800	50	0.4	0.24	0.0	0.0	0.0	0.0	0.8	0.05	0.384	0.336	0.0668	0.068	0.0864	0.05984	1.00104	0.048	0.95304	31800	30306.672
29	680	50	0.34	0.204	0.0	0.0	0.0	0.0	0.68	0.05	0.3264	0.2856	0.05678	0.0578	0.07344	0.050864	0.850884	0.048	0.802884	31800	25531.7112
30	600	50	0.3	0.18	0.0	0.0	0.0	0.0	0.6	0.05	0.288	0.252	0.0501	0.051	0.0648	0.04488	0.75078	0.048	0.70278	31800	22348.404
31	540	50	0.27	0.162	0.0	0.0	0.0	0.0	0.54	0.05	0.2592	0.2268	0.04509	0.0459	0.05832	0.040392	0.675702	0.048	0.627702	31800	19960.9236
32	480	50	0.24	0.144	0.0	0.0	0.0	0.0	0.48	0.05	0.2304	0.2016	0.04008	0.0408	0.05184	0.035904	0.600624	0.048	0.552624	31800	17573.4432
33	470	50	0.235	0.141	0.0	0.0	0.0	0.0	0.47	0.05	0.2256	0.1974	0.039245	0.03995	0.05076	0.035156	0.588111	0.048	0.540111	31800	17175.5298
34	460	50	0.23	0.138	0.0	0.0	0.0	0.0	0.46	0.05	0.2208	0.1932	0.03841	0.0391	0.04968	0.034408	0.575598	0.048	0.527598	31800	16777.6164
35	450	50	0.225	0.135	0.0	0.0	0.0	0.0	0.45	0.05	0.216	0.189	0.037575	0.03825	0.0486	0.03366	0.563085	0.048	0.515085	31800	16379.703
36	420	50	0.21	0.126	0.0	0.0	0.0	0.0	0.42	0.05	0.2016	0.1764	0.03507	0.0357	0.04536	0.031416	0.525546	0.048	0.477546	31800	15185.9628
37	410	50	0.205	0.123	0.0	0.0	0.0	0.0	0.41	0.05	0.1968	0.1722	0.034235	0.03485	0.04428	0.030668	0.513033	0.048	0.465033	31800	14788.0494
																				total	3353094.205
																				kg	3353.094205

COD values of individual volatile fatty acids expressed as $gO_2.g^{-1}$ (Williams, 1981)

VFA component	AC	Pro	I-Bu	N-Bu	I-Va	N-Va
CODs	0.96	1.4	1.67	1.7	1.8	1.87

Note : CODout(VFAout) = Amount of oxygen required to remove VFA assume only acetic acid was left in ML after treatment

Table J10. Oxygen consumption was calculated by the difference between the feed slurry CODw and the predicted CODw in ML.

	Trial2				Trial 3		
day	CODin $g.l^{-1}$	predicted CODout $g.l^{-1}$	(CODin -CODout)*31800 g	day	CODin $g.l^{-1}$	predicted CODout $g.l^{-1}$	(CODin -CODout)*31800 g
0	12.1	9.8	74515.1	0	13.2	10.6	81289.1
1	11.9	9.6	73283.4	1	13.1	10.6	80673.3
2	11.6	9.4	71435.9	2	13	10.5	80057.5
3	11.4	9.2	70204.3	3	12.8	10.3	78825.8
4	12.3	9.9	75746.7	4	12.7	10.2	78210.0
5	13.1	10.6	80673.3	5	12.1	9.8	74515.1
6	14	11.3	86215.8	6	11.5	9.3	70820.1
7	14.8	11.9	91142.4	7	10.9	8.8	67125.1
8	15.7	12.7	96684.8	8	10.3	8.3	63430.2
9	14.5	11.7	89294.9	9	10.1	8.1	62198.5
10	13.4	10.8	82520.8	10	10	8.1	61582.7
11	12.2	9.8	75130.9	11	9.9	8.0	60966.9
12	12.1	9.8	74515.1	12	9.5	7.7	58503.6
13	12	9.7	73899.2	13	9	7.3	55424.4
14	11.8	9.5	72667.6	14	8.6	6.9	52961.1
15	11.7	9.4	72051.7	15	8.2	6.6	50497.8
16	10.4	8.4	64046.0	16	8.4	6.8	51729.5
17	9	7.3	55424.4	17	8.5	6.9	52345.3
18	7.5	6.0	46187.0	18	8.7	7.0	53576.9
19	7.5	6.0	46187.0	19	8.4	6.8	51729.5
20	7.5	6.0	46187.0	20	8	6.5	49266.2
21	7.4	6.0	45571.2	21	7.7	6.2	47418.7
22	7.4	6.0	45571.2	22	7.4	6.0	45571.2
23	7.3	5.9	44955.4	23	7.1	5.7	43723.7
24	7.1	5.7	43723.7	24	6.8	5.5	41876.2
25	6.9	5.6	42492.1	25	6.6	5.3	40644.6
26	7	5.6	43107.9	26	6.4	5.2	39412.9
27	7	5.6	43107.9	27	6.2	5.0	38181.3
28	7.1	5.7	43723.7	28	6	4.8	36949.6
29	6.7	5.4	41260.4	29	5.9	4.8	36333.8
30	6.2	5.0	38181.3	30	5.9	4.8	36333.8
31	5.8	4.7	35718.0	31	5.8	4.7	35718.0
32	5.3	4.3	32638.8	32	5.8	4.7	35718.0
33	5.2	4.2	32023.0	33	5.6	4.5	34486.3
34	5	4.0	30791.3	34	5.4	4.4	33254.7
35	4.9	4.0	30175.5	35	5.3	4.3	32638.8
36	4.7	3.8	28943.9	36	4.8	3.9	29559.7
37	4.6	3.7	28328.0	37	4.3	3.5	26480.6
38	4.6	3.7	28328.0			total	1970030.2
39	4.6	3.7	28328.0			in kg	1970.0
40	4.5	3.6	27712.2				
41	4.5	3.6	27712.2				
42	4.5	3.6	27712.2				
43	4.5	3.6	27712.2				
44	4.4	3.5	27096.4				
45	4.3	3.5	26480.6				
46	4.2	3.4	25864.7				
47	4.1	3.3	25248.9				
48	4	3.2	24633.1				
49	3.9	3.1	24017.2				
		total	2489172.2				
		in kg	2489.2				

Energy consumption during farm scale Trial 2 and 3

Price of electricity varies widely depending on tariffs and the amount used.
Normally, the cheap rate is 2.6p/kWh for the period of 00:30 -0.7:30 and 7.0p/kWh for the rest day

5.7p.kWh^{-1} was used for the calculation of running cost

5.7 p.kWh^{-1}

Table J11. Energy and cost consumption during Farm-scale treatment Trial 2

Trial 2

	energy, kWh	cost, £	% of total
fill pump,	353	20.1	9
emptying pump	214	12.2	5
venturi pump	2806	159.9	71
compressor	510	29.1	13
foam breaker	53	3.0	1
total	3936.0	224.4	100.0
£.m^{-3}		0.49	
£.day^{-1}		4.6	

Note: Aeration energy consumption sumed energy consumption of venturi pump and compressor.

Trial 3

	energy, kWh	cost,£	% of total
fill pump,	260	14.8	12
emptying pump	181	10.3	8
venturi pump	1091	62.2	51
compressor	596	34.0	28
foam breaker	21	1.2	1
total	2149.0	122.5	100
£.m^{-3}		0.27	
£.day^{-1}		3.5	

note:

1. compressor was over sized
2. foam breaker run time was 1% of venturi run time
3. total volume of slurry (m^3) to be treated was 455 m^3
4. 49 days treatment for Trial 2 and 37 days for Trial 3

Oxygen requirement in Trial 3

Trial 3 could not use the dialy COD reduction for the caluclation of O_2 consumed because the COD in ML was greater than the in feed slurry . Therefore the total amount of entering into the reactor (oxygen required for the treatment) is estimated as below:

Table J12. Oxygen requirement calculation

Amount of air into the reactor		
4470 rpm is full speed = 50 Hz		
The blower was run at fixed speed at 15 hz, therefore		
Blower run at 1341 rpm		
Blower run at	15	Hz
	1341	min^{-1}
	0.15	bar
	1.6	kW
from the performance chart		
Airflow rate =	1.18	$m^3 min^{-1}$
Since aeration Power consumption was known		
=	1690	kWh
and the compressor power consumption was		
=	596	kWh
therefore :		
time run of blower	372.5	hr
	22350	min
Air vol. enter	26373	m^3
O_2 vol. enter air vol*0.21		
	5538.33	m^3
density of O_2	1.43	$kg.m^{-3}$
mass of O_2 enter	7914.27	kg
aeration efficiency	4.68	$kgO_2 kWh^{-1}$
***(100% O_2 transfer)		
O_2 flow rate enter	21.25	$kgO_2 hr^{-1}$
O.C	4	$kgO_2 hr^{-1}$
(assume respiration rate is 0)		
	0.25	
Therefore about	20 - 25%	utilization of O2
Therefore the O_2 consumed is		
	1979	kg
actually aeration efficiency		
	1.17	$kgO_2 kWh^{-1}$
VFA removed:	2559	kg
kgO_2/kgVFA removed	0.77	

Energy and oxygen calculation for Trial 3

Table J13. Energy consumption calculation

Power consumption

empty pump, kW	1.42			
fill pump, kW	2.39			
venturi pump, kW	2.64			
foam breaker, kW	0.5			
	running time			kWh
	15/05/2000	20/06/2000	diff./hr	
empty pump	369.48	496.7	127.22	180.7
fill pump	474.9	583.8	108.9	260.3
venturi pump	2933.5	3346.67	413.17	1090.8
foam breaker			41.317	21
			sub-total	1552.4
compressor, kWh	1324	1920		596.0
			total	2148.4
compressor power consumption, kWh				596
Aeration power consumption,kWh (compressor +venturi pump)				1686.8

Max O2 consumption in slurry storage tank = MaxCOD - minCOD

MaxCOD	13.2	$g.l^{-1}$
minCOD	4.3	$g.l^{-1}$
vol. of feed slurry in store	455	m^3
	455000	l
kgO_2 consumed =	4049.5	kg
aeration efficiency =	2.40	$kgO_2.kWh^{-1}$
$kWh.m^{-3}$ of aerated slurry =	3.7	
Total energy consumption kWh for whole system =	2148.4	
$kWh.m^{-3}$ in storage tank =	4.7	$kWh.m^{-3}$
	0.0047	$kWh.l^{-1}$

kgO_2/kg VFA removed calculation

total O_2 consumed =	4049.5	kg
total VFA reduction in feed slurry =		
maxVFA =	6.7	$g.l^{-1}$
minVFA =	0.41	$g.l^{-1}$
VFA removal	6.29	$g.l^{-1}$
VFA removed	2861950	g
VFA removed in kg	2862	kg
therefore :		
kgO_2/kgVFA removed =	1.41	