UNIVERSITY OF CAPE COAST

ANAEROBIC DIGESTION OF SHEA WASTE FOR ENERGY GENERATION

MARTIN AMPADU OFOSU

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BY

MARTIN AMPADU OFOSU

THESIS SUBMITTED TO THE DEPARTMENT OF AGRICULTURAL ENGINEERING OF THE SCHOOL OF AGRICULTURE, UNIVERSITY OF CAPE COAST IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF A DOCTOR OF PHILOSOPHY IN POSTHARVEST TECHNOLOGY

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DECLARATION

Candidate's declaration

I hereby declare that this thesis is the result of my own original work and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature…… Date…….

Name: Martin Ampadu Ofosu

Supervisors' declaration

We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the University of Cape Coast.

Principal Supervisor's Signature…… Date……

Name: Dr. E. D. Aklaku

Co-Supervisor's Signature.....…….. Date.....

Name: Prof. A. G. Carson

Co-Supervisor's Signature……..…… Date…….

Name: Mr. D. L. Lamptey

ABSTRACT

In search for an alternative source of energy and also in order to utilize the shea waste in an appropriate way and to reduce its negative impact on the environment, the waste was investigated to identify its potential in methane generation through anaerobic digestion.

The basic raw materials for the study were shea waste and cow dung. Input substrates were prepared with addition of predetermined amounts of water to bring the substrates to the required organic dry matter (odm) concentrations. The experiments were conducted on continuous feed system and under varying hydraulic retention times (HRT) and odm concentration of the waste. The experimental treatments were carried out in the following phases: cow dung fermentation at 30, 45 and 60 days HRT in 3 %, 5 % and 7 % odm; mono-fermentation of shea waste at 30, 45 and 60 days HRT in 3 %, 5 % and 7 % odm; co-fermentation of shea waste with cow dung in proportions of 50:50, 75:25 and 90:10 by volume, at 7 % odm and 30 days HRT; and co-fermentation of substrate 50:50 at 7 % odm and 20 days HRT.

The result of the experiments showed that process stability in anaerobic digestion of the shea waste could only be achieved through co-fermentation with cow dung in the ratio of 50:50 by volume at 7 % odm concentrations at 30 days HRT. Anaerobic digestion of shea waste was therefore found to be feasible in the generation of methane.

It is recommended that the design and construction of the biogas digester must be located below ground level to promote an even temperature regime.

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DEDICATION

This work is dedicated to my wife Fausty, and my children Abby and Kofi.

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ABBREVIATIONS AND ACRONYMS

AD	Anaerobic Digestion
BOD	Biological Oxygen Demand
^oC	degree Celcius
CD	cow dung
CH_4	methane
C:N	carbon nitrogen ratio
CO_2	carbon dioxide
COD	chemical oxygen demand
d	day
EPA	Environmental Protection Agency
EU	European Union
FAO	Food and Agriculture Organization
Fig.	figure
GWP	Global Warming Potential
HRT	Hydraulic Retention Time
H_2S	hydrogen sulphide
ICCWBO	International Chamber of Commerce, World Business Organization
IPCC	Intergovernmental Panel on Climate Change
JEA	Japan Environmental Agency
KWh	kilowatt hour
L_D	organic loading rate
NPK	nitrogen-phosphorus-potassium
odm , ODM	organic dry matter
ppm	parts per million
RISE-AT	Regional Information Service Centre for South East Asia on Appropriate Technology
SFP	scum-forming potential
SH	shea waste

TS	total solids
UNDP	United Nations Development Programmes
UN-FCCC	United Nations, Framework Convention on Climate Change
VAT	value-added tax
VITA	Volunteers in Technical Assistance
VFA	volatile fatty acids
VS	volatile solids

CHAPTER 1

INTRODUCTION

Agricultural crop and food processing residues are materials left after crops harvested from the field are processed into feed, food and other products. These residues called by-products or wastes, until recently were not considered harmful, and were thus used as landfills, or disposed of in soils and water courses in huge amounts. Every year large quantities of these wastes are produced as a result of human needs and activities. It is quite possible that if these wastes could be disposed of without any negative consequences, they would pose no problems.

Certainly, there may appear to be no drawbacks when waste is freely disposed of on locally available land. However, especially in large and regular volumes, the problems of disposal are very evident. For instance, disposal points located near residential areas or houses can attract complaints of odour nuisance. Moreover, people living near rivers and streams are very aware of the problems of pollution following run-off or spillage. There is always some evidence of soil and water pollution especially where repeated heavy doses of wastes have been dumped, and through the mechanism of leaching. Disease risks, both to livestock and the general public, are also matters of concern.

Greenhouse Gases

The world has become increasingly concerned about the emissions of gases like ammonia, nitrous oxide and methane into the atmosphere. These gases contribute to the build up of the environment greenhouse effect. Methane emissions occur in all anaerobic processes with organic materials. It has been estimated that methane emissions from agriculture contribute about 33 % to the global greenhouse effect, of which about 7 % result from animal excretion (JEA-EPA, 1990), this quantum being equivalent to 20-30 million tonnes of methane per year (AD-NETT, 2000). The greenhouse effect is, however essential to life. Without it, the average temperature of the surface of the earth would not be 15 ^{o}C but –6 ^{o}C (Burton and Turner, 2003). The issue of concern is the increasing concentrations of such gases in the atmosphere, which possibly give rise to an enhanced greenhouse effect (more correctly described as global warming) that may lead to changes in climate or have the potential to cause climate change.

The methane contained in biogas (refer to Table 1) is a potent greenhouse gas. According to the Intergovernmental Panel on Climate Change (IPCC), the Global Warming Potential (GWP) is an attempt to provide a simple measure of various greenhouse gas emissions. The GWP of a gas reflects the cumulative radiative forcing of that gas over a specified period of time beginning from the moment it is emitted. The GWP is expressed in terms of the radiative forcing of a gas to the forcing associated with the same mass of carbon dioxide over the same time horizon. For example, carbon dioxide has a GWP of 1. The IPCC is constantly evaluating the GWP values of 44 gases, using a time-horizon of 100 years. For example, in 1992, the GWP of methane was 11 times that of carbon

dioxide. By 1994, new findings prompted the IPCC to more than double the GWP of methane to 24.5. By 1996, the GWP of methane had dropped to 21 (UN-FCCC, 1996). This means that a given mass of methane could increase the atmosphere's radiative forcing by an amount 21 times more than the forcing associated with the same mass of carbon dioxide. The IPCC has calculated that 1 kg of methane has 63 times the warming effect of 1 kg of carbon dioxide for 20 years after the gases are produced (Burton and Turner, 2003). The increased abundance of methane will have important impacts on global climate change, tropospheric (ground-based) ozone, and the stratospheric ozone layer (Burton and Turner, 2003). The Environmental Protection Agency of the United States has also confirmed that the atmospheric concentration of methane is increasing at 1 % per year and has more than doubled over the past two centuries (Lusk, 1998). It is likely that any such change will have undesirable effects on agriculture. The current predictions of climatic change caused by human activities include a possible temperature increase of up to 4 ^{o}C within the next 40-75 years (Burton and Turner, 2003).

Mechanisms for implementing and establishing environmentally compatible technologies, which support the future 'recycling' of organic wastes, are required. IPCC reports that to stabilize atmospheric methane concentration at 1990 levels, global emissions need to be reduced by 15-20 % (Houghton *et al.*, 1990). Anaerobic digestion (AD) of organic materials produces methane, which, when burnt, produces CO_2 that has a lower GWP. The CO_2 can be absorbed by plants and kept within the terrestrial carbon cycle, thus further reducing the effects of global warming.

As a result of methane released into the atmosphere from agriculture and other human activities, the atmosphere contains about 1.4 ppm of methane (Ehalt, 1976). According to Ehalt (1976), the life expectancy of a methane molecule in the troposphere or lower stratosphere is about 1.5 to 7 years. Methane reacts with products of the ozone cycle in a process called tropospheric oxidation to regenerate carbon dioxide and complete the cycle (Ehalt, 1976). The effect of the destruction of the ozone layer is significant because ozone forms an atmospheric layer that shields the earth from some of the most dangerous forms of solar radiation (Cunningham and Saigo, 1990).

Energy And Development

Over the centuries, a wide variety of energy sources have been found, ranging from wind and hydropower to nuclear power plants. Nearly 90 % of all commercial energy in the world is generated by fossil fuels with about 40 % coming from petroleum (Cunningham and Saigo, 1990). However, none of our current major energy sources appears to offer security in terms of sustainability in supply or environmental degradation. There is the need therefore to develop alternative sources of sustainable and environmentally friendly energy.

The process to achieve sustainability in energy is global, ongoing and never-ending in a world, where 1.6 billion people live without commercial energy; where one billion of the world's population of six billion use nearly 60 % of the energy consumed and five billion, the other 40 % (ICC, undated). There is a close relationship between energy consumption and economic growth, especially in the initial phases of industrialization (Hohlfeld and Sasse, 1985), and it becomes more

than obvious that the long-term satisfaction of basic human needs in developing countries will entail a considerable increase in per-capita energy consumption.

Global economic growth is expected to average 1.7 % per annum in the next 30-40 years; growth in developing countries will be over 2 % per annum. This economic growth means at least 1.2 % or even 2 % per annum growth in global energy consumption for the most part in developing countries. Such growth amounts to almost a doubling of the present energy consumption by the year 2025, and eventually a tripling by 2050 (ICC, undated).

Wood fires have been a primary source of heating and cooking for thousands of years. The 1,500 million cubic metres of fuelwood collected in the world each year is about half of all wood harvested (Cunningham and Saigo, 1990). According to Cunningham and Saigo (1990), two billion people – about 40 % of the total world population – depend on firewood and charcoal as their primary energy source, and of these people, 1.5 billion do not have adequate and affordable supply. The problem is intensifying because rapidly growing populations create increasing demands for firewood and charcoal from a diminishing supply.

This energy problem is expected to worsen unless steps are taken immediately to provide alternative energy sources. According to Cunningham and Saigo (1990), the 1500 million cubic metres of fuelwood harvested annually is about 500 million cubic metres short of the needed amount. Cunningham and Saigo (1990) have estimated that by 2025, the worldwide demand for fuelwood would be 4400 million cubic metres, while supplies will not expand much beyond the present levels. This means that demand will be more than double the available

supply. In many countries the situation will be much worse than the world average.

In Northern Ghana, where wood and other fuels are either in short supply (Plate1) or unaffordable by the rural people, animal manure (cow dung) is dried and burnt as fuel. The dried dung of cattle on free range is collected during dry seasons to be used as fuel as shown in Plate 2. This may seem like a logical use of waste biomass, but it can intensify food shortages since this manure is not put back on the land as fertilizer to increase crop production and food supplies. This may lead to situations where the land would be depleted of nutrients and may not support the growth of grass as feed to the livestock.

Plate 1: Last tree in the vicinity

Plate 2: Dried cow dung

Given the uncertain outlook for energy supply and demand, it is appropriate to look closely at energy diversification, using local resources such as organic wastes. Technical advances and know-how related to renewable energy resources can be put to good use in both industrialized and developing countries, via technology transfer. Biogas technology, with all its capabilities as a potential decentralized source of energy in rural areas, can constitute a meaningful contribution toward the resolution of energy problems. The anaerobic digestion process is a simple waste treatment process, and a potential conversion system for wastes and biomass into valuable products: energy and fertilizer. The waste, which hitherto would have decomposed in landfill sites to release methane into the atmosphere, is used as a raw material.

Anaerobic digestion is a dynamically growing technology in the field of organic waste and biomass treatment. Agricultural biogas production offers not only ecological but also socio-economic benefits. New jobs could be created if the potentials of agricultural biogas production were exploited (Amon, 2003).

Problem Statement

The shea tree (*Vitellaria paradoxa*) is a major cash crop, which grows wildly in the savanna and sahelian vegetations. In Ghana the crop is predominantly found in the interior savanna zone, which lies between latitudes 8 ^{o}N and 11 ^{o}N, and within the catchments of the Black Volta, White Volta and the Oti rivers, covering an estimated area of 70,000 km^2, or about 66 % of Ghana's land area. The estimates of the total annual production of shea nuts are far from the exact figures due, in part, to the large expanse of land covered by the trees and the domestic consumption, which makes accurate assessment difficult. It is estimated however, that the population of shea trees growing naturally in Ghana is about 9.4 million with a potential of 100,000 metric tonnes of dried shea nuts per year (Ghana Cocoa Marketing Board (GCMB) News, 1980, quoted by Abbiw, 1990).

Shea nuts are normally processed at moisture content of 5.9 %, with 56.7 % oil on moisture free basis (MFB) to extract the fat (Head *et al.*, 1995). However, Lovett (undated) notes that the extraction rates from dry shea kernels to butter reached 35-40 % in Northern Ghana when women's groups used better kernels using traditional extraction methods. It is estimated that at least 60,000 metric tonnes of shea nuts are collected yearly for processing locally for the fat.

There are two methods of oil extraction from the nuts. One method is the mechanized extraction by the use of an oil expeller (De Smet Rosedown Mini 40 screw press). The crude fat obtained from this process is later clarified and solidified. The by-product from the processing is the cake, which has not found appreciable use up to this time. Mechanized processing yields 30-35% of shea butter from dried kernels (Addaquay, 2004). With the extraction by screw presses about 13 % of the fat is left within the cake (Personal communication with Dr Kyei of Shebu Industries, 2005). With production expected to increase from the current level of 5000 metric tonnes/year to 9000 metric tonnes/year just in one processing establishment (Personal communication with Dr Kyei of Shebu Industries, 2005), substantial amounts of fat will be retained in the 'waste'.

The alternative processing of the nuts relies on traditional technology. Traditional processing of shea nuts into butter leaves substantial amount of liquid waste. This waste has the potential to pollute the environment when it is produced regularly and in substantial quantities. The product contains suspended and/or dissolved organic matter and oil, and constitutes a high polluting load under normal physical assessment parameters. It had been deduced that on a normal working day, about three tank-loads (of capacity 9000 litres/ tank) of effluent were produced from the processing plant and discharged onto fields. Until the year 1997 the effluent from this plant used to be disposed in the open fields.

Following a site inspection embarked upon by personnel from EPA in Tamale on August 20, 1997 the attention of the management of Kassardjian Industries Limited was drawn to the wrongful and arbitrary disposal of shea waste. The management of the company was subsequently asked to submit the

environmental management plans for the company's activity (Personal communication with Mr. Eddie Telly, EPA-Tamale, 2005). With the inception of the Environmental Impact Assessment (EIA) instituted by EPA, it is imperative that industries undertake some form of effluent treatment so as to protect the environment. Treatment to reduce the pollution effect is essential prior to disposal.

Shea nuts contain 40–55 % fat (Head *et al.*, 1995), and it is estimated that for every metric tonne nuts processed, 450–600 kg of cake is produced. Industries employing the mechanized extraction by screw press remove only 30–35 % of fat with the remaining fat being left in the shea cake/waste. Stocks of cake (as shown in Plate 3) are sometimes burnt in order to provide space for the waste from subsequent processing. This cake/waste possesses the potential to pollute the environment and needs to be disposed of properly.

Plate 3: Heap of shea waste

Objectives

Primarily, the objective of the investigation is to study the suitability of anaerobic digestion (AD) to treat shea waste for biogas/methane production, determining the optimal and stable organic loading and the operational conditions at the steady state.

Specific objectives of the study are to:

a. Investigate the best treatment option under AD for the waste from shea-butter extraction.

b. Determine the characteristics of the waste (pH, TS, VS).

c. Evaluate the performance of AD under varying hydraulic retention time (HRT) and organic dry matter (odm) concentrations.

d. Determine the obtainable biogas / methane yield in AD.

e. Determine the quantitative value and chemical composition (CH_4, CO_2, H_2S) of the biogas.

f. Evaluate the nutrient value of the digested material.

Hypotheses

The specific objectives were used to formulate hypotheses to guide the study. The null hypotheses H_0 used for the study were:

a. AD is not an option for the treatment of waste from shea butter extraction.

b. The characteristics of the waste are not suitable for AD.

c. AD does not show any change in performance under varying HRT and odm concentration.

d. AD does not yield any appreciable amount of biogas / methane.

e. The quantitative value and chemical composition of the biogas obtained are not acceptable with respect to combustibility.

f. There is no difference in the nutrient value between the digested and the raw material.

The alternate hypotheses H_1 formulated were:

a. AD is the best option for the treatment of waste from shea butter extraction.

b. The characteristics of the waste is suitable for AD.

c. AD shows changes in performance under varying HRT and odm concentration.

d. AD gives appreciable biogas / methane yields.

e. The quantitative and value and chemical composition of biogas obtained are acceptable with respect to combustibility.

f. There is difference in the nutrient value of the digested and raw materials.

Justification

The implementation and promotion of biogas technology in the agricultural sector can be achieved especially for the protection of the environment. The energy problem in the savanna regions of Ghana is getting increasingly acute due to deforestation activities of the local communities. Trees are cut down to provide energy for cooking and other processing activities. Processing of shea for the butter also relies on some form of energy to accomplish the process. Sometimes the shea trees that provide the nuts are felled and used as firewood or raw material in the charcoal business.

This project examines in depth the AD of shea waste in order to determine its economic and environmental competitiveness, as a viable option for the

processing of biodegradable organic materials. It is an idea of looking at by-products of processing as a *resource, not a waste*, and it is central to much of the more recent thinking on the whole subject of good environmental management and sustainable alternative energy option. AD is one of the few technologies that through implementation and dissemination, creates a wide breadth of positive impacts. AD has developed from a comparatively simple technique of biomass conversion, with the main purpose of energy production, into a multi-functional system including, the treatment of organic waste and wastewaters in a broad range of organic loads and substrate concentrations; energy production and utilization; improvement of sanitation and reduction of odours; and production of high quality fertilizer.

With an estimated production of 39,000 metric tonnes of shea waste per year, it is important that these materials are utilised in an appropriate way in order to reduce their negative impact on the environment. There is therefore an urgent need for research in this area of waste treatment.

CHAPTER 2

LITERATURE REVIEW

Overview of Anaerobic Digestion

Anaerobic digestion (AD) is brought about by a consortium of interdependent and symbiotic populations of heterotrophic microorganisms, which are capable of utilizing a diverse spectrum of substrates in the absence of oxygen for the synthesis of new cellular materials and production of various end-products (Ghaly, 1996). The microorganisms carrying out the reactions in anaerobic digestion are bacteria, and that class of bacteria is known as ‘anaerobes’; bacteria that live without oxygen and may indeed be killed by oxygen. There is a gradation in tolerance to oxygen among anaerobic bacteria, but many of the digester bacteria are amongst the anaerobes, which are the least tolerant of oxygen.

The process of AD results in the production of a mixture of gases generally called biogas. Biogas is composed of methane, carbon dioxide, hydrogen sulphide and some inert gases (Table 1). AD has been demonstrated to be technically feasible for a wide range of feedstock based on moisture content, and it produces biogas with high methane content typically around 60 %, which can be manipulated upwards.

Table 1. Biogas composition

Component	Composition by volume
Methane	55 – 70 %
Carbon dioxide	30 – 45 %
Hydrogen sulphide	200 – 4000 ppm
Hydrogen	5 – 10 %
Nitrogen	1 – 2 %
Water vapour	0.3 %

Source: Yadav and Hesse, 1981

Biogas comprises principally the combustible methane (CH_4) and the incombustible carbon dioxide (CO_2). The quality of the biogas is determined by the composition of methane and carbon dioxide. The quality of the biogas is therefore a crucial factor in determining the viability of the biogas AD process.

Stages of AD

Hydrolysis/liquefaction

The first stage (liquefaction) involves the hydrolysis and conversion of insoluble complex material to soluble ones and the reduction of polymers to monomers. Fermentative bacteria hydrolyze the substrate polymers, such as carbohydrates, fat and proteins, to simple soluble compounds. The hydrolytic activity is of significant importance in high organic waste and may become rate limiting. Some industrial operations overcome this limitation by the use of chemical reagents to enhance hydrolysis. This application of chemicals to enhance

the first step has been found to result in a shorter digestion time and provide a higher methane yield (RISE-AT, 1998).

Acetogenesis

The second stage (acidogenesis – production of acids by bacteria) involves the fermentation of the monomers into a variety of end products, which include volatile acids, alcohols, carbon dioxide and hydrogen. The principal acids produced are acetic acid (CH_3COOH), propionic acid (CH_3CH_2COOH), butyric acid ($CH_3CH_2CH_2COOH$), and ethanol (C_2H_5OH). This is brought about by the obligate H_2-producing acetogenic bacteria, which oxidize the propionate, butyrate, and long-chain fatty acids to acetate, CO_2 and H_2.

Methanogenesis

In the third stage (methanogenesis), the end products of the fermentation process (acetate, butyrate, propionate, formic acid, hydrogen and carbon dioxide) are then fermented by another group of anaerobes (methanogens) into methane and carbon dioxide with trace quantities of other gases (hydrogen sulphides, ammonia, nitrogen, mercaptans and amines). The methane fermenters are not actually bacteria, but a new type of culture, formed inside the digester during the digestion process (Cilliers, 2000). In this stage methane is produced by the methanogens in two ways: either by means of cleavage of acetic acid molecules to generate carbon dioxide and methane, or by reduction of carbon dioxide with hydrogen. Methane production is higher from reduction of carbon dioxide but limited hydrogen concentration in digesters results in that the acetate reaction is the primary

producer of methane (Omstead *et al.*, 1980). Acetic acid then has been generally regarded as the main precursor since it was shown that 73 % of the methane in the domestic sewage digester came from acetate (Hobson and Wheatley, 1993). The methanogenic bacteria include *methanobacterium, methanobacillus, methanococcus and methanosarcina.* Methanogens can also be divided into two groups: acetate and H_2/CO_2 consumers. Methanosarcina spp. and methanothrix spp. (also, methanosaeta) are considered to be important in AD both as acetate and H_2/CO_2 consumers (Verma, 2002). The methanogenesis reactions can be expressed as follows:

$$CH_3COOH \rightarrow CH_4 + CO_2$$

(acetic acid) (methane) (carbon dioxide)

$$2C_2H_5OH + CO_2 \rightarrow CH_4 + 2CH_3COOH$$

(ethanol)

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

(hydrogen) (water)

It is necessary that the aspects of the AD processes of liquefaction and methanogenesis be well balanced. If the methane bacteria are absent, the digestion process may only succeed in liquefying the material and may render it more offensive than the original material. On the other hand, if liquefaction occurs at a faster rate than methanogenesis, the resultant accumulation of acids may inhibit the methane bacteria and the bioconversion process as well (UNU, 1979).

AD of liquid organic wastes is becoming an interesting alternative for bio-treatment of many kinds of polluted effluents of municipal and industrial origin. This is especially important if the level of BOD is higher than 2 g/l because for higher BOD levels, AD is more economical than aerobic digestion due to low solubility of oxygen in water, which in turn puts an upper limit on the mass transfer from air to the liquid phase (Auria *et al.*, 1995). A reduction in BOD and dry matter minimizes the chance of creation of soil anaerobic conditions, and reduces the pollution of drainage water after field application of digested slurry. This reduction in BOD can be as high as 90 % (SEPA, 1999).

AD can be employed as a first biological treatment process necessary for partial stabilization of agricultural and food processing wastes prior to utilization or disposal, as well as for the production of biogas (Ghaly and Ben-Hassan, 1989; Parsons, 1984; Kugleman and Jerri, 1981). According to Borja *et al*. (1994) citing Edewor (1986), Ng *et al.* (1987), and Ma and Ong (1988) anaerobic biological systems offer the greatest potential for the treatment of Palm Oil Mill Effluent (POME), since these systems do not have the high-energy demand associated with the aeration required by aerobic biological systems.

Anaerobic processes are well established for the treatment of high-strength industrial wastewaters (Van Der Merwe and Britz, 1993). The development of new high-rate anaerobic bioreactor designs, with increased biomass retention and tolerable to toxic and shock loadings, has led to the treatment of extremely recalcitrant industrial waste streams (Stronach *et al*., 1987). Anaerobic treatment of cheese whey for biogas production and the reduction of the pollution potential have been reported by several authors (Mah, 1983; Ghaly and Pyke, 1991; Ghaly,

1989; Yan *et al*., 1989). AD technology has been used successfully as a means of storing and treating livestock manure (Aubart and Fauchille, 1983; Cowley and Wase, 1981; Hobson, 1990). AD systems in which biogas fuel is generated appear to do an excellent job of processing odorous compounds. The AD process stabilizes slurries so that they do not putrefy or create odour. This allows them to be stored much easier and for longer periods. AD of swine manure for methane gas production reduced the odour emission rate from land-applied digested slurry by 91 % compared with untreated pit-stored slurry (Pain *et al*., 1990). In some cases, such systems are now being installed with odour control as one of the primary objectives (Wilkie *et al*., 1995). Volatile Fatty Acids (VFA) in slurry can damage crops. Digestion reduces the concentration of VFAs from thousands of parts per million, to about 250 ppm (Boyd, 2000).

It seems likely that AD of wastes for pollution control, and energy and fertilizer production has a very good future and its use has increased rapidly in many countries (Hobson and Wheatley, 1993). An immense amount of work has been done on AD in the last ten years (Hobson and Wheatley, 1993), some of this have not had any results yet, but some have been immediately exploited in practice and much information has been obtained on new feedstocks and new digesters.

Ibrahim *et al.* (1984) showed that at a temperature of 45 ^{o}C, an anaerobic contact digester could be operated at a maximum organic load of 6.2 kg COD/m^3day, giving a percentage reduction of around 94 %; a higher loading of 7.0 kg COD/m^3day was tolerable at the higher temperature of 50 ^{o}C. Cail and Barford (1985) used a semi-continuous mesophilic anaerobic digester with a volumetric loading of 12.6 kgCOD/m^3day (HRT of 6 days). Ng *et al*. (1985) showed an

effective treatment with a two-phase anaerobic fermentation system giving a treatment efficiency of 85 % with a total HRT of 31 days with no cell recycle. The data obtained by Edewor (1986) showed that after a 10-day retention time a single-stage anaerobic contact digester gave a COD removal efficiency of 93.8 %.

Bentonite is used in plant oil refineries for cleaning and decolourizing vegetable oils (Angelidaki *et al.*, 1990) and the refining process results in a waste product with high oil content. In a biogas digester, neutral lipids (fat and oil) are hydrolysed to long-chain fatty acids (LCFA) and glycerol by extracellular hydrolytic enzymes produced by fermentative bacteria. The main part of the energy content of the oils is conserved in the LCFA, which are then fermented by hydrogen-producing acetogenic bacteria via beta-oxidation (Weng and Jeris, 1976). The products of this degradation (acetate and hydrogen) are finally converted into biogas (methane and carbon dioxide) by methanogenic bacteria (Bryant, 1979). The methane yield from oil is higher than from most other organic materials. The theoretical gas yield of glyceride trioleate (GTO) is, for example, 1.4 Nm^3 per kilogram of oil (Nm^3 = volume at 0 ^oC and 1 bar) with methane content of 70 % (Weng and Jeris, 1976). In comparison, manure typically results in a gas yield of approximately 0.4 Nm^3 per kilogram of added organic matter, with lower methane content. Therefore, waste with a high content of oil constitutes an attractive substrate for biogas production.

Factors of AD

The rate at which microorganisms grow is of paramount importance in AD process. This rate can be enhanced by the operating parameters of the digester and

this will increase the anaerobic degradation efficiency of the system. Each of the various types of bacteria responsible for the three stages of methanogenesis is affected differently by those parameters (Hohlfeld and Sasse, 1985) and interactive effects between the various determining factors are possible. However, it is only these factors and their respective qualitative effects on the process of fermentation that can be predicted. Various factors such as biogas potential of feedstock, design of digester, inoculum, nature of substrate, pH, temperature, loading rate, hydraulic retention time (HRT), C:N ratio, volatile fatty acids (VFA), etc. influence the biogas production.

Feedstock

Feedstock is defined to include any substrate that can be converted to methane by anaerobic bacteria. Feedstock for anaerobic digestion can be derived from various agricultural, industrial and municipal sources. The feedstock for anaerobic digestion, vary considerably in qualitative and quantitative composition, homogeneity, fluid dynamics and biodegradability (Steffen *et al*., 1999). Suitable feedstock for the biomethane process includes animal excrements, night soil, organically burdened industrial wastewater (example from the production of sugar or alcohol, food processing, etc) and organic agricultural residue such as grass, coffee pulp, banana peels, etc. (Hohlfeld and Sasse, 1985). Animal manures exhibit good nutrient balances, and are relatively biodegradable. The range of biodegradability reported varies from 28 – 70 %. This variation is partly due to the diet of the animals and the amount of bedding to the animal that is also used for digestion (Marchaim, 1992). It is emphasized that in the selection of wastes for

digestion, the total solid content, the percentage of volatile solids, the C:N ratio and the biodegradability must be carefully considered. According to Steffen *et al.* (1999), wastes containing less than 60 % of volatile solids are rarely considered as valuable substrates worthwhile for AD. The feedstock influences the reactor configuration (design and operational considerations) and has a comprehensive influence on the bacteria physiology. It also dictates the quality of the products such as biogas, anaerobic surplus sludge and the necessity of effluent post-treatment at the end of digestion process. The feedstock may also determine the purpose and the objectives of the anaerobic treatment process (AD-NETT, 2000). For example, the main objective of treatment of industrial wastewater by AD is not generally the generation of methane with subsequent energy production or the quality of the sludge as a potential soil conditioner, but the reduction of COD in the effluent as much as possible.

Wastes often contain numerous disturbing and inhibiting components. Among the most unwanted components are straw, wood shavings, sand, glass, metals and plastics, and measures are taken to avoid such components upstream of the digesters. Inhibitory components, metabolites and products like volatile fatty acids, ammonia and H_2S, are carefully controlled, when using feedstock such as chicken manure. Heavy metals usually are not present in toxic concentrations in agricultural feedstocks (AD-NETT, 2000).

Substrate Composition and Biodegradability

Organic materials for biogas generation basically come under any form of biomass namely carbohydrate, protein and fat. The degradation rates of waste

organic matter can vary significantly with the substrate composition, for example, protein-, carbohydrate-, and fat content (Steffen *et al*., 1999). Table 2 shows the theoretical gas yield and gas composition of fermentation from carbohydrates, fat and protein.

Table 2. Theoretical gas yields and gas composition from organic materials

Substrate	Theoretical biogas output (l_N/kg odm)	Theoretical composition (vol. -%)
Carbohydrate	746	CH_4 – 50; CO_2 – 50
Fat	1390	CH_4 – 72; CO_2 – 28
Protein	800	CH_4 – 60; CO_2 – 40

Source: VDI, 2004

Steffen *et al*. (1999) indicated also that carbohydrates and proteins show the fastest conversion rates. According to them, fat provides the highest biogas yield, however, due to its poor bioavailability, it requires the highest retention times. It is also noted that the distribution of organic macromolecules like proteins, fats and carbohydrates in the feedstock is of great importance, as their degradation leads to the formation of volatile fatty acids (VFA), the main substrates for bacteria of the last two stages of AD. It was also observed that high fat contents of substrate increase VFA considerably, whereas high protein content leads to large amounts of ammonia (NH_3) (Steffen *et al*., 1999). Assessment of the efficiency of the biogas process beside the biogas production output and biogas quality is the rate of degradation of the organic dry matter. In AD it is not the entire organic dry

matter of the substrate, which is digested to biogas. The decomposition efficiency mainly depends on the chemical composition (energy and nutrient content) of the initial input material, the reactive conditions in the digester (e.g. temperature) and the retention time of the substrate in the digester. Digestion of pig slurry has been identified to produce higher biogas yields and methane contents than cow slurry because pig slurry has a slightly higher fat content (Steffen *et al*., 1999).

Substrate Temperature

Operating temperature is an important factor influencing digester efficiency. Though the operating temperature is critical, stabilizing the temperature and keeping it stabilized are even more important. Variations of plus or minus 1 ^{o}C in a day may force the methane-producing organisms into periods of dormancy (Mattocks, 1984). The organisms consume acids, and without them acids will accumulate and the pH will fall, impeding the effectiveness of the whole biogas system (Mattocks, 1984). Anaerobic fermentation requires an ambient temperature of between 3 ^{o}C and approximately 70 ^{o}C (Hohlfeld and Sasse, 1985). Table 3 shows the three different temperature ranges as distinguished in AD.

Table 3. Temperature ranges of AD

Type	Temperature, ^{o}C
Psychrophilic (or cryophilic)	10 - 20
Mesophilic	20 – 40
Thermophilic	40 – 60

Source: Hohlfeld and Sasse, 1985

The metabolic activity of the bacteria increases with temperature and organic material degrades more rapidly at higher temperatures because the full range of bacteria is at work. Thus, a digester operating at a higher temperature can be expected to produce greater quantities of biogas. However the amount of free ammonia also increases with temperature, thus the biodigestive performance could be inhibited or reduced as a result. The process of biomethanation is very sensitive to change in temperature. The degree of sensitivity, in turn, is dependent on the temperature range. According to Hohlfeld and Sasse (1985), brief fluctuations not exceeding the following limits may be regarded as uninhibitory with respect to the process of fermentation:

Psychrophilic	+/- 2 ^{o}C/h
Mesophilic	+/- 1 ^{o}C/h
Thermophilic	+/- 0.5 ^{o}C/h

The methanogenic bacteria seem to be ubiquitous at least in all anaerobic environments and obviously survive a wide temperature range. It is therefore not surprising to find that the change from mesophilic to thermophilic temperatures or vice versa is not a problem in animal waste digesters as long as the change occurs

smoothly (slow change, low loading). However, it might take months before mesophilic cultures are adapted to psychrophilic temperatures. Once the adaptation to low temperature is complete, the system reacts very well to stress situations (Wellinger *et al*., 1985). The ultimate gas yield of psychrophilic digestion is on average significantly lower than at mesophilic temperatures. Differences reported are in the range of 30 % for cattle manure (Wellinger *et al*., 1985) and 22 % for sewage sludge (Maly and Fadrus, 1971).

Within practical time limits (up to 100 days) the degradation at 22 ^{o}C of sewage sludge (Fair and Moore, 1934), cattle manure (Wellinger *et al*., 1985) and swine manure (Stevens and Schulte, 1979) takes about two times longer than at 35 ^{o}C. On the other hand, there is less difference between mesophilic and thermophilic digestion. There is a faster degradation at the higher temperatures (Maly and Fadrus, 1971; Baserga *et al*., 1995), but ultimate gas yields are similar (Beck and Abdel-Hadi, 2001). The main difference is the higher volumetric methane yield per day, which can be reached with thermophilic digestion, thus allowing higher specific methane yields from a given volume of a biogas reactor.

Thermophilic AD also offers other advantages over mesophilic digestion: increased rates of volumetric methane production per day, lower viscosity, less biomass formation, increased conversion rate of organic matter from waste to biogas, and more effective and faster pathogen inactivation (Dohanyos, 2001). The optimum temperature for mesophilic digestion is generally accepted to be about 35 ^{o}C and the thermophilic optimum between 55 and 60 ^{o}C (Hobson and Wheatley, 1993). However, increase in temperature increases the rate of polysaccharide hydrolysis and fermentation but does not increase the extent of hydrolysis of fibres

(Hobson and Wheatley, 1993) so the ultimate degradation of manure solids at long retention times is the same whatever the temperature. A temperature between 32 °C and 35 °C has proven most effective for stable and continuous production of methane. Biogas produced outside this range will have a higher percentage of carbon dioxide and other gases than within this range (Hobson and Wheatley, 1993).

Conventional anaerobic digesters are commonly designed to operate in either the mesophilic temperature range or thermophilic temperature range. There are usually two reasons why the mesophilic and thermophilic temperatures are preferred. Firstly, a higher loading rate of organic materials can be processed and, because a shorter HRT is associated with higher temperatures, and increased outputs for a given digester capacity result. Secondly, higher temperatures increase the destruction of pathogens that may be present in the raw substrate.

Nutrients Availability

Bacteria need more than just a supply of organic substances as a source of carbon and energy. In addition to carbon, oxygen and hydrogen, the generation of biogas requires an adequate supply of nitrogen, sulphur, phosphorous, calcium, magnesium and a number of trace elements (Hohlfeld and Sasse, 1985). Agricultural residue usually contains adequate amounts of the aforementioned elements, hence their suitability for biogas production.

Loading Rate

Loading rate is the amount of raw materials fed per unit volume of digester capacity per day. The organic loading rate (OLR) describes the amount of organic material (expressed as chemical oxygen demand or volatile solids), which is fed daily per m^3 of digester working volume (AD-NETT, 2000).

The specific gas yield decreases in inverse proportion to the loading rate (Hohlfeld and Sasse, 1985). If the plant is overfed with raw materials, volatile fatty acids will accumulate with a concurrent drop in pH and methane production will be inhibited. The result can be a complete digester failure. On the other hand, if the plant is underfed, the gas production will be low.

Retention time

Retention time is the average period that a given quantity of input remains in the digester to be acted upon by methanogens. The retention time can only be accurately defined in batch-type facilities.

For continuous systems, the calculations are based on a mean HRT arrived at by dividing the digester volume (V_D) by the daily influent rate (Hohlfeld and Sasse, 1985):

$$HRT = \frac{D_{LV}}{D_{FR}}, \qquad [1]$$

where D_{LV} is the digester liquid volume in m^3,

D_{FR} is the digester flow rate in m^3/day.

The retention time is dependent on temperature and up to 35 ^oC, the higher the temperature, the lower the retention time (Lagrange, 1979). Selection of a

suitable retention time also depends on the type of substrate used (Hohlfeld and Sasse, 1985). The minimal HRT is dependent on the type of material to be digested. The lower the degradation rate, the slower the doubling time of the bacteria, and the higher the HRT. The rate-limiting step for agricultural waste usually is the hydrolysis. The rate of degradation of the basic classes of compounds increases in the following order (AD-NETT, 2000): Cellulose $\Rightarrow$ Hemicellulose $\Rightarrow$ Proteins $\Rightarrow$ Fat $\Rightarrow$ Carbohydrates. As a result, the digestion of pig manure with its high fat content requires lower HRTs than cattle manure which contains comparably high cellulose and hemi-cellulose concentrations.

Even though lipids (fat) are fairly rapidly degraded they may be the reason for problems with inhibition. Lipids and their hydrolysis products, the long chain fatty acids (LCFA), might absorb to surfaces and as such hinder (physically) the attack of exo-enzymes, which hydrolyse the substrate and the transport of substrates through bacteria membranes (Demeyer and Henderickx, 1967; Hanaki *et al*., 1981; Rinzema, 1988). High concentrations of LCFA are also known to inhibit its own degradation (Hanaki *et al*., 1981) and also methane formation (Hanaki *et al*., 1981; Angelidaki *et al*., 1990; Angelidaki and Ahring, 1992).

pH value of substrate

The acid concentration in aqueous systems is expressed by the pH value, i.e. the negative logarithm, base 10, of the concentration of hydrogen ions. At neutral conditions, water contains a concentration of 10^{-7} hydrogen ions and has a pH of 7. Acid solutions have a pH less than 7 while alkaline solutions are at a pH

higher than 7. The optimum biogas production is achieved when the pH value of input mixture in the digester is between 6 and 7 (FAO, 1997). It has been determined (RISE-AT, 1998) that an optimum pH value for AD lies between 5.5 and 8.5.

The pH in a biogas digester is also a function of retention time. During digestion, the two processes of acidification and methanogenesis require different pH levels for optimal process control. In the initial period of fermentation (the process of acidification), as large amounts of organic acids are produced by acid forming bacteria, the pH inside the digester can decrease to below 5. This inhibits or even stops the digestion or fermentation process. Methanogenic bacteria are very sensitive to pH and acid concentration within the digester and their growth can be inhibited by acidic conditions (FAO, 1997). Methanogenic bacteria do not thrive below a pH of 6.5. Later as the digestion process continues, concentration of ammonia increases due to digestion of nitrogen, which can increase the pH to above 8. When the methane production level is stabilized, the pH range remains buffered between 7.2 and 8.2 (FAO, 1997).

Bacteria require suitable conditions of pH and temperature to grow optimally and the bacteria concerned in the reactions in anaerobic digesters vary with respect to optimum pH for growth (Hobson and Wheatley, 1993). If the pH of the content of a digester drops it indicates failure of the buffering mechanism and hence too much acid is being produced. A better measure of the stability of a digester is its alkalinity (Eggling *et al.*, 1979).

Carbon to Nitrogen Ratio (C:N ratio)

This is the relationship between the amount of carbon and nitrogen present in organic materials. Nitrogen present in the feedstock has two benefits: (a) it provides an essential element for synthesis of amino acids, proteins and nucleic acids; and (b) it is converted to ammonia which, as a strong base, neutralizes the volatile acids produced by fermentative bacteria, and thus helps maintain neutral pH conditions essential for cell growth. An overabundance of nitrogen in the substrate can lead to excessive ammonia formation, resulting in toxic effects. It is important that the proper amount of nitrogen be in the feedstock, to avoid either nutrient limitation (too little nitrogen) or ammonia toxicity (too much nitrogen).

The composition of the organic matter added to a digestion system has an important role on the growth rate of the anaerobic bacteria and the production of biogas (Marchaim, 1992). A C:N ratio ranging from 20 to 30 is considered optimum for anaerobic digestion (FAO, 1997). If the C:N ratio is very high, the nitrogen will be consumed rapidly by methanogens to meet the protein requirements and will no longer react on the left over carbon of the material. As a result, gas production will be low. On the other hand, if the C:N ratio is very low, nitrogen will be liberated and accumulated in the form of ammonium ion (NH_4^+). NH_4^+ will increase the pH value of the content in the digester. Various studies have shown that free ammonia is far more toxic than the ammonium ion (Marchaim, 1992). A pH higher than 8.5 will start showing toxic effect on methanogen population (FAO, 1997). Optimum C:N ratios of the digester materials can be achieved by mixing materials of high and low C:N ratios, such as organic solid waste mixed with sewage or animal manure. It is also noted that

since not all of the carbon and nitrogen in the feedstock are available to be used for digestion, the actual available C:N ratio is a function of feedstock characteristics and digestion operational parameters, thus overall C:N values can actually vary considerably from less than 10 to over 90, and still result in efficient digestion (Marchaim, 1992).

Mixing

Many substrates and various modes of fermentation require some sort of substrate agitation or mixing in order to maintain process stability within the digester. The purpose of mixing in a digester is to blend the fresh material with digestate containing microbes. Mixing prevents scum formation and sedimentation, and avoids temperature gradients within the digester. Furthermore, mixing provides a uniform bacterial population density and prevents the formation of dead spaces that would reduce the effective fermentation volume. However, excessive mixing can disrupt the microbes so slow mixing is preferred. The kind of mixing equipment and amount of mixing varies with the type of reactor and the solid content in the digester. The two very important aspects of digester mixing are the intensity and duration of mixing. Most of the literature on AD emphasizes the importance of adequate mixing to improve the distribution of substrates, enzymes and microorganisms throughout the digester (Chapman, 1989; Parkin and Owen, 1986; Lema *et al*., 1991). However, the information available in the literature about the effect of the intensity and duration of mixing on the performance of anaerobic digesters are contradictory (Karim *et al*., 2005). Several studies indicated that a lack of sufficient mixing in low solids digesters dealing with

municipal waste resulted in a floating layer of solids (Diaz and Trezek, 1977; James *et al*., 1980; Stenstrom *et al*., 1983). Chen *et al*., (1990) observed higher methane yield in the case of a 4.5 m^3 digester under unmixed conditions than continuously mixed conditions. In another study, Ben-Hasson *et al*., (1985) observed 75 % lower methane production rate from diary cattle manure under continuously mixed conditions than unmixed conditions. On the contrary, Ho and Tan (1985) reported greater gas production for a continuously mixed digester than for an unmixed digester fed with palm oil mill effluents, and Hashimoto (1983) found higher biogas production from beef cattle wastes under continuously mixed conditions than under intermittent mixing conditions. At the same time, Dague *et al.* (1970), Mills (1979) and Smith *et al*. (1979) recommended intermittent mixing of anaerobic digesters over continuous mixing. It has been observed that very rapid mixing disrupts the structure of flocs inside a biological reactor, which disturbs the syntrophic relationships between organisms, thereby adversely affecting the reactor performance (Whitmore *et al*., 1987; Dolfing, 1992; Stroot *et al*., 2007).

Inoculums (Inoculants)

Inoculum is said to be any material, such as previously digested feedstock, that is added to a newly started digester to hasten the degradation of organic matter and the production of methane. The age and quantity of the inoculant (starter sludge) have a decisive effect on the course of fermentation (Hohlfeld and Sasse, 1985).

Digesters may be inoculated from some of the feedstock which has been allowed to stand for some time (weeks or months) in tanks or lagoons and which has begun to degrade anaerobically. The bacteria in this case may have come from the feedstock or may have come from the air or soil. The stored feedstock will then have at least small numbers of all the types of bacteria needed in the digester and these can be developed when the waste is transferred to the digester. However, the most certain way of inoculating a digester is to use organisms from a long-running and active digester treating the same waste (Hobson and Wheatley, 1993).

Type of Digestion

Mono-fermentation

Mono-fermentation is the AD of a single organic substrate with the help of micro-organisms (inoculums).

Co-fermentation

In AD, co-fermentation is the term used to describe the combined treatment of more than one organic waste with complementary characteristics. This is one of the main advantages of the anaerobic technology. The co-fermentation or co-digestion of organic wastes involves the mixing of the various substrates in varying proportions. There are numerous non-agricultural organic wastes that have been introduced to farm digesters as co-substrates. These additional feedstocks are derived mainly from agro- and food industries as well as from municipalities (biogenic wastes). Typically co-substrates are digested with animal manure as the predominant substrate (Steffen *et al.*, 1999). The manure is essential

for the digestion of the other substrates in order to have a relatively stable process. It has been shown that the performance of digesters could be considerably improved by means of co-substrate addition (Steffen *et al*., 1999). The improvement of the buffer capacity is also reported as a positive effect in the co-fermentation process (Mshandete *et al*., 2004). Investigations have shown that up to 80 % co-substrate addition are applied in some cases in agricultural digesters (Steffen *et al.*, 1999). The feedstocks may include:

- food remains from large kitchens, hospitals, schools, etc
- animal wastes from slaughterhouses (blood, stomach contents, fat),
- organic wastes from the food processing industry (fruit and vegetable remains, fish processing wastes),
- organic wastes from the biochemical industry (fermentation slops),
- organic wastes from textile industries (wastewater),
- organic wastes from the pharmaceutical industry (spent tissues, contaminated eggs, spent blood plasma) and
- source separated, organic fraction of municipal solid waste (OFMSW).

An overview of co-fermentation of biogenic wastes and energy crops in Germany showed that more than 80% of all biogas plants are operated with co-fermentation of non-agricultural wastes or specially cultivated energy crops (Weiland, 2001). Beside the farm-scale plants approximately 18 large-scale co-fermentation plants with a total reactor capacity between 1500 and 10000 m^3 are in operation in Germany (Weiland, 2001). Pig and cow manure are mainly used as basic substrate. Non-agricultural wastes from food and agro industry, e.g. pulps, oil seed residues or overlaid foodstuffs, are the most applied co-substrates because

these wastes are normally free of foreign substances, pathogens and heavy metals and are often finely crushed promoting the bio-availability for biogas formation. The biogas yield from energy crops is 4 – 8 times higher than the gas yield from pure manure, and fat containing residues and meal residues from canteens and restaurants result even in 20-fold higher gas yields (Weiland, 2001). Weiland (2001) also emphasized that co-fermentation is the leading technology in order to produce energy from waste and energy crops. Experiences show that economic viability of biogas plants is reached through co-fermentation (Köttner, 1994). The observation made is that nowadays investors in biogas technology are less environment orientated and more profit orientated, therefore economical energy production is very much in the foreground.

Digester Design Variations

There are two general design characteristics of digesters: batch feed and continuous feed. The batch digester is loaded, sealed, and after a period of gas collection, is emptied. A batch digester can essentially be any suitably sized container or tank that can be sealed and fitted with a means to collect the biogas. A common use of laboratory batch-digester has been to determine the digestibility of a substrate and/or to determine the methane yields from substrates (Hobson and Wheatley, 1993). The continuous feed digester receives substrate on a continuous or daily basis with a roughly equivalent amount of effluent removed.

Batch digesters

Batch digesters are loaded with feedstock, subjected to digestion, and then discharged and loaded with a new batch. In batch systems the fresh substrate is fed together with an inoculum (approx. 10 % of digester liquid volume) of digested sludge from the first batch into a reaction vessel (Burton and Turner, 2003). The substrate is anaerobically degraded, at first with an increasing daily gas production. The daily gas production reaches a maximum after approximately10 to 14 days, depending on the microbial availability of the nutrients in the waste material, and thereafter it decreases to reach a steady rate of about half maximum production (Burton and Turner, 2003).

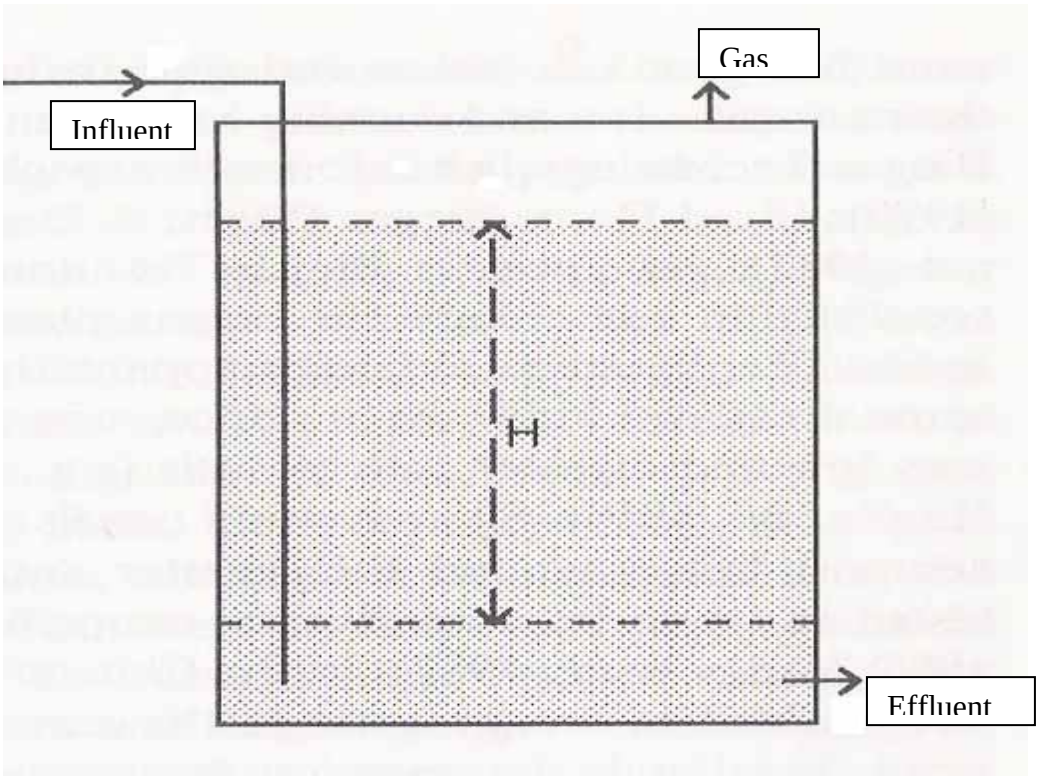

Figure 1: Diagrammatic representation of batch digester (source: Hobson and Wheatley, 1993)

To compensate the unsteady gas production at least three to four batch digesters are operated in parallel but filled at different times. This system is mainly used for the digestion of fibrous substrates with limited microbial availability such as straw-rich solid waste. The main attraction of batch processing is the simplicity and low cost. Figure1 shows a schematic diagram of a batch digester. The digester is gradually filled up over the depth H and then emptied, retaining the sludge below H as inoculum for the next filling.

Continuous feed digesters

There are many designs and construction methods of such digesters but the Chinese and Indian digesters are the widely used. The Indian and Chinese designs are less expensive and easier to build and operate, but those benefits are countered by fairly inefficient gas production. Although the Indian design produces slightly more gas than the Chinese design, it is slightly more expensive and has the added maintenance requirements associated with the floating dome (Mattocks, 1984). The Chinese digester (Figure 2) is an almost spherical underground tank made of concrete or concrete-lined brick or stone with inlet and outlet pipes. Gas collects in the top of the digester, and the gas pressure varies as more or less gas is collected.

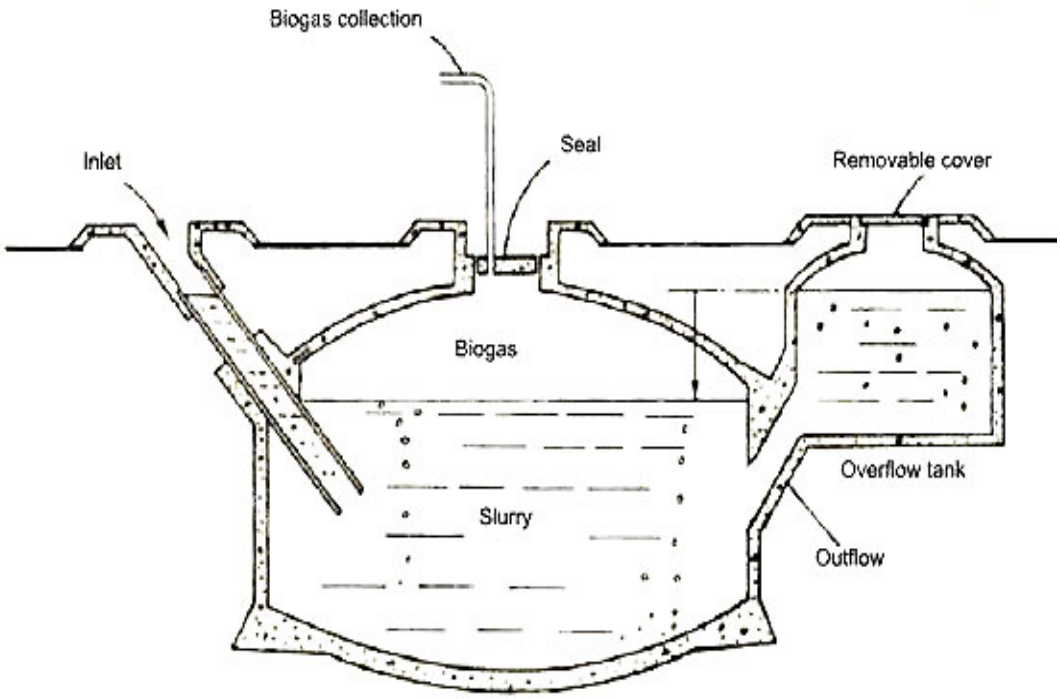

Figure 2: Chinese fixed dome design (source: Institute of Science in Society, 2006)

The Indian digester (Figure 3) is a vertical brick cylinder, partly buried in the ground and with inlet and outlet pipes running from near the bottom. In some cases, the cylinder has a dividing wall so that the slurry circulates from the inlet over the wall and to the outlet. The gas-holder is a floating metal drum over the digester and this can be provided with a mixing paddle which can be occasionally turned by rotating the gas-holder.

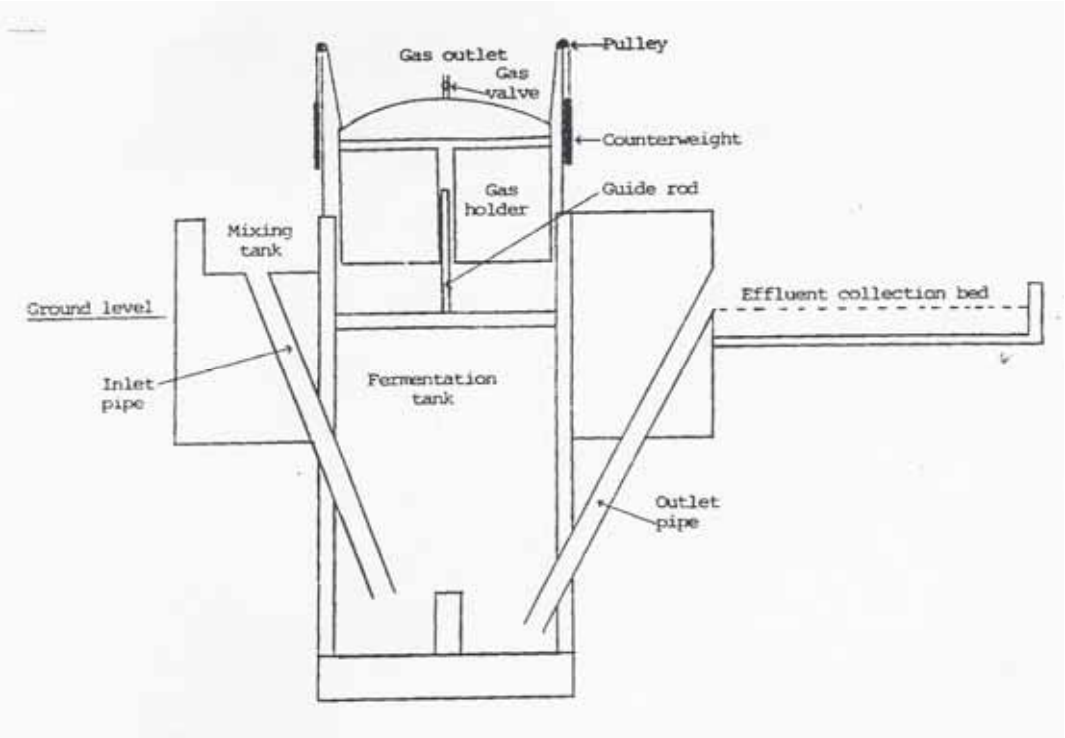

Figure 3: Typical Indian biogas plant (source: Mattocks, 1984)

Development and Present Status of AD Technology

The industrialization of AD began in 1859 with the first digestion plant in Bombay, India. Research led by Buswell and others (Lusk, 1997) in the 1930s identified anaerobic bacteria and the conditions that promote methane production. The oldest publication on the influence of temperature on methane formation was by Popoff in 1875 (AD-NET, 2000). Popoff found that river sediments could form biogas at temperatures as low as 6 ^{o}C. Popoff also observed that the composition of the gas formed did not change with temperature (AD-NETT, 2000).

Prior to 1920, most of the AD took place in anaerobic ponds (Verma, 2002). As the understanding of AD process control and its benefits improved, more sophisticated equipment and operational techniques emerged. The result was

the use of closed tanks and heating and mixing equipment to optimise AD (Verma, 2002). The primary aim of waste stabilization in due course led to the basic municipal sludge digester. This design then spread throughout the world. However, methane production suffered a setback as low-cost coal and petroleum became abundant. AD systems made a comeback during the World War II with fuel shortages hitting Europe but after the war AD was once again forgotten (Verma, 2002).

While the developed world shunned AD except as a wastewater sludge digestion technique, developing countries such as India and China embraced this technology. These countries saw gradual increase in small-scale AD systems used mostly for energy generation and sanitation purposes (Verma, 2002). In the developed countries, industrial expansion and urbanization coupled with low-cost electricity resulted in aerobic composting and landfilling becoming the choice technologies for waste treatment, until recent times (Verma, 2002). The energy crisis in 1973 and again in 1979 triggered renewed interest in the development of simple AD systems for methane production as an energy source (Verma, 2002). India, China and most countries in South-east Asia responded to the crisis with marked expansion of AD (Verma, 2002). Most of the AD systems were small digesters using combined human, animal and kitchen wastes. Many community digesters were installed to produce large volumes of biogas for village electrification (Verma, 2002). Europe, North America and the Soviet Union became involved in AD research for methane production from animal manure. The United States of America established energy programmes, emphasizing on the AD of biomass for energy production (Verma, 2002). During the energy crisis of the

1970s, the search for alternative energy resources led to investigations to determine whether the AD technologies developed in India and China were transferable to farms in the United States. Although, the technologies were useful in providing fuel for cooking and lighting in developing economies, most were much too small to be useful to American farmers (Lusk, 1997). For example, the typical small-scale digester had a daily production equivalent to the same amount of energy as contained in one gallon of propane (VITA, 1979).

The rush for deployment of AD systems to meet energy needs also led to many foreign-aid projects. Unfortunately, knowledge on AD was still in a fledgling state and numerous digester failures were reported. For example China, India and Thailand reported 50 % failure rates, while failures of farm digesters in the United States of America approached 80 %. Europe and Russia also experienced high farm digester failure rates (Lusk, 1997). Nevertheless, those designs that succeeded furthered the interest in research and development of AD. Apart from biogas production, AD found wider acceptance as an inexpensive technology for waste stabilization, nutrient recovery, reduction in biological oxygen demand (BOD), and sludge treatment. The dominant application of AD technology has been in farm-based facilities. About six to eight million family-sized, low-technology digesters were used to provide biogas for cooking and lighting fuels with varying degrees of success (Verma, 2002).

Over the years AD systems have become more complex and more diverse, and not limited to agriculture or animal waste treatment as it used to be. India and China have now adopted a trend towards larger and more sophisticated farm-based systems with better process control to generate electricity. The technology is now

being applied for municipal waste treatment as well as industrial wastes (Verma, 2002). Taiwan flared most biogas from waste treatment and has cut down river pollution, caused by direct discharge from the animal production industry, by simply using standard AD systems that served 5,000 farms (Lusk, 1996).

Status of AD in Developed Economies

Currently, Europe is under pressure to explore the AD market because of two significant reasons: high energy prices and stringent environmental regulations, especially controls on organic matter that go to landfills as well as further expansion of landfills. As a result of environmental pressures, many nations have implemented or are considering methods to reduce the environmental impacts of waste disposal. In Europe, AD facilities generally have had a good record in treating a wide spectrum of waste streams like farm, industrial, and municipal wastes. According to Lusk (1996), some AD facilities in Europe have been in operation for over 20 years and more than 600 farm-based digesters currently operate in Europe, where the key factor is their simplicity. Lusk (1996) says around 250 of these systems have been installed in Germany alone in the past five years. In addition to farm digesters, Europe leads in large centralized AD systems. Between 1987 and 1995, more than 150 new AD plants were constructed in Europe (Verma, 2002). In Europe, there are 30 large centralized digesters, of which 15 are in Denmark alone, and 30 more are under construction (Verma, 2002).

An overview of the implementation of biogas technology in Sweden showed that the technology has had a general positive trend in the country since

the year 1990 (Nordberg, 2001). The main reason for this development was the effort to replace landfilling of nutrient-rich, wet organic waste with sustainable alternatives. In accordance with the EU directive on landfilling, a tax on putting organic waste into landfills was introduced on 1st January 2000, together with a proclaimed ban on landfilling organic waste by the year 2005 (Nordberg, 2001). The Swedish Environmental Protection Agency estimated that biological waste treatment (composting and anaerobic digestion) would increase from the current annual 0.4 million tonnes to 0.8 million tonnes in five years (Nordberg, 2001). The number of biogas plants in operation in Sweden as at the year 2001 was about 220, with 134 of them being sewage sludge treatment facilities (Nordberg, 2001). At 60 sites the biogas was generated from landfills or cell digesters at landfills. Between 1991 and 2001 (Nordberg, 2001), ten centralized full-scale plants treating solid wastes were constructed in Sweden. The interest in using biogas as vehicle fuel has increased as a result of the change in waste management policy. Units for upgrading biogas are also in operation as well as filling stations for compressed biogas (CBG). As at the year 2004, Sweden had 20 plants producing biomethane and ran 2300 buses on it (Biocycle, 2005). The major incentive for using biogas as vehicle fuel is that upgraded gas gives the best net income, compared with alternatives. Biogas has been classified as the most environmental friendly fuel (except for hydrogen and electricity) and was free from tax (excluding VAT) for ten years (Nordberg, 2001). In Denmark, as at the year 2000 there was an increasing number of large-scale biogas plants, treating more than one million cubic metres animal wastes and 250,000 cubic metres of other wastes annually (Westermann, 2001).

The AD technology is also used for treating industrial wastewater. The treatment of high-organic industrial wastewater by AD is less costly than by aerobic composting. Over 35 industries have been identified using AD, and these include chemical processing, fibre, food waste, meat and milk, and pharmaceuticals.

Status of AD in Africa

Africa is endowed with substantial renewable energy resources. The region has 1.1 Gigawatts of hydropower capacity, 9000 Megawatts of geothermal potential and abundant biomass, solar and significant wind potential (Karekezi and Ranja, 1997). The renewable energy resource potential in Africa has not been fully exploited, mainly due to the limited policy interest and investment levels. In addition, technical and financial barriers have contributed to the low levels of uptake of renewable energy technologies in the region (Karekezi and Ranja, 1997). Beyond concerns about sanitation, successful adoption of biogas in Africa is highly dependent on political, economic, logistical, and social factors. A key to successful adoption of biogas technology appears to be direct observation and experience. The technology is often perceived to be complicated.

Biogas obtained from AD of organic materials has attracted considerable attention in Africa over the last three decades (Karekezi and Kithyoma, 2003). This is a simple biomass energy technology at the small-scale level, which requires relatively limited level of investment. The raw material is animal dung, which is plentiful in many rural areas in sub Saharan Africa. The technical viability of this technology has been repeatedly proven in many field tests and

pilot projects but numerous problems arose as soon as mass dissemination was attempted (Karekezi and Kithyoma, 2003).

The degree of adoption of biogas technology is insignificant compared to the degree of energy scarcity and necessity on the continent. There is limited evidence from many African countries on the low dissemination levels of the technology, the general consensus is that the larger combined septic tank/biogas units that are run by institutions such as schools and hospitals are more viable than small-scale digesters (Karekezi and Kithyoma, 2003).

Table 4: Small and medium scale biogas units in selected sub-Saharan African countries

Country	Number of plants
Tanzania	>1,000
Kenya	500
Botswana	215
Burundi	279
Zimbabwe	200
Lesotho	40
Burkina Faso	20

Source: Karekezi, 2002.

Even though, Tanzania signed the UN Framework Convention on Climate Change and developed a comprehensive environmental policy, placing high priority on worldwide environmental issues such as global warming, the country

lacked the technical experience required to construct large-scale biogas plants (UNDP, 1992). Tanzania had emphasized development of renewable energy in its 1992 energy policy; most of the country's biogas units are for household gas production needs. Most of the continent's biogas units are small, designed only for the production of cooking and lighting gas from cow manure in rural areas. Table 4 shows AD distribution for seven African countries.

Recently, Africa has seen a reasonable amount of adoption in biogas technology. Somewhat larger-scale biogas plants now operate successfully in a number of countries (Brown, 2006). Biodigesters in five of Rwanda's largest jails provide more than half of the prison kitchens' energy, and the Institute for Scientific Research and Technology in Kigali plans to install some 1,500 biogas digesters by 2009 in settlements and villages where rural Rwandans were relocated after the genocidal wars of the mid-1990s (Brown, 2006).

Status of AD in Ghana

The degree of dissemination and adoption of the biogas technology in Ghana is not any different from the entire sub Saharan Africa, excluding South Africa. In spite of the tremendous benefits of AD, which are known by the population, not much has been achieved in terms of practical dissemination of the technology. Biogas technology in Ghana started with a pilot project by the Government of Ghana (GOG) in 1987 at Appolonia in the Greater Accra Region (Osei-Safo, undated). The project has ten 50 m^3 digesters, which operate on cowdung because the inhabitants of the locality are predominantly cattle farmers.

The biogas produced is used in the generation of electricity with the digested slurry being used as manure on their vegetable farms (Osei-Safo, undated).

The inventory of digesters in Ghana showed digester capacities ranging between 0.35 and 50 m^3. Almost all the digesters are of the Chinese fixed-dome design constructed with burnt-bricks. These digesters are installed to address specific environmental problems; treatment of wastewater from animal slaughterhouses and hospitals. In Ghana, most slaughterhouse waste is discharged without treatment directly onto wasteland or into rivers and streams leaving the environment around such places unhygienic with attendant bad odour and flies (Aklaku *et al*., 2006). The biogas obtained from the treatment of hospital wastewater is used to heat water for patients and that produced from slaughterhouses is used to singe animals instead of the use of firewood and old lorry tyres.

The benefits of biogas technology have been recognised in Ghana even with the limited number of installations in operation. It is established that Ghana has the potential to adopt the technology on a wider and larger scale, especially in the northern sector, where climatic conditions are comparatively more favourable with significant concentration of livestock. The northern region alone can boast of 40.9 % of cattle and 26.13 % of pigs out of the total for the country (NRI, 1996). In view of the current soaring cost and scarcity of commercial energy locally, it is imperative to exploit this renewable energy resource, which has positive implications for our environment.

CHAPTER 3

MATERIALS AND METHODS

Materials

Fermentation Unit

The biogas laboratory was established on the Nyankpala Campus of the University for Development Studies in November 2005 for the purpose of this investigation with six horizontal half-technical fermentation plants. Each fermentation unit comprised a digester (fermenter) with a manual stirrer, a pressure compensation bottle, a gasholder with a counterweight and an attached scale. The components of the fermentation unit with other accessories are shown in the schematic diagram in Figure 4.

Digester/fermenter. The digester is a steel cylindrical tube of net capacity 74 litres when filled with water. Silicon sealant was used to effect the gas and water-tight seal. The digester was provided with an inlet for the inflow of substrate, an outlet for the outflow of the digested slurry and a pipe through which the generated biogas escaped to the gasholder via the pressure compensation bottle. The inlet and outlet are at 45^{o} to the horizontal. The quantity of the digested slurry generally corresponded to daily amount of intake to the digester. The

digesters were half-technical plants, which are close in performance to those found in the field. The digesters were arranged in the laboratory above the ground.

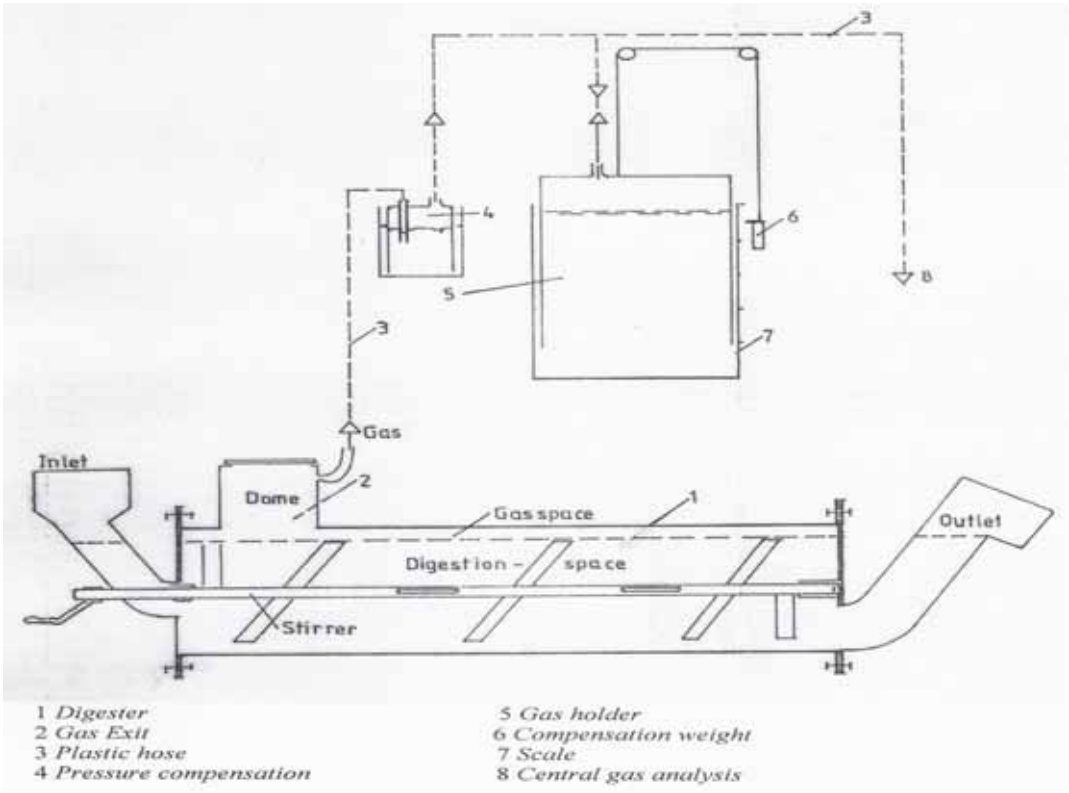

Figure 4: Schematic diagram of the fermentation unit

Stirrer and stirring. The stirrer was made of a steel rod with blades attached, which runs the horizontal length of the digester. The stirrer was operated manually. Stirring of substrates was undertaken just before and after feeding the digester. This was done to ensure uniform and consistency in the slurry from the digester as well as an even distribution of bacteria within the substrate. About ten revolutions stirring was undertaken at any of these times.

Pressure compensation bottle. This was a conical flask partially filled with water and hermetically sealed with a rubber lid. The lid had two perforations through which two plastic pipes were passed. One pipe was passed down through the perforation to about half-way inside the depth of water in the flask. This pipe delivered the biogas produced from the digester through the water. The other pipe was passed down through the perforation to about 0.5 cm into the space within the flask and it served as an exit pipe of the biogas after it had bubbled through the water. This exit pipe was connected to the gasholder. The pressure compensation bottle stabilised the pressure within the digester and also created the pressure to enable the biogas to fill the gasholder.

Gasholder. The gasholder comprised two metal cylinders (the diameter of one cylinder is 2 cm greater than the other) with one side each open. The larger cylinder was filled with water up to about 3 cm to the top, whilst the smaller cylinder with a perforation in the lid and a pipe fitted in the hole was inverted over the water in the larger cylinder until it was well-seated over the water. The pipe fitted into the lid of the inverted cylinder served as the entry point of biogas to the gasholder. The biogas was collected and stored over water with the water serving as a sealant. As the biogas was drawn into the gasholder the inverted cylinder moved upwards, creating space for the gas. Thus the upward movement made by the inverted cylinder corresponded to the volume of biogas collected in the gasholder at atmospheric pressure. The gasholder served as storage for the biogas produced.

Counterweight. The counterweight consisted of a solid steel of about 5 kg weight connected to the centre of the top of the inverted cylinder of the gasholder by a steel wire passing over two steel pulleys. The top cylinder of the gasholder was guided in its upward movement by the counterweight.

Scale. A scale was drawn on paperboard, screwed to wood and attached to the side of the gasholder for the calibration of the gasholder. The scale was attached to the gasholder by gluing. As the gasholder was filled, a pointer fixed on top of the counterweight moved downward the scale to determine the volume of biogas in the gasholder.

Laboratory equipment

The following laboratory equipments were used for the experimental investigation.

Weighing machines:

1. Soehnle electronic weighing scale

   Capacity: 50 kg x 20 g

2. Mettler PM 480 Delta Range top loading electronic balance

   Capacity: 410 g x 0.01 g

Oven:

Wagtech ventilated oven: 0 – 300 ^{o}C

Furnace:

Gallenkamp muffle-furnace: 0 – 1100 ^{o}C

pH-meter:

WTW pH 323A digital meter with pH electrode Sentix 41

Thermo-hygrograph:

Casella standard thermo-hygrograph to monitor ambient temperature of laboratory

Thermometer:

Digital thermometer Checktemp 01 with a probe

Gas analyser:

Sewerin SR2-DO equipped with a 2 m probe hose. Sewerin SR2–DO is a combined measuring instrument for a number of different gases. It consists of the basic instrument, incorporating a pump and a data memory for documentation purposes, and sensors for methane/carbon dioxide (CH_4/CO_2) and hydrogen sulphide (H_2S).

Methane/carbon dioxide CH_4/CO_2 sensor

Measurement range: 0 – 100 vol.% in steps of 0.1 vol.% to 9.9 vol.% (CH_4)

or in steps of 1 vol.% (CO_2).

Hydrogen sulphide H_2S sensor

Measurement range: 4 –2000 ppm, up to 998 ppm in steps of 2 ppm

from 1000 ppm in steps of 10 ppm.

Deep freezer:

Samples of both fresh and digested substrates that were to be analysed at later dates were kept in a deep-freezer to prevent decomposition. Operating temperature was –16 ^{o}C.

Substrates

Shea waste

Shea cake is the by-product in the production of shea butter, and it is the main feedstock in this investigation. In the course of the laboratory investigation, the cake was periodically collected from Shebu Industries at Savelugu, a distance of 22 km northward from Tamale. The cake was stored in polypropylene sacks at ambient conditions in the laboratory. In order to acquire fluid properties and to enable it to be applied as feedstock in a digester, the cake was always soaked for about 30 minutes in a measured quantity of water to obtain an appropriate substrate concentration for digestion. For soaking, 7 litres of water per kg of shea waste were used.

Cow dung

Cow dung is the basic substrate in anaerobic digestion. Cow dung was the main source of inoculum for the biogas process and it was also used as control for the investigation. Fresh cow dung was collected on daily basis from a kraal in a neighbourhood village Kpachi, which is about 2 km from the Nyankpala campus of the University for Development Studies.

Methods

All substrate feeding and gas parameter readings in the course of the experiments were taken daily at 10.00 a.m. Input substrates were always prepared minutes before reading were taken so that the digesters could be fed immediately after the readings.

Characterization of raw material and effluent

The basic raw materials for the investigation were shea waste and cow-dung. The total solid content (TS), organic dry matter (odm) content, ash content and the moisture content of these basic materials were determined as by the method described later in this chapter. However, carbon, nitrogen, raw fibre and raw fat of the input substrate as well as the nitrogen-phosphorus-potassium (NPK) value of the effluents were determined from samples sent to the Soil Research Institute in Kumasi.

Preparation of input substrates

The initial feeding of the digester was done with the basic substrate cowdung mixed with water in a ratio of 1:1 by weight, to produce an inoculum for the experiment. Thirty-eight kilograms of cow dung was blended in 38 kg of water in order to obtain adequate amount of substrate to fill one digester. Each digester was filled with cow dung and the substrate was allowed to stand for two weeks for the production of the inoculum. This process was repeated, wherever appropriate before the commencement of any experimental phase. Aside the preparation of the inoculum, the experimental investigations were undertaken in five phases.

Phase I comprised the preliminary trial with cow dung to determine the most productive and viable treatment to be used as control for the investigation. This involved substrates with three different organic dry matter (odm) concentrations 7 %, 5 % and 3 %. The initial primary substrate prepared in the ratio 1:1 by weight (cow dung to water ratio) has odm of about 8 %, and the appropriate amounts of water were added to bring them to the required

concentration. However, it is worthy of note that whilst cowdung to water ratio of 1:1 by weight yielded a substrate of odm concentration of 8 % in the dry season, the same ratio mixture produced about 7% odm in the wet season when the cattle grazed on fresh matter and took in adequate water.

Phase II was the investigation on the viability of mono-fermentation of shea waste. Shea cake was soaked in water for at least 30 minutes to soften it. The initial shea to water ratio was 1:7 by weight, giving an odm concentration of shea of approximately 11 %. Further sample dilution was undertaken to achieve the expected input substrate concentrations of odm 7 %, 5 % and 3 %. Process stability of mono-fermentation of shea waste with ash at 30 days HRT was also tested, with the shea waste substrate at 7 % odm. For this trial 10 g of ash were added to the daily amount of input substrate (2.6 kg) for one treatment.

Phase III involved the co-fermentation trials of the two substrates, shea and cowdung. Organic dry matter concentration at 7 % for cow-dung and shea waste was prepared separately. A mixture of shea and cowdung was made in a shea to cow dung ratio by volume of 50:50, 75:25 and 90:10. These treatments were to test the viability of co-fermentation of shea with cow dung.

Phase IV was to test the viability of co-fermentation of the substrates at HRT 20 days and the effect of ash as a pH buffer in the substrates. Shea and cow dung mixture in the ratio of 50:50 by volume was used at a 7 % odm. However, 10 g of ash were added to the daily amount of input substrates (3.9 kg) for one treatment. Substrate preparation was undertaken as in phase III.

Phase V was the confirmation test of the co-fermentation trials at 7 % odm concentration for the 50:50 shea to cow dung ratio by volume and the fermentation

of cow dung, which was used as control. Shea and cow dung mixture substrate preparation was as undertaken in phase III.

Experimental trial runs

The trial experiments commenced in a laboratory at Nyankpala from January 19, 2006. The experiments were undertaken at ambient conditions with no temperature control of the substrates. With the limited number of digesters available, six in total, preliminary trials in phases I and II were conducted on one digester for one experimental treatment to determine the trend of the results, whilst treatments in phase III were duplicated.

Trial treatments

Phase I. Fermentation of cow dung

The trials were conducted using three odm concentration values, 7 %, 5 % and 3 % in combination with three hydraulic retention times (HRT) 60, 45 and 30 days. The basic feedstock for the trial was cow dung. The objective of this phase was to determine the optimal production treatment to be used as control in the investigation. All treatments proceeded at ambient conditions. The trials were conducted from January 19, 2006 to April 19, 2006.

Phase II. Mono-fermentation of shea waste

Phase II was to determine the viability of the mono-fermentation process as an option in the anaerobic digestion of shea waste. This phase consisted of nine treatments: three odm concentrations 7 %, 5 % and 3 % combined with three

hydraulic retention times 30, 45 and 60 days. To observe the behaviour of the fermentation process during the transition from cow dung feeding to shea waste feeding, for the 60 days retention time at 7 %, 5 % and 3 % odm concentrations, when the feeding of the cattle slurry was terminated at the steady phase, the feeding with shea waste at the respective odm concentration continued from there. Organic dry matter concentrations of 7 %, 5 % and 3 % of cow dung were replaced respectively with 7 %, 5 % and 3 % odm of shea waste. All the three treatments were run at 60 days HRT. However, anaerobic fermentation of the shea waste at 45 days and 30 days was commenced after the initial 2-week incubation of cattle slurry in order to obtain the inoculant. The appropriate odm concentrations of 7 %, 5 % and 3 % were prepared daily and fed to the corresponding digesters in quantities based on the HRT. Additional treatment to test the process stability of mono-fermentation of shea waste with ash at 30 days HRT was also undertaken, with the shea waste substrate at 7 % odm. The trials under this phase were conducted from May 5, 2006 to July 4, 2006.

Phase III. Co-fermentation of shea waste with cow dung

The co-fermentation or co-digestion of organic wastes involves the mixing of the various substrates in varying proportions. To determine the optimum shea to cow-dung ratio for the anaerobic digestion and to ensure process stability, three co-fermentation treatments were chosen. The three treatments selected under this phase were the shea-waste to cow dung ratio (by volume) of 50:50, 75:25 and 90:10 in percentage terms. Organic dry matter concentration for the three treatments was 7 % conducted at a retention time of 30 days. Each treatment was

duplicated. This experimental phase was carried out from June 14, 2006 to July 16, 2006.

Phase IV. Co-fermentation of shea waste with cow dung at 20 d HRT

This phase comprised two parts: co-fermentation of 50:50 by volume of substrate of 7 % odm concentration at 20 days HRT with and without ash. The ash was used as a pH buffer. Two treatments were involved in this phase and each treatment was duplicated. The objective was to test the viability of the process at 20 days retention time and to determine the effect of ash on process performance. Table 5 shows the treatments carried out under the co-fermentation of shea with cow dung at 20 days HRT with an odm concentration of 7 %. Experimental period was from August 16, 2006 to September 15, 2006.

Table 5. Experimental treatments in co-fermentation at 20 d HRT

HRT (d)	pH buffer	Treatment SH:CD
20	-	50:50
20	10g ash/daily input	50:50

SH: shea waste, CD: cow dung

Main experimental run

Phase V. Co-fermentation of shea waste with cow dung and control

This phase comprised two treatments: co-fermentation of shea waste with cow dung (50:50 by volume) and pure cattle manure digestion as control. The two treatments were run parallel at odm concentration of 7 % at 30 days HRT. Each

treatment was replicated three times. Table 6 shows the treatments in this phase: the co-fermentation of shea with cow dung, and the anaerobic digestion of cow dung, which was run parallel to the co-fermentation process and was used as control for the investigation. Experimental period was from October 21, 2006 to December 16, 2006.

Table 6. Treatments on co-fermentation and control

HRT (d)	Concentration, odm (%)	Treatment SH:CD
30	7	50:50
30	7	0:100

SH: shea waste, CD: cow dung

Gas parameters determination

Biogas yield

The biogas yield was determined daily. The volume of the biogas produced was determined by the position of the pointer on the counterweight on the calibrated scale attached to the gasholder.

Biogas composition

The analysis of the biogas to determine its quality (composition), namely methane (CH_4), carbon dioxide (CO_2) and hydrogen sulphide (H_2S), was carried out daily. In order to reduce the amount of water vapour exposure on the equipment and to protect the equipment against excessive corrosion, a portion of the pipe (about 2 cm long) through which the biogas was directed to the equipment

for analysis was filled with anhydrous calcium chloride ($CaCl_2$) powder. The analysis to determine the biogas composition was carried out daily by connecting the probe from the gas analyser to the exit pipe of the gasholder.

Substrate parameters

pH value of substrates

The pH values for the input and outflow substrates were measured daily. During the measurements, the pH electrode was kept in the substrate until the reading was stabilized.

Temperature

The temperature of the fermenter content was measured daily. The thermometer consists of a 1 m cable with a probe. To measure the temperature of the fermenter content about 8 cm of the probe was inserted in the substrate until the reading was stabilized.

Total solids (TS) and organic dry matter (odm)

The total solids and the organic dry matter contents of the input and outflow substrates were determined. The total solids and organic dry matter contents of the input substrate were determined daily, whilst those of the outflow substrate were determined at weekly interval. To determine the total solids (dry weight), a sample of the substrate up to 35 g was placed in a Wagtech ventilated oven at a temperature of 106 ^{o}C for 24 hours. Top loading electronic balance Mettler PM 480 Delta Range was used in the weight measurements. To determine

the organic dry matter (volatile solids) of the substrate, the dry matter removed from the ventilated oven was afterwards placed in a Gallenkamp muffle-furnace at a temperature of 530 ^{o}C for 4 hours. The corresponding loss of weight after burning in the furnace was thus the odm content or the volatile solids (VS) of the sample. The percentage odm of the substrates was then computed/calculated from the formula below:

$$\text{odm (\%)} = \frac{W_{DM} - W_{ash}}{W_{LS}} * 100 \qquad [2]$$

where W_{DM} is the weight of dry matter, g;

W_{ash} is the weight of ash, g; and

W_{LS} is the weight of liquid substrate, g.

Input substrate

Digester feeding was carried out on daily basis therefore the weight of fresh substrate fed into the digester was measured daily using Soehnle weighing scale to determine the organic loading rate.

Degradation of odm

To determine the degree of degradation of the odm, samples of the effluent from digester were analysed for the odm content once weekly in the course of the experiment.

Laboratory temperature

The ambient temperature and the relative humidity of the laboratory were recorded continuously. Graph sheets for recording of room temperature and relative humidity were changed weekly.

Computed parameters

These are parameters, which are important and influence the reactor process, and they can only be obtained by using available results with the help of formulae. The average values of the following parameters were obtained with the use of Microsoft Excel® programme:

- **Hydraulic Retention Time (HRT)**

For a specific digester volume (V_D) in litres (l) and a known daily supply of feedstock (S_d), l/d; the hydraulic retention time (HRT) can be calculated thus:

$$HRT = \frac{V_D}{S_d} \qquad [3]$$

where HRT is in days, d.

If a specific retention time is required for a given digester volume, the daily supply of feedstock (S_d) is calculated thus:

$$S_d = \frac{V_D}{HRT} \qquad [4]$$

The HRT for the experiments were chosen arbitrarily, and based on the known digester volume the daily digester feeding S_d was calculated.

- **Volume of water required for dilution to expected concentration**

To arrive at an expected concentration (C_{exp}) of odm in feedstock, the amount of water needed for dilution (V_{dil}) of a known quantity (V_{ac}) and known (estimated) concentration (C_{ac}) is calculated:

$$V_{dil} = \frac{V_{ac} (C_{ac} - C_{exp})}{C_{exp}} \quad [5]$$

where: V_{dil} – volume of water to dilute substrate to expected concentration (l),

V_{ac} - actual volume of substrate to be diluted (l),

C_{ac} – actual concentration of substrate to be diluted (%),

C_{exp} – expected concentration of substrate after dilution (%)

- **Digester loading (L_D)**

The digester loading or the organic loading rate indicates how much odm per unit volume of digester capacity per day has to be supplied to the digester. Digester loading (L_D), in g odm/l*d, is calculated from the relationship between the daily feed supplied (S_D), the proportion of odm in the feed or substrate (%), daily amount of odm in substrate (C_{odm}), and the digester volume (V_D).

$$L_D = \frac{C_{odm}}{V_D} \quad [6]$$

$$C_{odm} = odm\ (\%) \times S_D \qquad [7]$$

where L_D is the digester loading, in g odm/l*d

S_D is the daily digester feeding (g/d),

C_{odm} is daily digester feeding in terms of odm (g odm/d), and

V_D is digester volume in litres (l).

- **Total Biogas and Methane yield**

These were values read daily from the scale as the quantity of biogas produced. Specific gas production per day (G) represents the gas production of a specific feed material in a specific retention time at specific digester temperature.

- **Daily Methane yield (M)**

The methane yield, M in litres was obtained from the quantity of biogas measured, G in litres, and the methane proportion (CH_4 %) in the biogas produced:

$$M = \frac{G * CH_4\,(\%)}{100} \qquad [8]$$

- **Substrate specific biogas yield (G_{odm})**

$$G_{odm} = \frac{G}{q_{odm}} \qquad [9]$$

where G_{odm} is in l/g odm, and

q_{odm} is the quantity odm in the input substrate (g odm).

- **Substrate specific methane yield (M_{odm})**

$$M_{odm} = \frac{M}{q_{odm}} \quad [10]$$

where M_{odm} is the substrate specific methane yield in l/g odm

- **Reactor specific biogas yield (G_R)**

$$G_R = \frac{G}{V_D} \quad [11]$$

where G_R is in l/l*d,

G is the daily biogas yield in l/d, and

V_D is the digester volume in litres.

- **Reactor specific methane yield (M_R)**

$$M_R = \frac{M}{V_D} \quad [12]$$

where M_R is in l/l*d,

M is the daily methane yield in l/d.

- **Degradation (Degree of Digestion) (R)**

The degradation during the retention period was estimated from the difference between odm concentrations in the fresh substrate (C_{fr}) and the slurry (C_{sl}), and is expressed in percentage:

$$R\ (\%) = \frac{C_{fr} - C_{sl}}{C_{fr}} * 100 \qquad [13]$$

Data Processing

Data obtained from measurements of substrate and gas parameters were processed on the computer programme Microsoft Excel®. Physical quantities obtained from processed data included organic dry matter concentration of substrates, organic loading rates, daily methane yield, substrate- and reactor-specific biogas/methane yields. Mean values, standard deviation and graphical representations showing the relationships between the relevant factors or parameters of the experiments were also obtained from the Microsoft Excel programme. Coefficient of variation and degree of degradation value were calculated from standard formulas. Statistical differences between treatments were determined using GenStat® programme. Results of the analysis were presented in tables and graphs.

CHAPTER 4

RESULTS

Graphs and tables have been presented to explain the results of the experiments. Ratios presented as substrate treatments were found not to be compliant in Microsoft Excel® programme. Legends for graphical representations for substrate treatments in ratios were suffixed with the sign % in order to stay compliant in the programme. For example, substrate of mixture of shea to cow dung ratio 50:50 is presented in graphical representation as 50%:50%.

Characterization of raw material

Table 7 shows the characteristic of the basic raw materials, shea waste and cow dung determined during the investigation. The characteristics of the cow dung change depending on the season. Between May and November, cattle in the Northern region graze on green materials and they have access to a lot of water, therefore the dung has higher moisture content than in the dry season, when the feed for the cattle is mostly dried materials and drinking water for animals is scarce.

Table 7. Characterization of shea waste and cow dung

Parameter	Shea waste		Cow dung	
	In fresh raw material (%)	In dried material (%)	In fresh raw material (%)	In dried material (%)
Dryweight, TS	90.8	100	17.7	100
Organic dry matter	85.9	94.6	14.1	79.6
Ash content	4.9	5.4	3.6	20.4
Moisture content	9.2	0.0	82.3	0.0
Nitrogen	1.34		1.54	
Carbon	47.83		40.86	
Raw fibre	6.9			
Raw fat	12.5			
C:N	36:1		27:1	

Table 8. pH-values of input substrates and mixtures

	Shea waste 100%			SH:CD mix			Cow dung 100%
	3%	5%	7%	50:50	75:25	90:10	7%
pH-value	5.69	5.58	5.50	6.68	6.37	6.07	7.03
pH-value with 10 g ash per 3.9 kg substrate	-	-	-	7.17	-	-	-
pH-value with 10 g ash per 2.6 kg substrate	-	-	6.98	-	-	-	-

SH: shea waste, CD: cow dung

Table 8 shows the pH-values of the input substrates and mixtures used during the investigation. Shea waste to cow-dung ratio in the mix is at 7 % odm.

Table 9 shows the fertilizer values of the influent substrate and effluent slurry from the main experimental investigation. Effluents taken for analysis are those digested at 30 days HRT.

Table 9. N:P:K levels in raw substrate and effluent slurry

Material	Nitrogen (%)	Phosphorus (%)	Potassium (%)
Fresh cow dung	1.54	0.34	0.66
Fresh substrate50 % SH+50 % CD	1.93	0.28	0.46
Effluent cow dung	1.75	0.34	0.39
Effluent 50 % SH+50 % CD	2.19	0.29	0.71

SH: shea waste, CD: cow dung

Cow dung Fermentation

Methane content in cow dung fermentation

The quality of biogas is determined by the composition of methane and carbon dioxide (CO_2) in the mix. The methane content of the biogas produced within the fermentation period of the cow dung at the operating (ambient) temperatures and retention times ranged from 55.82 % to 61.88 % by volume as shown in Appendix A-1. Figure 5 shows the average values of methane content in the biogas from the digestion of cow dung at different odm concentrations.

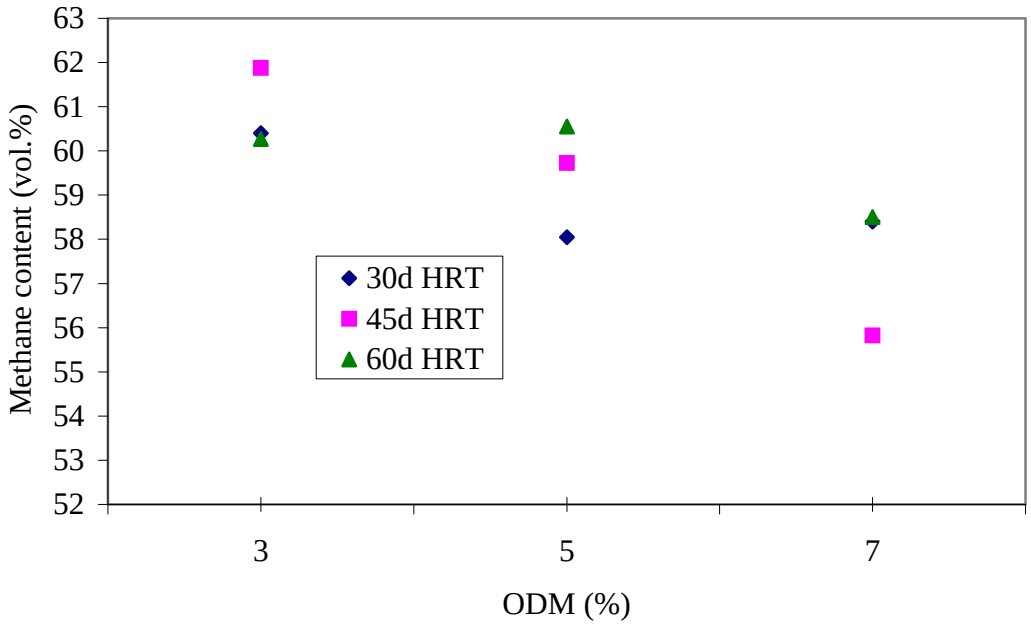

Figure 5: Methane yield in biogas from cow dung

Carbon dioxide content in cow dung fermentation

The carbon dioxide composition in the biogas measured daily may predict the stability of the production process.

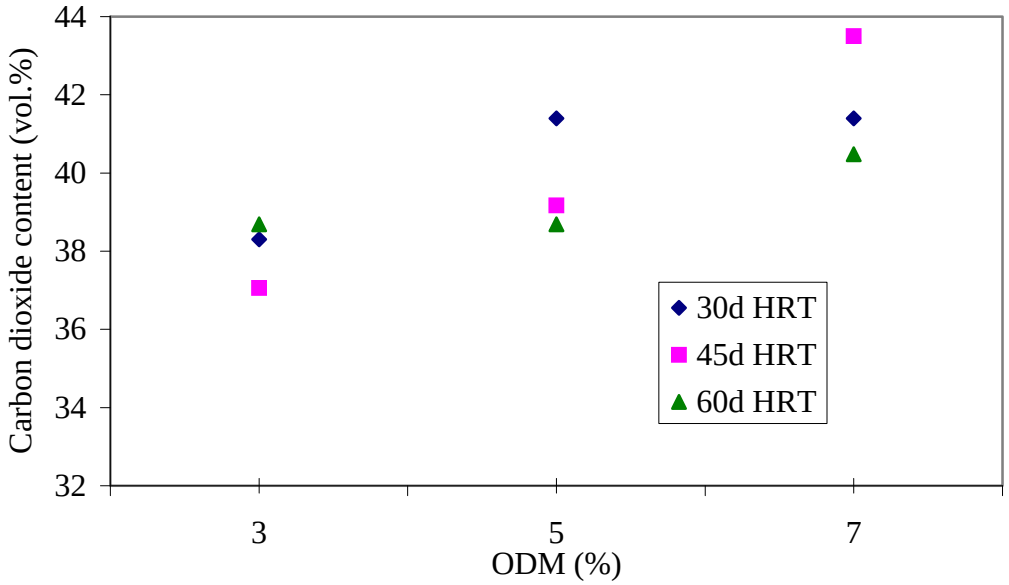

Figure 6: Carbon dioxide yield in biogas from cow dung

Figure 6 shows the average values of CO_2 yields in biogas from the digestion of cow dung. The CO_2 content, throughout the duration of the experiment of the anaerobic digestion of cow dung at the operating (ambient) temperatures and retention times, ranged from 37.06 % to 43.50 % by volume.

Reactor specific gas yield in cow dung fermentation

This is the volume of biogas produced by a unit volume of the digester in a day. It is the average volume gas produced divided by the usable digestion volume of the digester. Figures 7 and 8 show the reactor specific biogas yield and reactor specific methane yield respectively. Their values depended on the odm concentration of the substrate, the HRTs and the operating (ambient) temperatures.

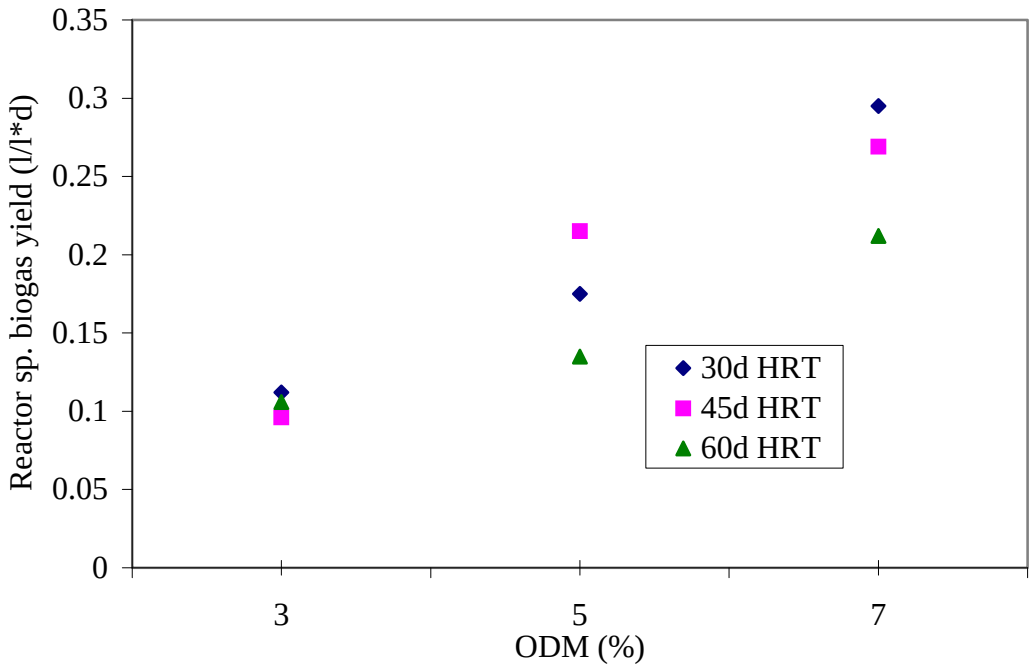

Figure 7: Reactor specific biogas yield from cow dung fermentation

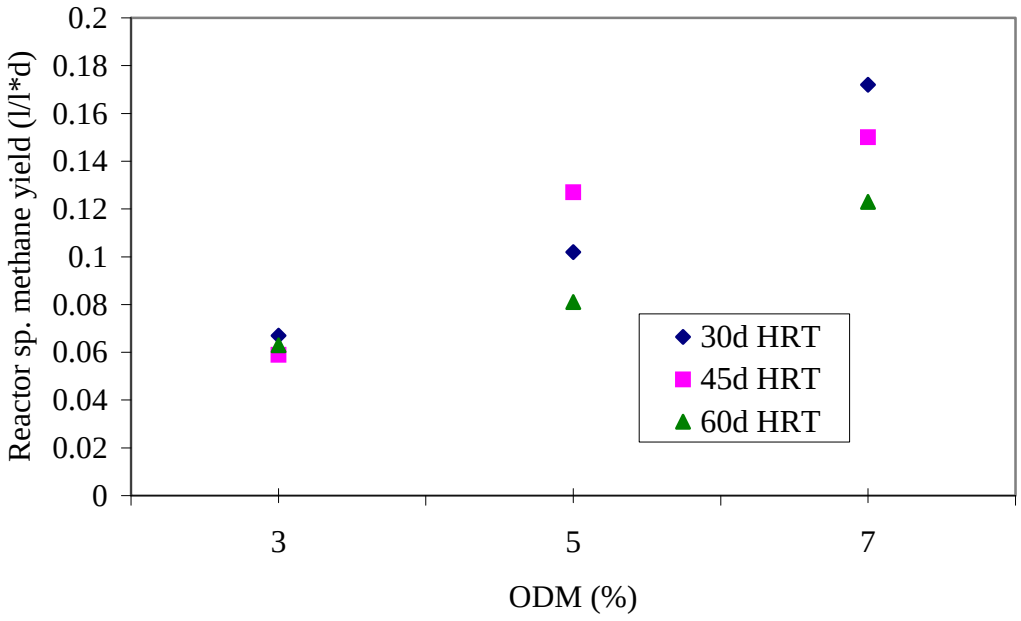

Figure 8: Reactor specific methane yield from cow dung fermentation

Reactor specific biogas yield values varied from 0.096 to 0.295 l/l*d, whilst the reactor specific methane yield values varied from 0.059 to 0.172 l/l*d. Methane production for energy generation is one of the objectives of this investigation. Comparing results from the trial run of cow dung, the variable, 7 % odm concentration at HRT of 30 days for the fermentation period showed average methane content of 58.40 % and the reactor specific biogas yield value of 0.295 l/l*d. This treatment is chosen as the optimum for the cow dung fermentation and is used subsequently as the control for the investigation.

Substrate specific gas yield in cow dung fermentation

Figures 9 and 10 show the substrate specific biogas and methane yields from the fermentation of cow dung, which depended on the odm concentration of

the substrate and the substrate retention time. Substrate specific gas yields also depended on the operating (ambient) temperatures.

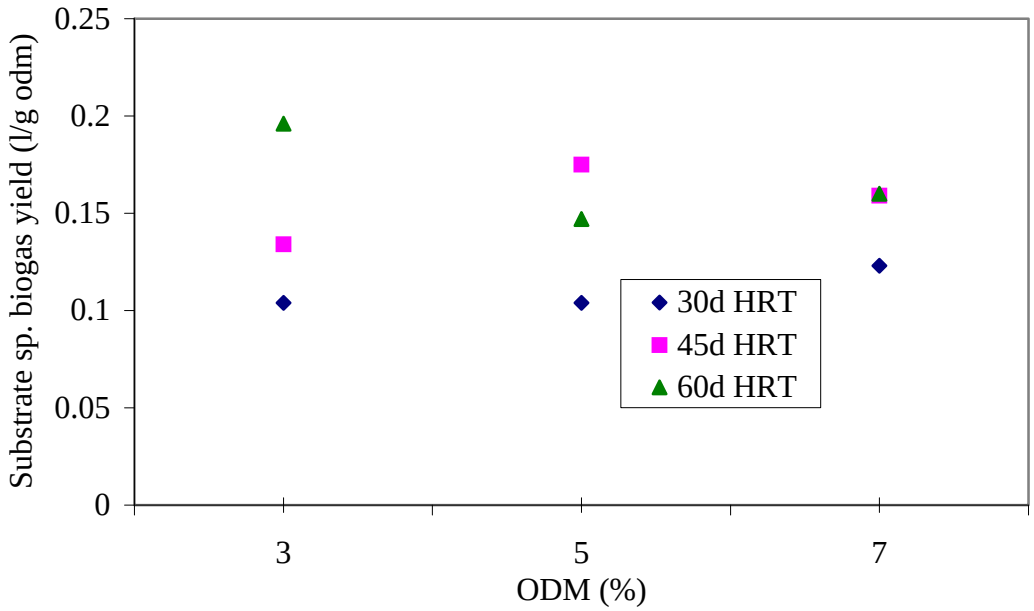

Figure 9: Substrate specific biogas yield from cow dung

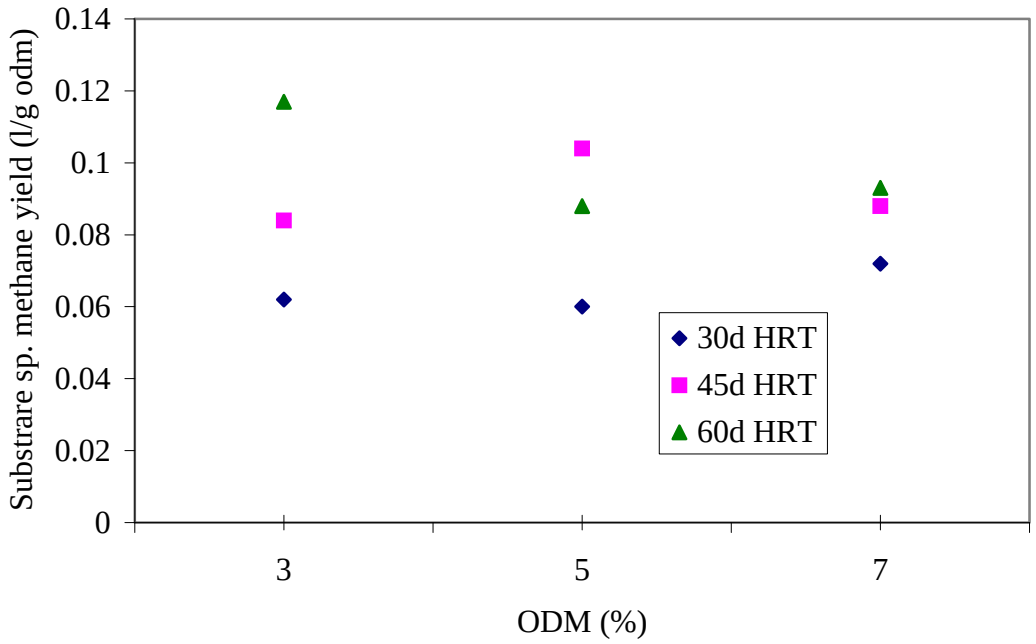

Figure 10: Substrate specific methane yield from cow dung

Substrate specific biogas yields at the operating temperatures ranged from 0.104 l/g odm to 0.196 l/g odm, whilst the substrate specific methane yields ranged from 0.060 to 0.117 l/g odm.

pH-values in cow dung fermentation

Figure 11 is the graphical representation of the digester content pH-values in the fermentation of cow dung at various odm concentrations. pH at 3 % odm concentrations are highest, whilst that at 7 % odm concentrations are the lowest. Appendix A-2 shows the mean pH-values of the digester content at corresponding odm concentrations.

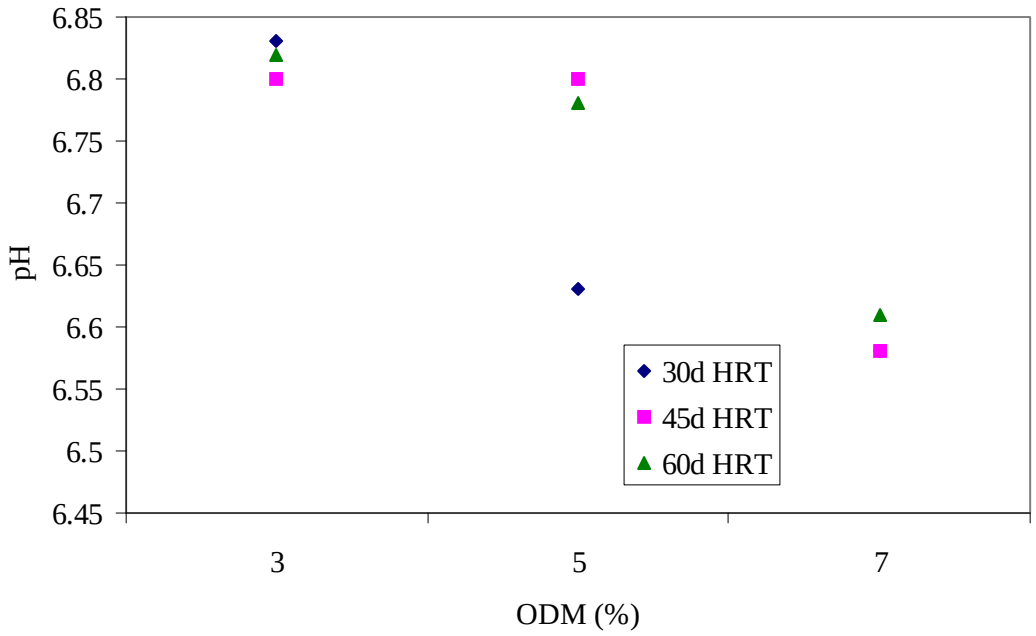

Figure 11: Digester content pH-values in cow dung fermentation

Biodegradation in cow dung fermentation

The odm content of the effluent slurry and for that matter the biodegradation (degree of digestion) depends on the operating temperature and the retention time. Figure 12 is the graphical representation of the odm content of the effluent compared to the reactor input odm concentration. Values for effluent odm content are only those from reactors with 7 % odm concentration input substrate.

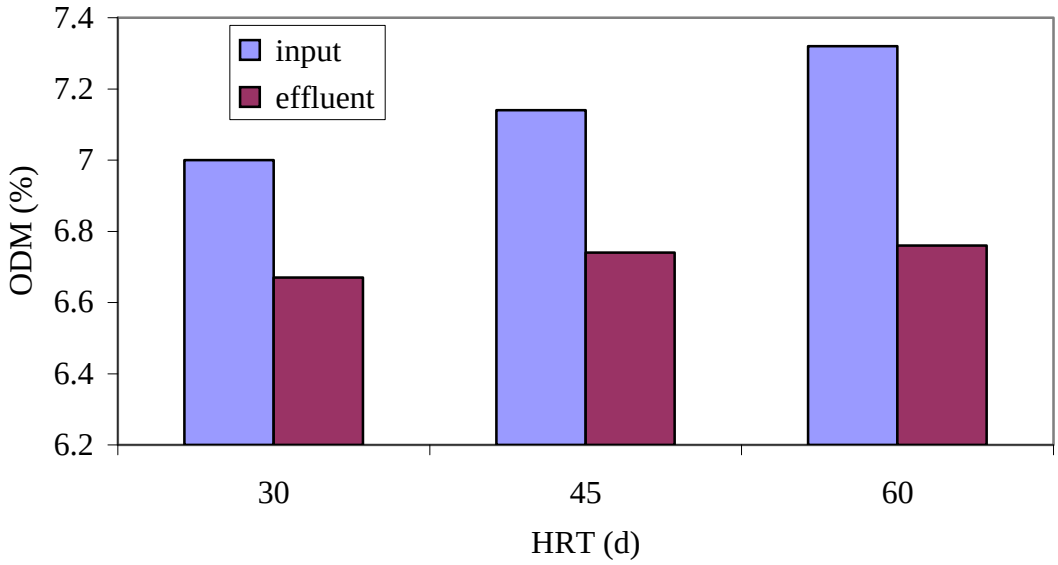

Figure 12: Average odm content of effluent in cow dung fermentation from 7 % odm of input substrate

The degree of degradation in AD depends on the kind and composition of the input substrate as well as on the reaction condition in the digester. Figure 13 illustrates the degradation of the substrate against retention times. The highest odm degradation was obtained from 7 % odm running on 60 days HRT, whilst the lowest degradation was attained from 7 % odm operating on 30 days HRT.

Appendix A-3 shows the degradation values from the 7 % odm concentration input substrate.

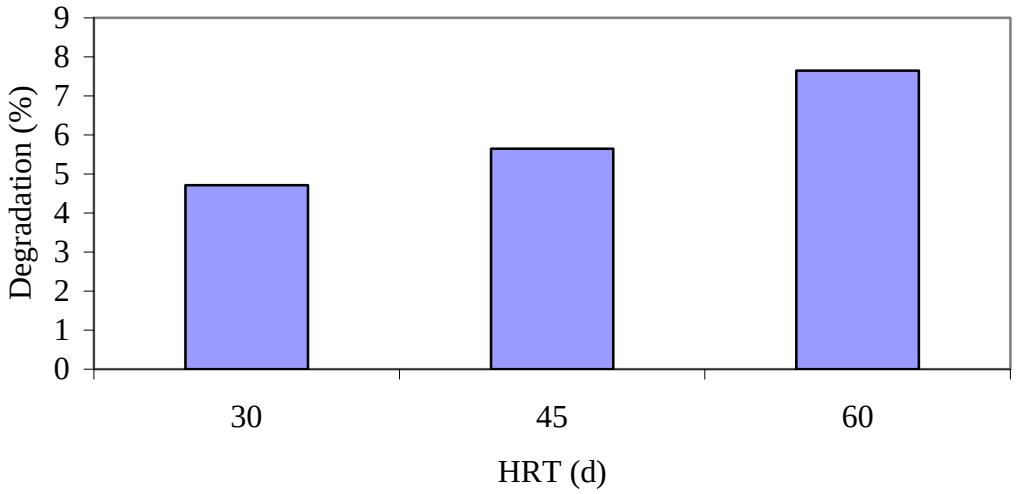

Figure 13: Mean degradation of degradation of odm from cow dung fermentation

Mono-fermentation of shea waste

Gas parameters in mono-fermentation of shea waste

Figure 14 shows daily methane production at 60 days HRT from the steady state in cow dung fermentation to the start-up phase in pure shea waste feeding. Seven days after resumption of feeding with pure shea substrate, methane production at 7 % odm had increased three-fold, whilst production at 5 % odm and 3 % odm had both doubled, in comparison with methane production from the pure cow dung at the steady state.

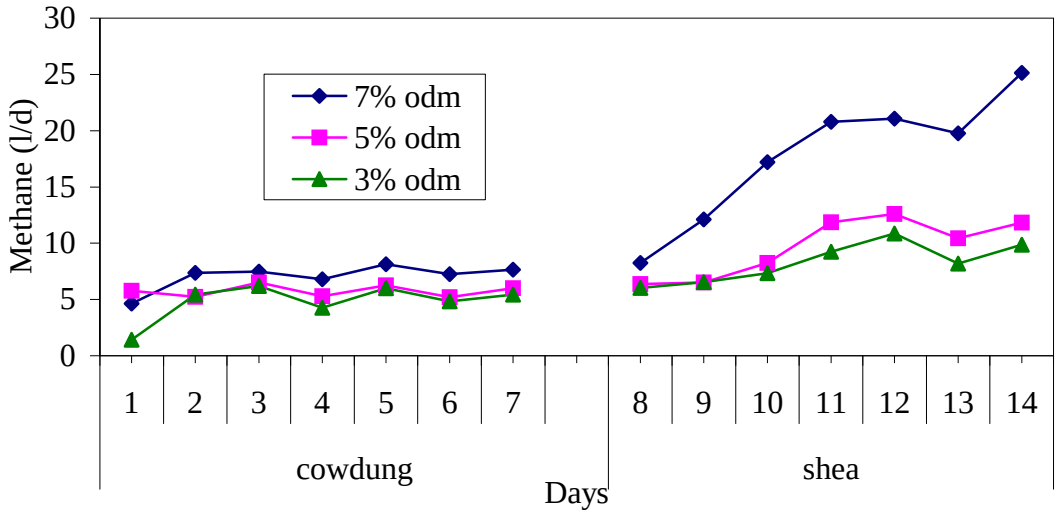

Figure 14: Methane production at transition at 60 days HRT (7 days before and after addition of pure shea substrate)

Methane content in mono-fermentation of shea waste

Methane content from mono-fermentation of shea waste at 7 %, 5 % and 3 % odm concentrations for 60 days HRT is shown in Figure 15a. For shea waste fermentation at 3 % odm at 60 days HRT, the methane content dropped initially from 57 % by volume of the biogas to 56 %, then it increased gradually to 67 %, and dropped again to 63 % at the time of termination of the feeding after 56 days

in operation. The experiment was terminated because biogas production per day had reduced to 4.6 litres/day as shown in Figure 17a.

For the digestion of shea waste at 5 % odm at 60 days HRT, the methane content dropped initially from 58 % by volume biogas to 56 %, and then rose to 65 % and dropped again to 60 % until the experiment was terminated on the 49th day. Biogas production was almost zero at the time of the termination as shown in Figure 17a. At 7 % odm of shea waste and at 60 days HRT, the methane content at first dropped from 59 % by volume of the biogas to 54 %, and then increased to 67 % and dropped again to 58 % when the experiment was terminated due to almost zero biogas production as shown in Figure 17a. The experiment had run for 50 days before feeding was terminated.

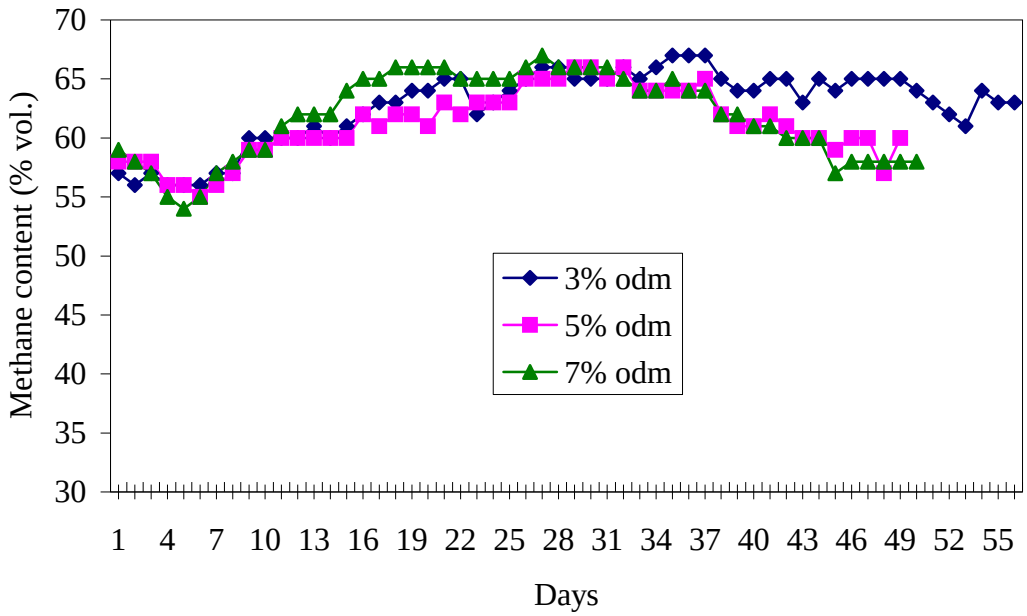

Figure 15a: Methane content in mono-fermentation of shea waste at 60 days HRT

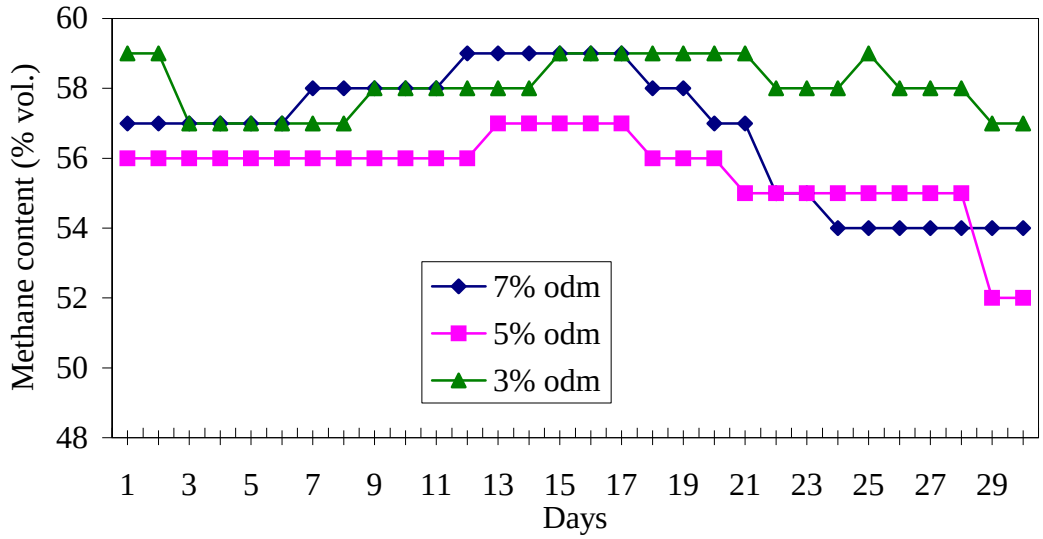

Figure 15b: Methane content in mono-fermentation of shea waste at 45 days HRT

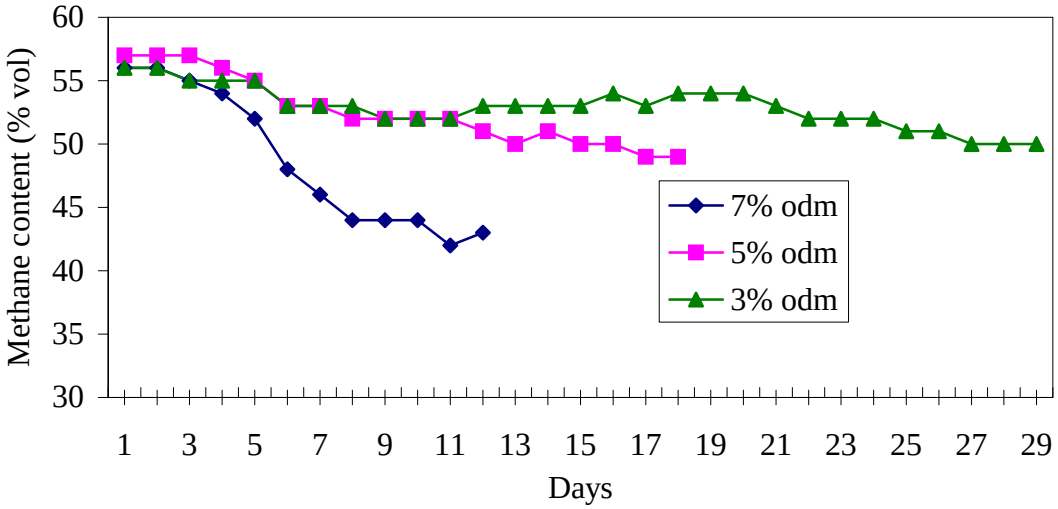

Figure 15c: Methane content in mono-fermentation of shea waste at 30 days HRT

Methane content at 45 days HRT for odm concentrations of 3 %, 5 % and 7 % is shown in Figure 15b. Methane content in biogas from 3 % odm fluctuated in

the range 57-59 %. From 5 % odm the methane content was in the range 52-57 %, whilst the methane content from 7 % odm was in the range 54-59 %. The methane content fluctuations at 45 days HRT followed similar trend as at 60 days HRT from the starting phase till day 30 when the experiments were terminated (Figure 15b).

At 30 days HRT the methane content showed a gradual decrease from the beginning of the experiments until their termination as shown in Figure 15c. The methane content at 7 % odm decreased at a faster rate than at 5 % and 3 % odms, whilst at 3 % odm the level of decline was slower. The rate of decreasing methane content for 5 % odm was between 7 % and 3 % odm. At 3 % odm, the methane content ranged between 50 and 56 % with the experiment terminating on day 29. The methane content at 5 % odm ranged between 49 and 57 % with the experiment terminating on day 18, whilst at 7 % odm the methane content ranged between 42 and 56 % with the experiment termination made on day 12 (Figure 15c).

Mean values for methane content in biogas from the mono-fermentation of shea waste for the various fermentation periods are shown in Appendix A-4. The highest methane content of 62.8 % was attained at 60 days HRT and at 3 % odm, whilst the lowest value of 48.7 % was attained at 30 days HRT and at 7 % odm (Appendix A-4).

Carbon dioxide content in mono-fermentation of shea waste

The carbon dioxide content in biogas from the mono-fermentation of shea waste fluctuated widely during the fermentation period depending on the odm and

HRT (Figures 16a, b and c). The fermentation process was never stabilised. For 60 days HRT, the carbon dioxide content in the biogas ranged between 33 % and 45 % by volume as in Figure 16a; for 45 days HRT, the carbon dioxide content ranged between 41 % and 48 % by volume as in Figure 16b, whilst for 30 days HRT the carbon dioxide content ranged between 43 % and 58 % by volume as shown in Figure 16c.

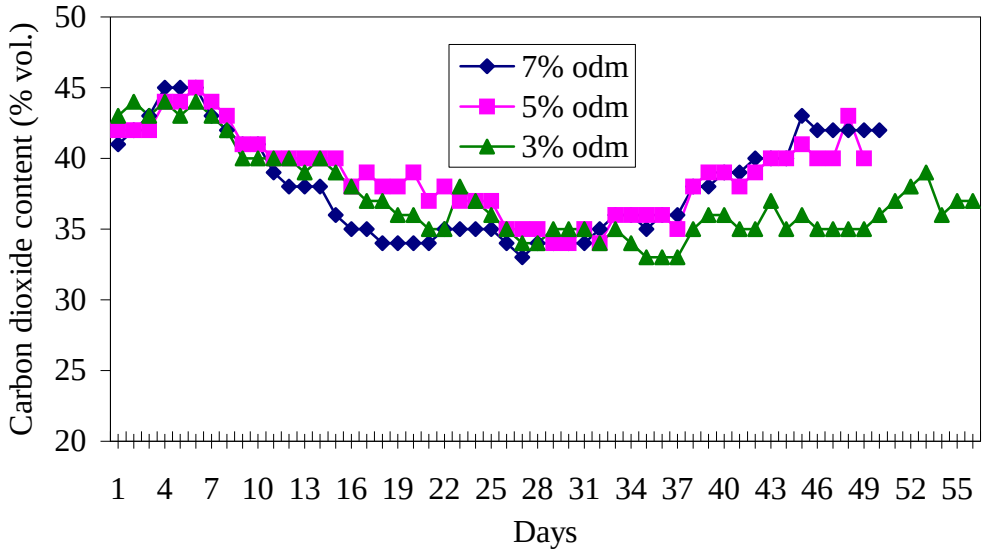

Figure 16a: Carbon dioxide content in biogas from mono-fermentation of shea waste at 60 days HRT

At 60 days HRT and at 7 % odm, CO_2 content fluctuated between 33 % and 45 % before the experiment was terminated on day 50. At 5 % odm the CO_2 content fluctuated between 34 % and 45 % until the termination of the experiment on day 49, whilst at 3 % odm the CO_2 content was between 33 % and 43 % with the experiment being terminated on day 56. The lowest carbon dioxide content in the biogas was 33 % from the 3 % odm, whilst the highest of 45 % was obtained from 7 % odm and 5 % odm (Figure 16a).

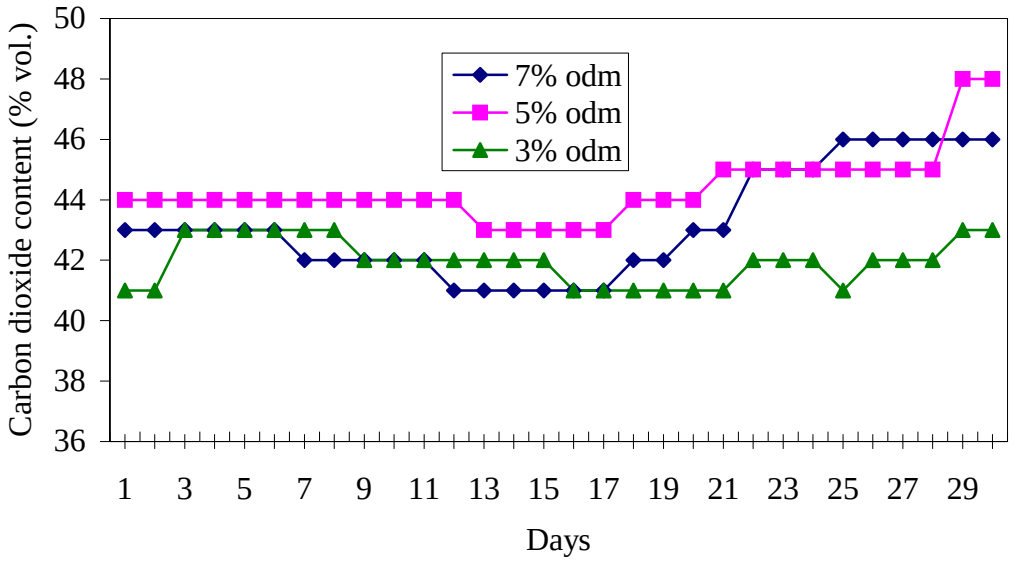

Figure 16b: Carbon dioxide content in biogas from mono-fermentation of shea waste at 45 days HRT

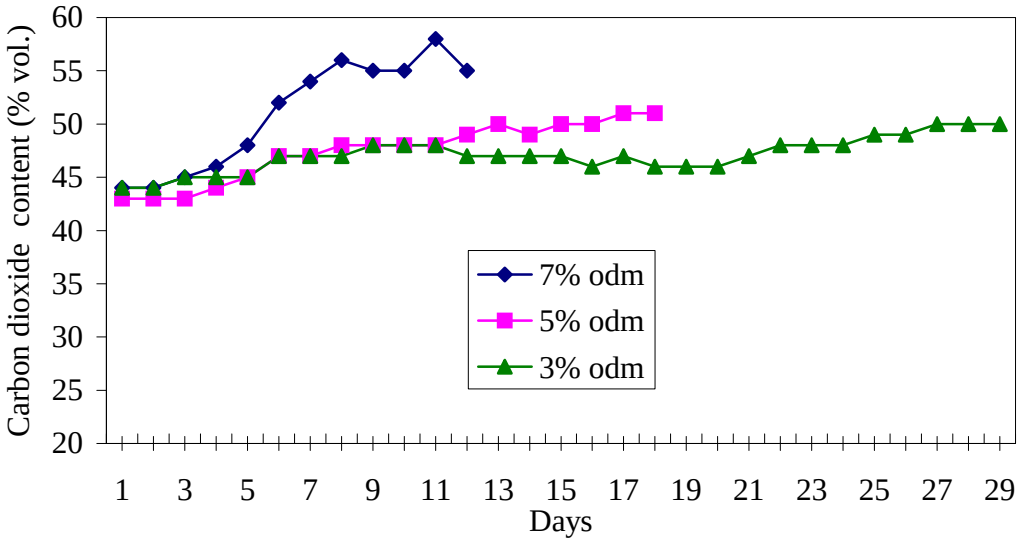

Figure 16c: Carbon dioxide content in biogas from mono-fermentation of shea waste at 30 days HRT

At 45 days HRT and at 7 % odm, CO_2 content fluctuated between 41 % and 46 %. At 5 % odm the CO_2 content fluctuated between 43 % and 48 %, whilst at 3 % odm the CO_2 content was between 41 % and 43 %. All the experiments

were terminated on day 30. The lowest carbon dioxide content in the biogas was 41 % from the 3 % odm and 7 % odm, whilst the highest of 48 % was obtained from 5 % odm (Figure 16b).

At 30 days HRT and at 7 % odm, CO_2 content fluctuated between 44 % and 58 % before the experiment was terminated on day 12. At 5 % odm the CO_2 content fluctuated between 43 % and 51 % until the termination of the experiment on day 18, whilst at 3 % odm the CO_2 content was between 44 % and 50 % with the experiment being terminated on day 29. The lowest carbon dioxide content in the biogas observed was 43 % from the 5 % odm, whilst the highest of 58 % was obtained from 7 % odm (Figure 16c).

Specific biogas yield in mono-fermentation of shea waste

Anaerobic digestion of shea waste under mono-fermentation was highly unstable. Consequently, the experiments for all the treatments had to be terminated before the expected end of the experimental period. No steady phase was attained in any of the treatments during the period of the experiment (Figures 17a, b and c). Biogas production after reaching the peak started to decrease on daily basis, despite the daily digester feeding, to such low levels that the experiments had to be terminated as shown in Figures 17a, b and c. In all treatments gas production decrease was slower at 3 % odm, whilst the decrease in gas production was fastest at 7 % odm. The rate of decrease at 5 % odm was between that at 7 % and 3 % odm.

The highest reactor specific biogas yield over the fermentation period of 50 days attained was 0.43 l/l*d at 7 % odm and at 60 days HRT, whilst the lowest was 0.20 l/l*d at 3 % odm and at 60 days HRT.

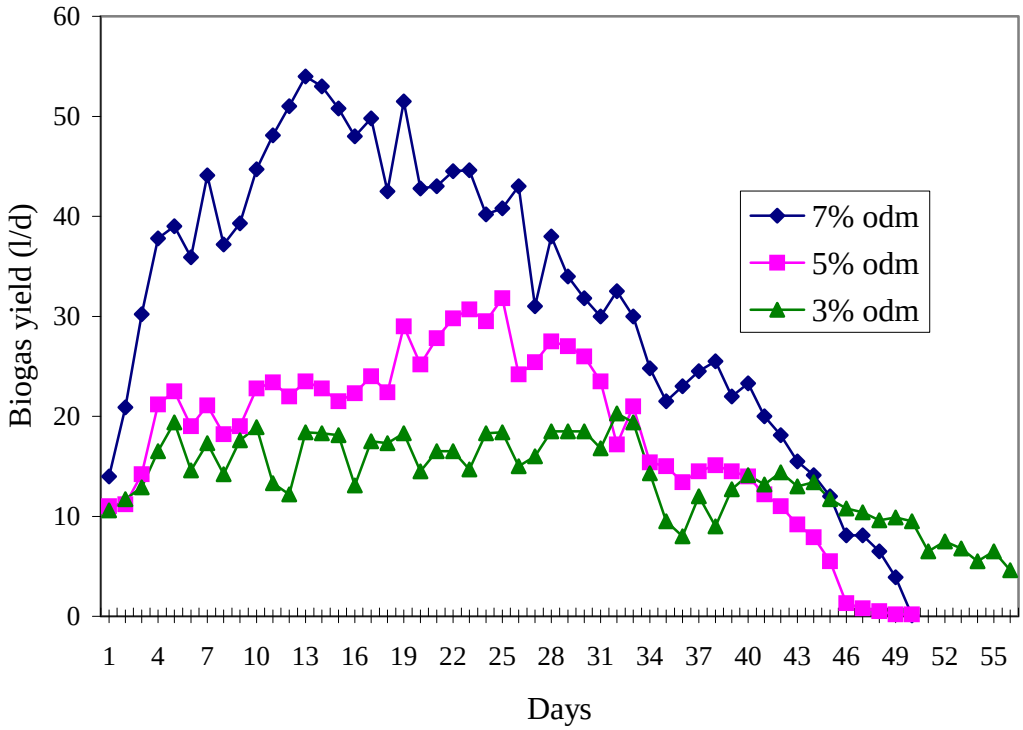

Figure 17a: Biogas yield in mono-fermentation of shea waste at 60 days HRT

Mean values for substrate specific biogas/methane yield over the different fermentation periods are shown in Appendix A-5. At 60 days HRT the mean highest substrate specific biogas yield attained over the fermentation period of 50 days was 0.40 l/g odm at 3 % odm, whilst the mean lowest was 0.29 l/g odm at 5 % odm. At 45 days HRT the mean highest substrate specific biogas yield attained over the fermentation period of 30 days was 0.35 l/g odm at 3 % odm, whilst the mean lowest was 0.23 l/g odm at 7 % odm (Appendix A-5).

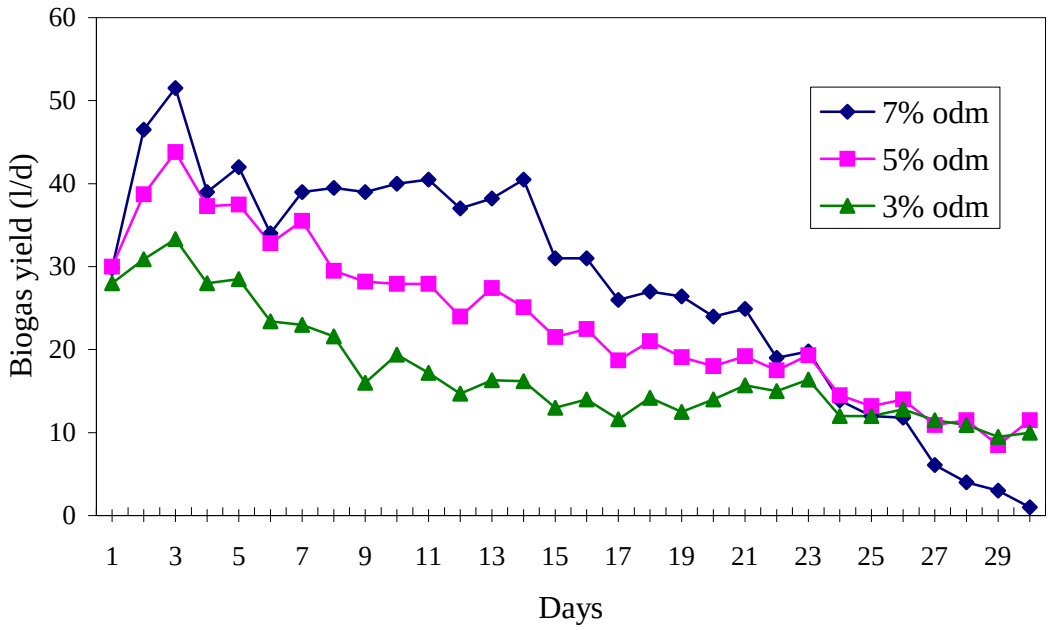

Figure 17b: Biogas yield in mono-fermentation of shea waste at 45 days HRT

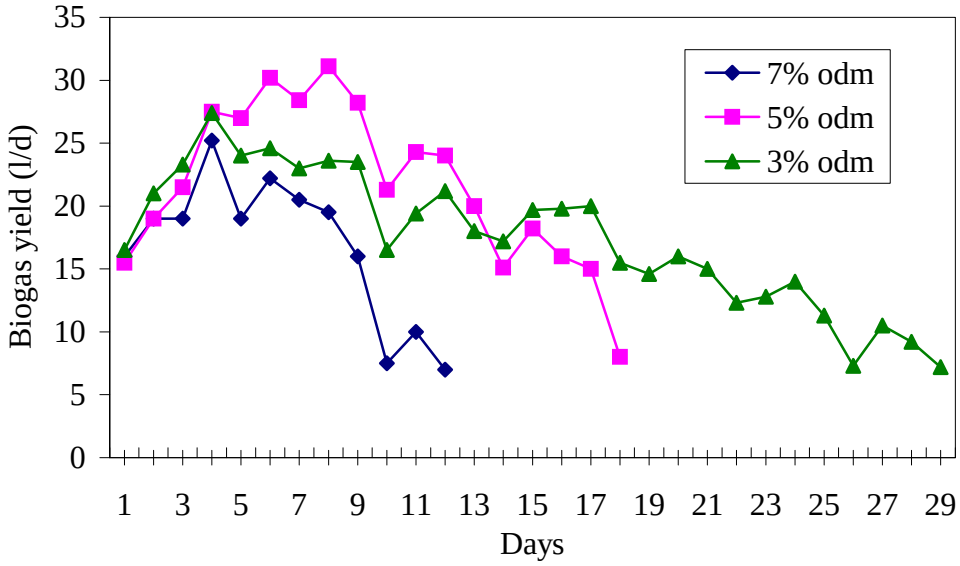

Figure 17c: Biogas yield in mono-fermentation of shea waste at 30 days HRT

At 30 days HRT the highest substrate specific biogas yield attained over the fermentation period of 12 days was 0.29 l/g odm at 3 % odm, whilst the lowest was 0.10 l/g odm at 7 % odm (Appendix A-5).

For 60 days HRT, the experiments at 7 % and 5 % odm were terminated on day 50, whilst that at 3 % odm was terminated on day 56 (Figure 17a). For 45 days HRT, the experiment 7 %, 5 % and 3 % odm were all terminated on day 30 (Figure 17b). The three experiments under 30 days HRT were terminated at different times depending on the gas production trend as shown in Figure 17c.

For the three HRTs the mean highest substrate specific biogas yield values were attained at 3 % odm concentration of substrate.

pH-values in mono-fermentation of shea waste

The pH-values for the basic substrate, the shea waste, under any of the odm concentrations fell below the optimal pH range for anaerobic digestion of organic materials. pH-values for the input substrate ranged between 5.44 and 5.69 (Table 10). The pH-value of the substrates in the digesters for the mono-fermentation process decreased progressively with time and affected the production of biogas, and eventually led to the termination of the experiments. The mean values for pH of reactor contents during the mono-fermentation process are shown on Appendix A-6. For 60 days HRT, the pH of the reactor contents was between 6.25 and 6.41; for 45 days HRT, the pH of the reactor contents was between 6.23 and 6.35, whilst for 30 days HRT the pH was between 6.27 and 6.61 (Appendix A-6).

Table 10. Fermentation parameters in mono-fermentation of shea waste

Treatment	HRT (d)	Mean odm (%)	Input pH-value	Temp. ^{o}C	Loading rate, L_D ($g_{odm}/l*d$)
1	60	2.84	5.54	30.9	0.50
2		4.84	5.47	31.3	0.86
3		6.75	5.44	31.6	1.22
4	45	2.87	5.69	28.9	0.68
5		4.90	5.60	28.9	1.18
6		6.85	5.32	29.2	1.67
7	30	3.00	5.69	28.0	1.04
8		4.89	5.58	27.8	1.71
9		6.69	5.57	28.2	2.35

Biodegradability in mono-fermentation of shea waste

In spite of the daily feeding of the digesters, the production of biogas decreased progressively to levels so low that all treatments had to be terminated before the end of the scheduled fermentation periods. Average degradation for 7 % odm of input substrate for 30 days, 45 days and 60 days HRTs were 1.74 %, 4.12 % and 7.01 % respectively.

Mono-fermentation of shea waste with and without ash at 30 days HRT

Methane content in mono-fermentation with and without ash

Figure 18 shows daily methane content in the biogas produced from mono-fermentation of shea waste with and without ash at 30 days HRT and at 7 % odm of substrate.

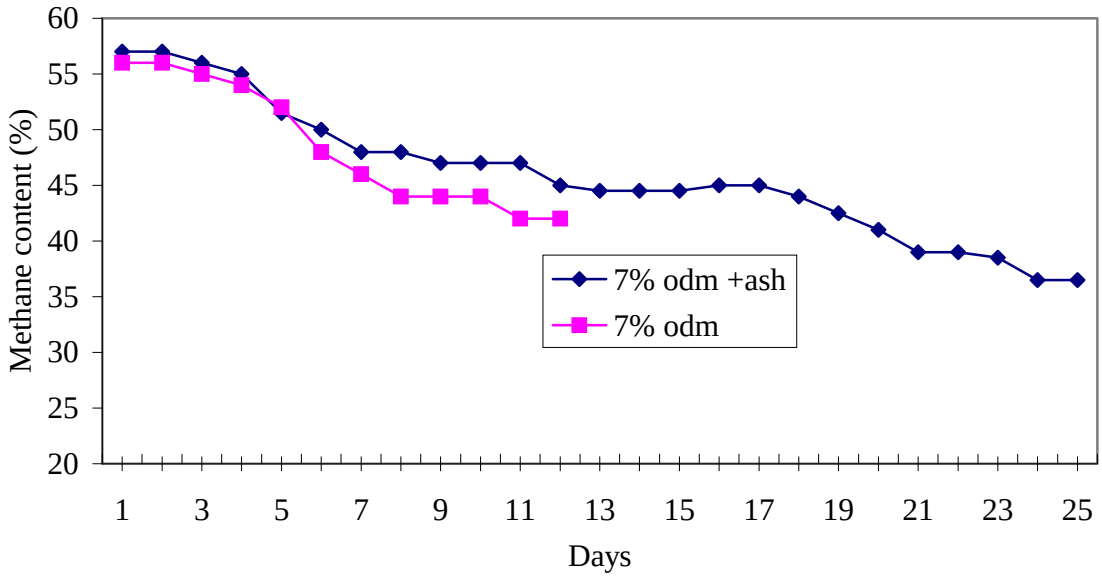

Figure 18: Methane content in mono-fermentation with and without ash

The methane content in both treatments showed a gradual decrease from the beginning of the experiments until their termination as shown in Figure 18. The methane content from treatment without ash decreased at a faster rate than in the treatment with ash. Methane content from the treatment without ash on the 6th day was 48 %, whilst the treatment with ash on the same day produced 50 % methane. The treatments were terminated due to decreasing methane contents.

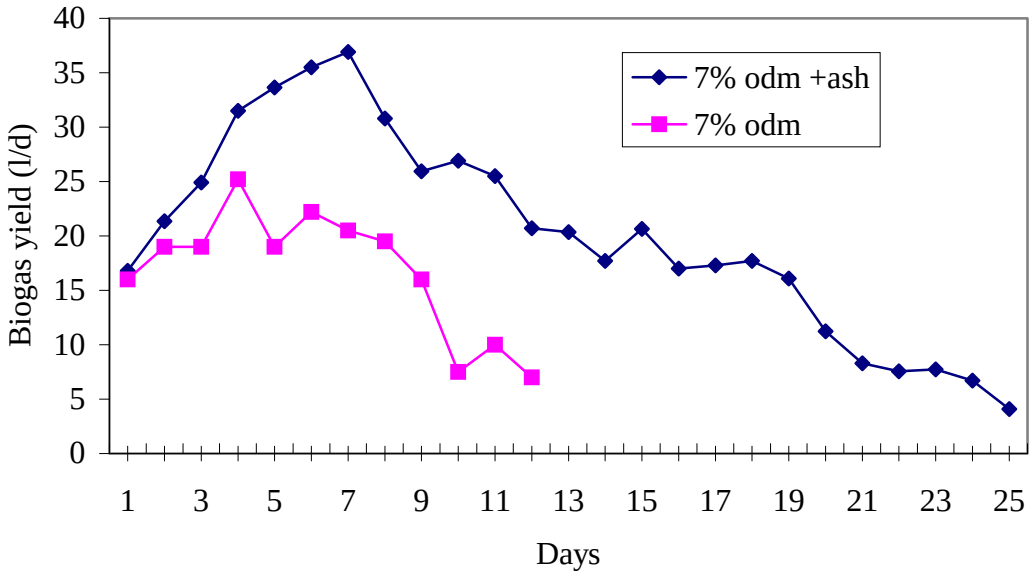

Figure 19a: Biogas yield from mono-fermentation with and without ash

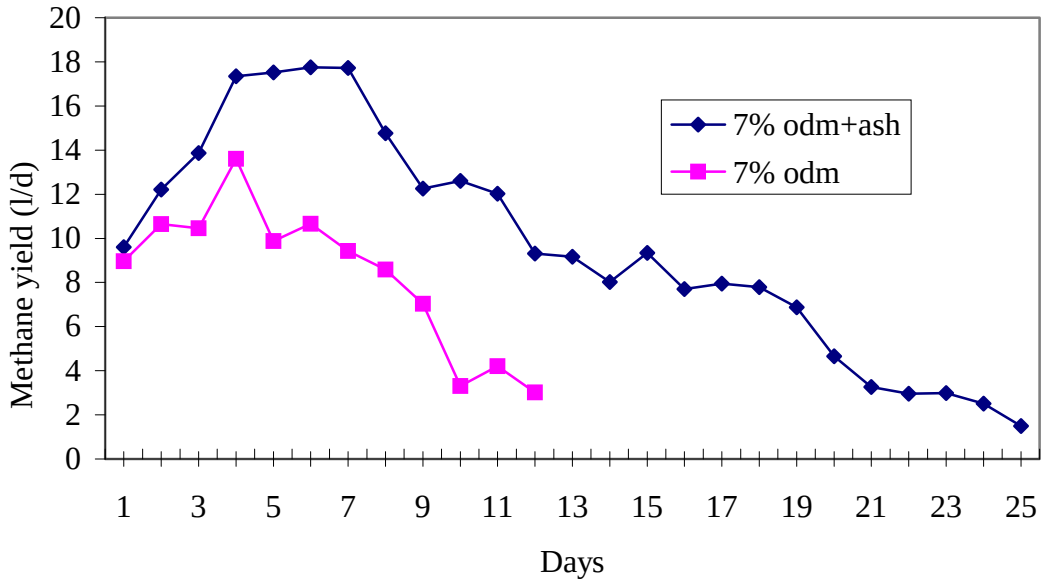

Figure 19b: Methane yield in mono-fermentation with and without ash

The experiments for the two treatments had to be terminated because no steady phase in biogas and methane production was attained during the period of the experiment (Figures 19a and 19b). Biogas and methane productions after

reaching the peak decreased daily, despite the daily digester feeding until the experiments were terminated as shown in Figures 19a and 19b.

pH-values in mono-fermentation with and without ash

The pH of the substrates in the digesters for the two treatments decreased progressively with time and affected the production of biogas, which eventually led to the termination of the experiments (Figure 20). However, the pH of the substrate with ash decreased more slowly than that of the substrate without ash. The mean values for pH of reactor contents of the treatments with and without ash on day12 were 6.519 and 5.686 respectively.

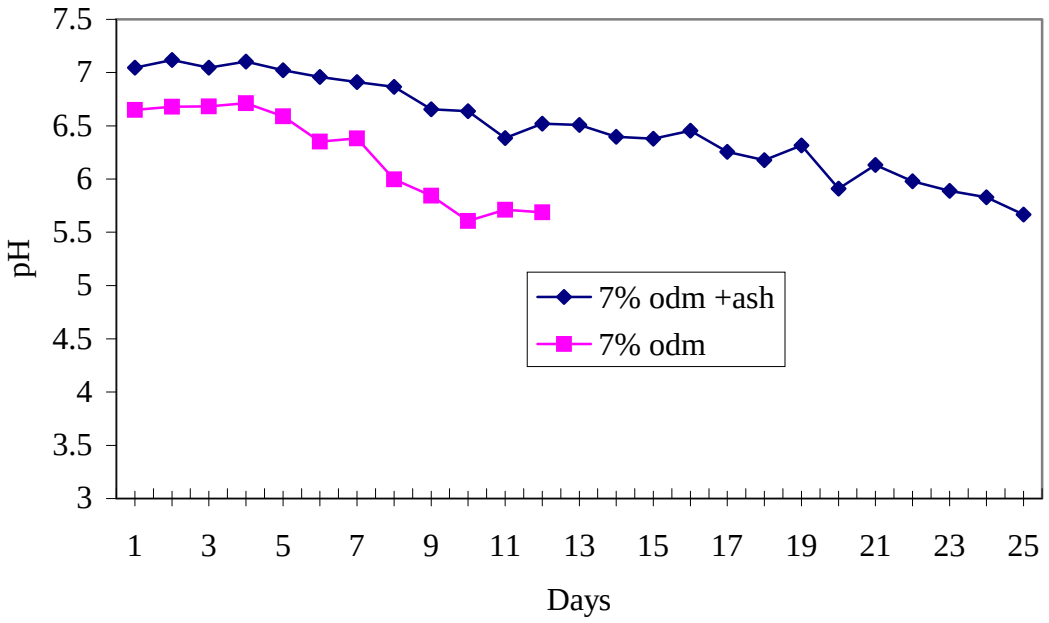

Figure 20: pH values of reactor content in mono-fermentation with and without ash

Co-fermentation trials of shea waste with cow dung

Methane content in co-fermentation trials

The methane content of the biogas produced during the co-fermentation trials for shea to cow dung ratio of 50:50 at the operating (ambient) temperatures and retention time of 30 days ranged from 56 % to 64 % by volume, with a mean value of 60.9 % by volume at the end of 33-day digestion period. However, in the case of shea to cow dung ratio of 75:25 and 90:10, the AD process was unstable, with the methane content decreasing daily from 60 % by volume of biogas until the experiments were terminated when values were below 50 % by volume as shown in Figure 21.

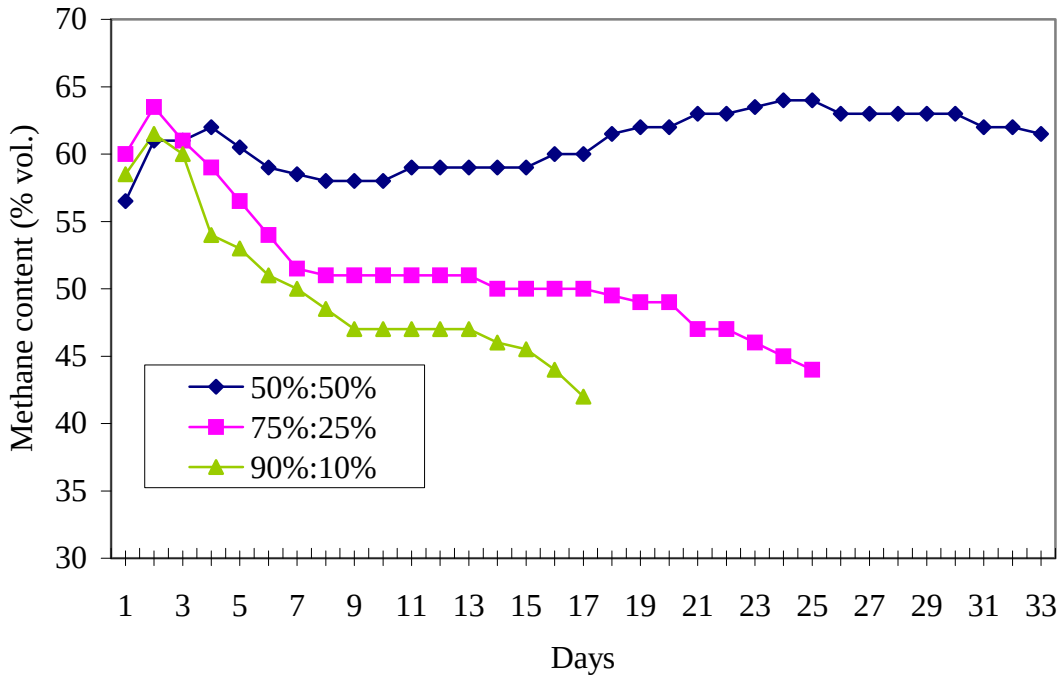

Figure 21: Methane content in co-fermentation trials

The mean values for the methane content in biogas from the co-fermentation of shea waste with cow dung are shown on Appendix A-7. The

highest mean methane content in biogas was about 60.9 % from the 50:50 mix, whilst the lowest was 49.9 % from the 90:10 mix.

Carbon dioxide content in co-fermentation trials

The carbon dioxide content of the biogas in the co-fermentation trials for shea to cow dung ratio of 50:50 at the operating (ambient) temperatures and HRT of 30 days ranged from 36 % to 43.5 % by volume. In the case of shea to cow dung ratio of 75:25 and 90:10, the carbon dioxide content in the biogas by volume ranged between 40 % and 55 % by volume of biogas and between 41.5 % and 58 % by volume respectively, until the experiments were terminated as shown in Figure 22. The highest mean CO_2 content in biogas was 50.1 % from the 90:10 mix, whilst the lowest was 39.2 % from the 50:50 mix.

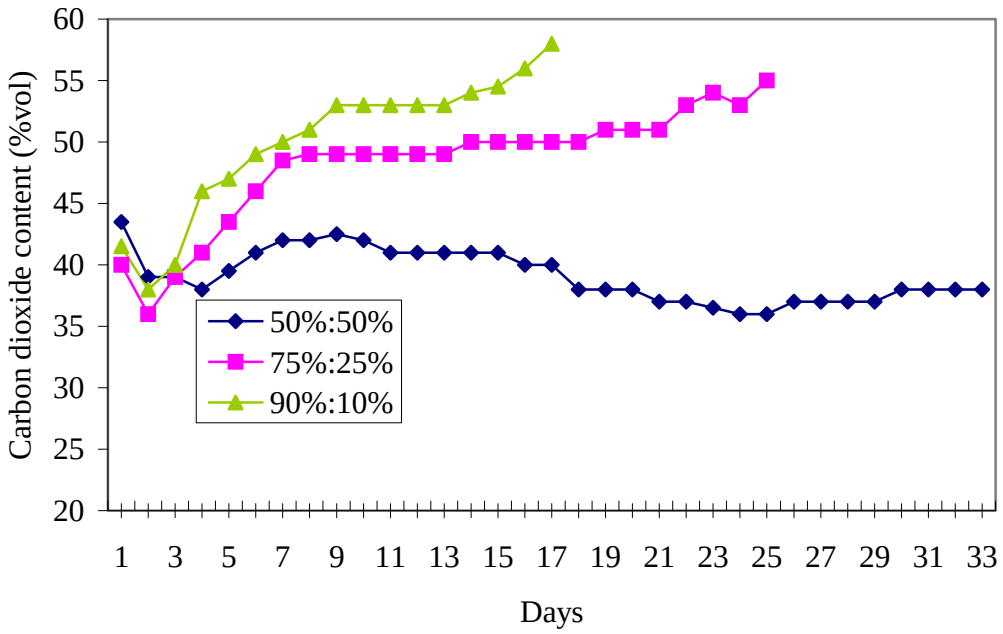

Figure 22: Carbon dioxide content in co-fermentation trials

Reactor specific gas yield in co-fermentation trials

The reactor specific biogas yield during the co-fermentation trials for shea to cow dung ratio of 50:50 by volume for the fermentation period was 0.55 l/l*d, whilst the reactor specific methane yield for the same substrate was 0.34 l/l*d at the operating (ambient) temperatures and HRT of 30 days.

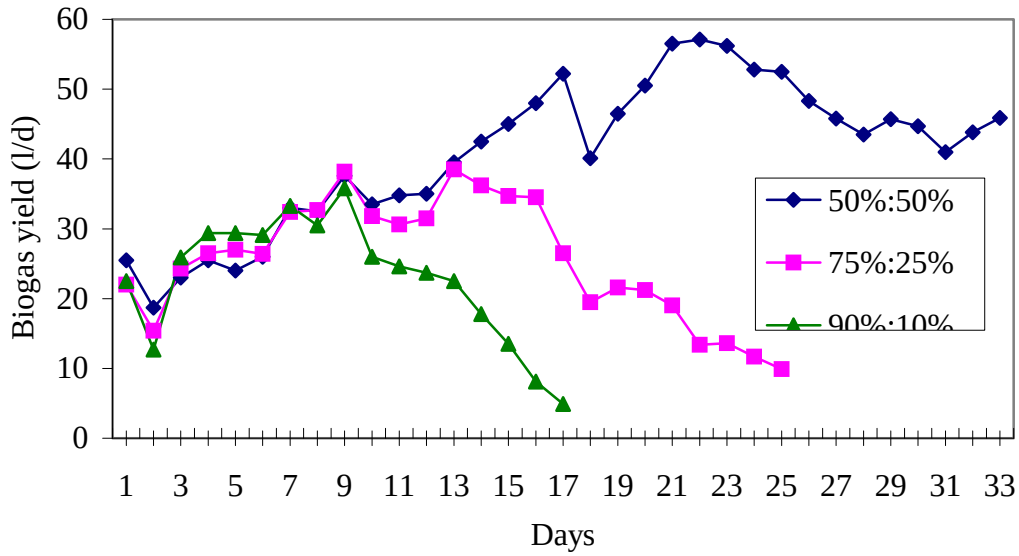

Figure 23a: Daily biogas yield in co-fermentation trials

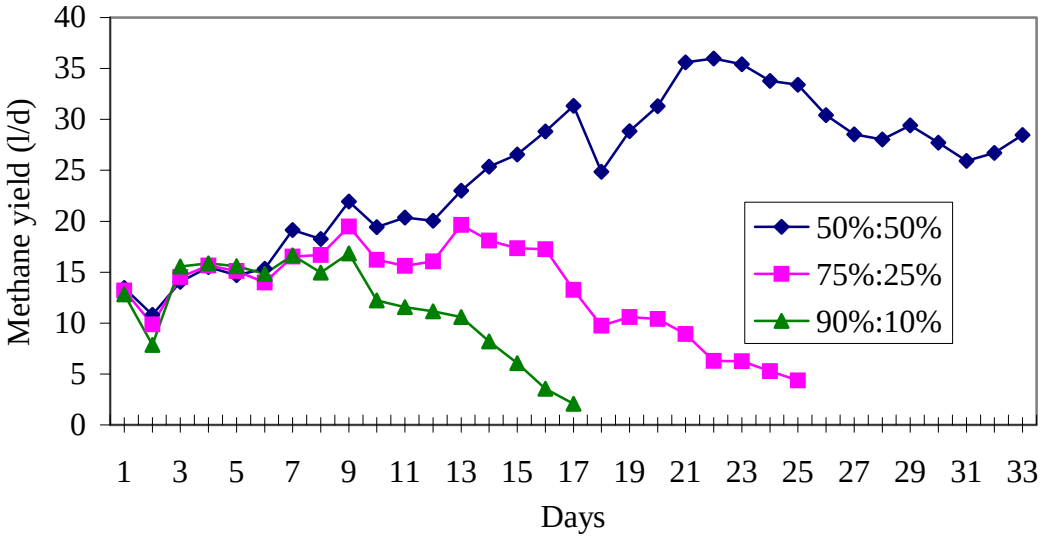

Figure 23b: Daily methane yield in co-fermentation trials

The reactor specific biogas and methane yields for substrate 75:25 were 0.35 l/l*d and 0.18 l/l*d respectively, whilst that for the substrate 90:10 were 0.31 l/l*d and 0.16 l/l*d respectively. In the case of substrates 75:25 and 90:10, the AD process was unstable leading to a decrease on almost daily basis of the biogas/methane yields after reaching their peak as shown in Figures 23a and 23b.

Substrate specific gas yield in co-fermentation trials

The average substrate specific biogas yield during the co-fermentation trials for shea to cow dung ratio of 50:50 by volume for the fermentation period was 0.24 l/g odm, whilst the substrate specific methane yield for the same substrate (50:50) was 0.15 l/g odm at the operating (ambient) temperatures and HRT of 30 days. With the shea to cow dung ratio of 75:25 and 90:10, the AD process was unstable, resulting in low values for substrate specific biogas/methane yields. The mean values of substrate specific biogas/methane yields are shown in Appendix A-8.

pH-values in co-fermentation trials

pH for substrate 50:50 in the digester had an average value of 6.95 showing some stability in biogas production over the experimental period from the mean input substrate value of 6.68 (Figure 24). The pH-values for substrates 75:25 and 90:10 in the digester showed declining trends, an indication of process instability. The pH values for the three treatments are shown in Figure 24.

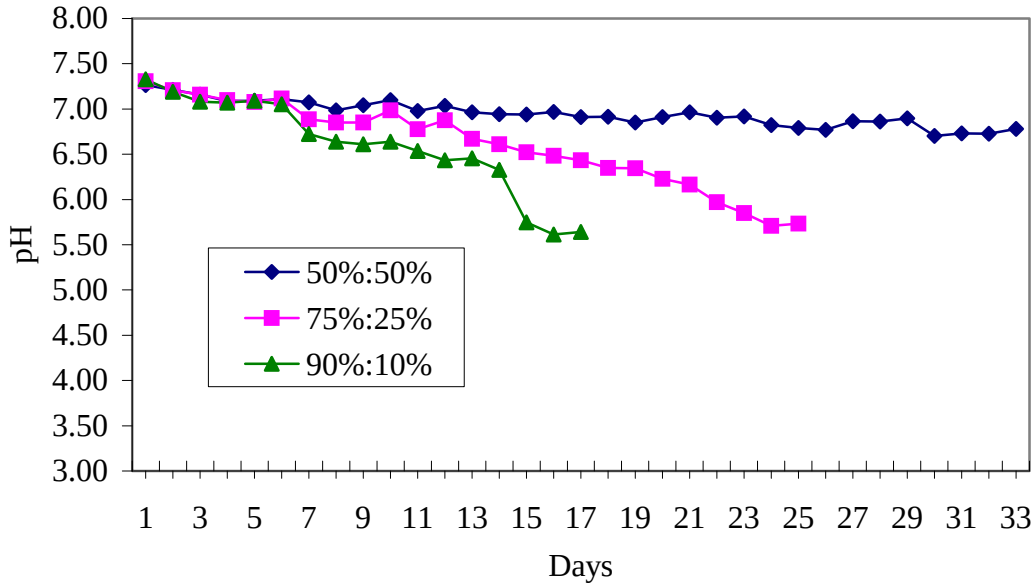

Figure 24: pH-values in co-fermentation trials

Biodegradability in co-fermentation trials

The degradation in anaerobic fermentation of odm depends on the composition of input substrate and the reaction conditions. The rate of degradation of the odm is an assessment of the efficiency of the biogas process. Effluent samples were taken at every six-day interval to determine the odm. Degradation of the mix 50:50 at the end of the retention period was found to be 10.97 % at the operating temperatures and HRT of 30 days. Though, degradation for 75:25 and 90:10 were 13.26 % and 13.06 % respectively, the experiments were not stable and were terminated before the scheduled periods.

Co-fermentation of shea waste with cow dung at 20 days HRT

Methane content in co-fermentation with and without ash

As can be seen from Figure 25, the methane content in biogas from the co-fermentation of shea waste with cow dung in the ratio 50:50 at 7 % odm and without ash ranged from 46 to 63 % by volume. The methane content from the substrate with ash buffer at the steady state of the biogas production ranged from 52 to 53.5 %, with a mean value of 52.83 % by volume of the biogas. The ash buffer appeared to have stabilized the process compared to the substrate without ash, whose methane content was on the decline as shown in Figure 25.

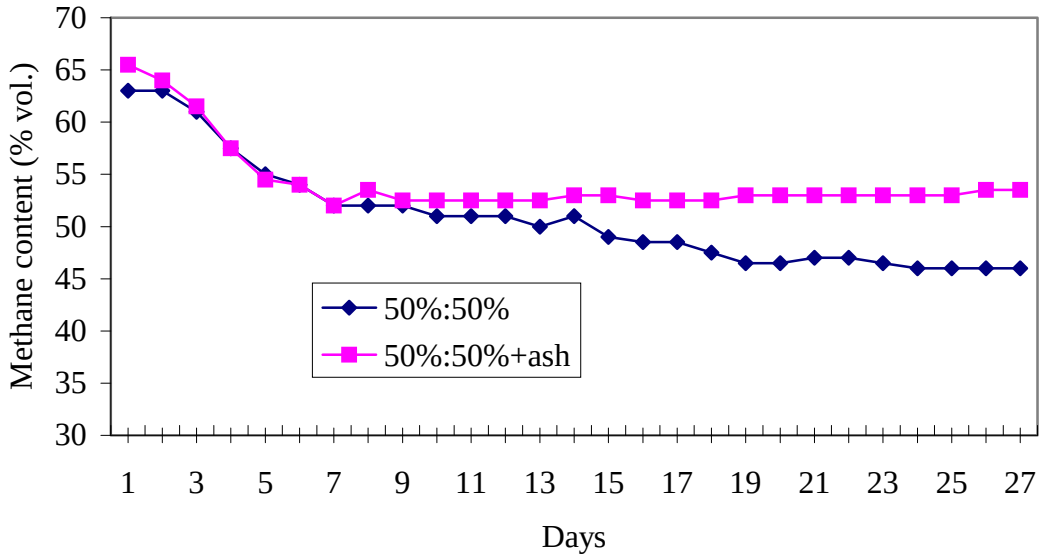

Figure 25: Methane content in co-fermentation with and without ash

Appendix A-9 shows the mean values from two replications in the two treatments over the fermentation period of 27 days. The substrate with ash buffer attained mean methane content of 54.3 %, whilst the substrate without ash addition

attained 50.9 %. However, the methane content of the substrate without ash at the day of termination of the experiment showed declining trend.

Carbon dioxide content in co-fermentation with and without ash

The CO_2 content from the substrate 50:50 without ash increased from the beginning of the experiment at 36.5 % by volume of biogas till the time of termination on the 27th day when it had reached 54 % by volume of the biogas as shown in Figure 26. The mean CO_2 content from the substrate 50:50+ash over the fermentation period was 45.4 %, whilst the mean CO_2 for the substrate without ash was 49.0 %.

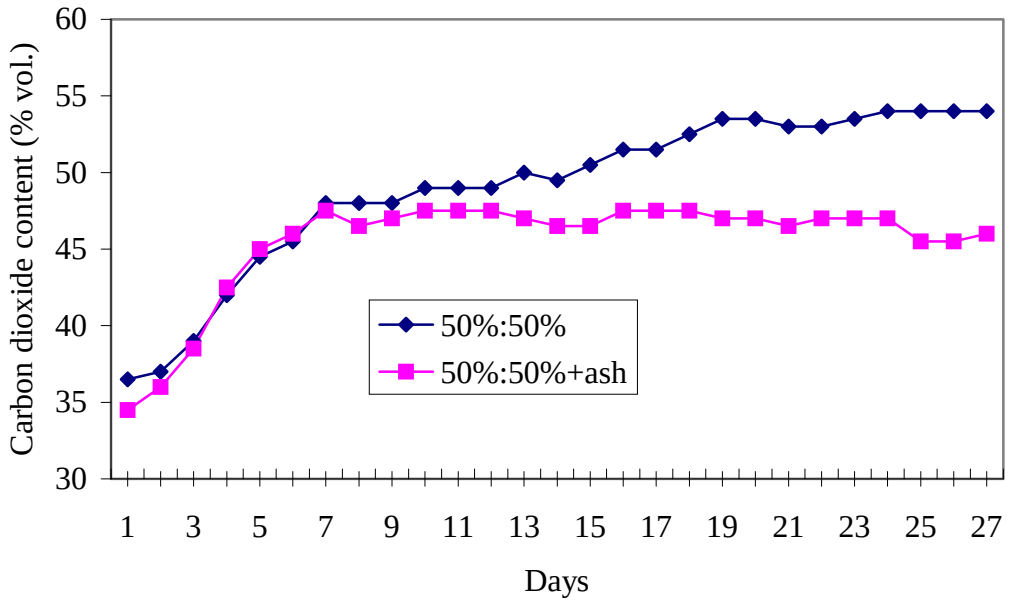

Figure 26: Carbon dioxide content in co-fermentation with and without ash

Specific biogas yield in co-fermentation with and without ash

Figures 27a and 27b show the daily biogas and methane yields from the co-fermentation of shea waste with cow dung at 7 % odm and 20 days HRT. Whilst

the production of gas had reached a steady state under the treatment with an ash buffer, production of gas under the treatment without ash was declining.

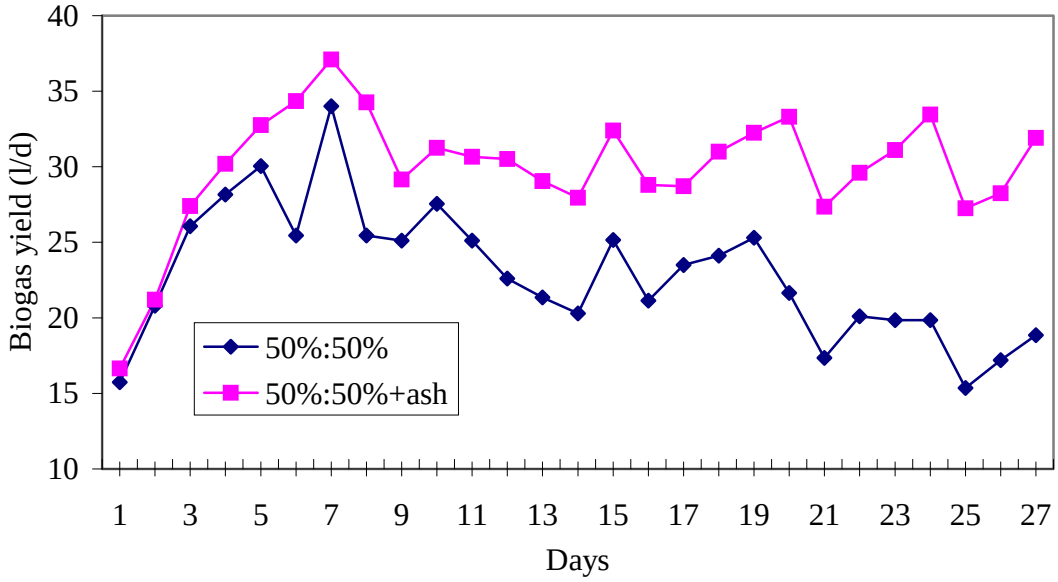

Figure 27a: Daily biogas yield in co-fermentation with and without ash

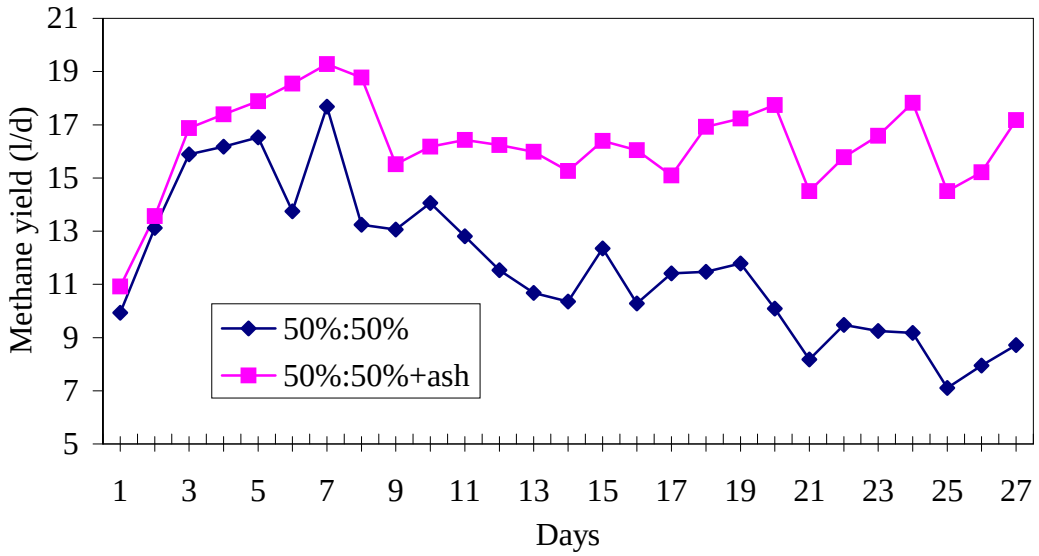

Figure 27b: Daily methane yield in co-fermentation with and without ash

Reactor specific gas yield in co-fermentation with and without ash

Figures 28 shows the reactor specific biogas yields for co-fermentation of shea waste with cow dung, with and without ash at 20 days HRT for the fermentation period.

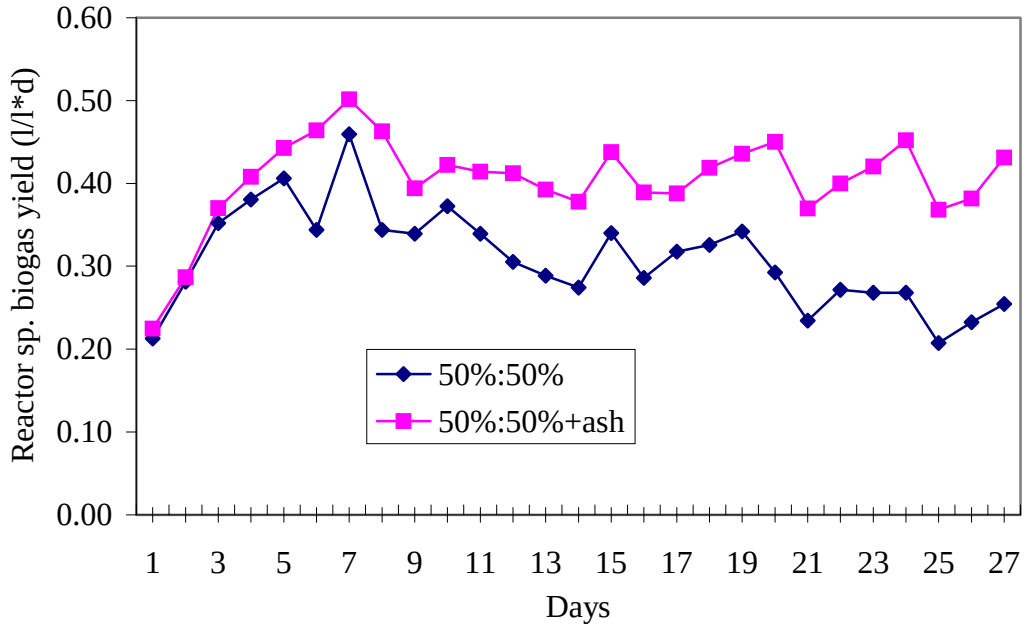

Figure 28: Reactor specific biogas yield in co-fermentation with and without ash

The average reactor specific biogas yield for substrate 50:50+ash during the fermentation period was 0.41 l/l*d, whilst the average reactor specific methane yield for the same substrate for same period was 0.22 l/l*d. For substrate 50:50 (without ash) the reactor specific biogas and methane yields are respectively 0.31 l/l*d and 0.16 l/l*d.

Substrate specific gas yield in co-fermentation with and without ash

The mean substrate specific biogas yield for substrates 50:50+ash and 50:50 during the fermentation period were 0.11 l/g odm and 0.09 l/g odm respectively, whilst the mean substrate specific methane yield for the same substrates 50:50+ash and 50:50 for the same period were 0.06 l/g odm and 0.04 l/g odm respectively.

pH-values in co-fermentation with and without ash

The average pH-values for the fermentation period for the two treatments of co-fermentation of shea waste with cow dung, and with and without ash at 20 days HRT are 6.75 and 6.51 respectively, and presented in graphical form in Figure 29.

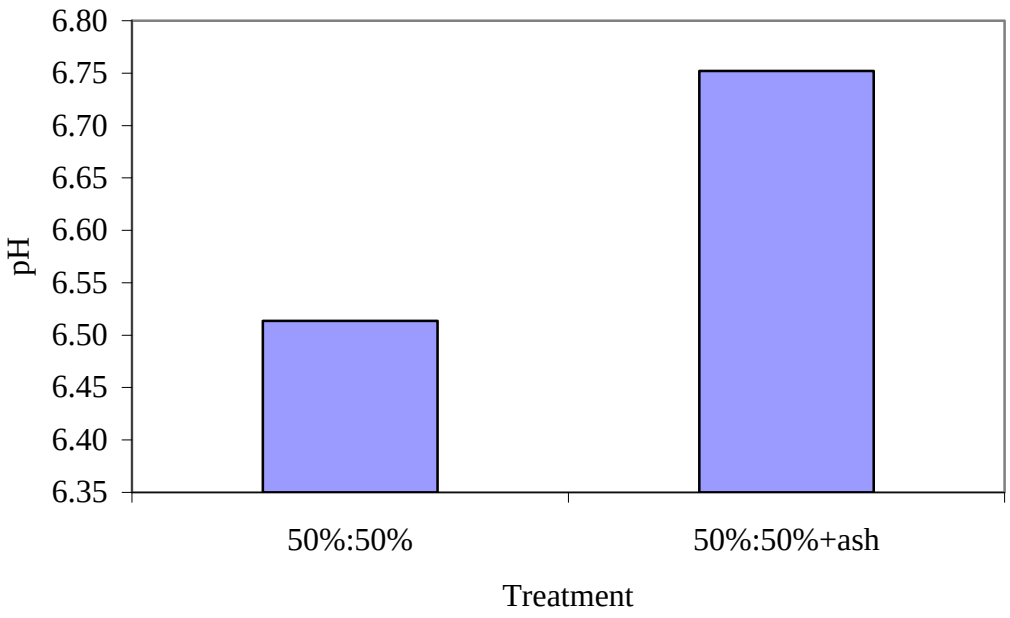

Figure 29: Average pH-value of reactor content in co-fermentation with and without ash

A test mean difference using ANOVA indicates that the co-fermentation treatment with ash (with mean pH = 6.752) was significantly higher than the co-fermentation treatment without ash (with mean pH = 6.514) at $p < 0.001$ (LSD = 0.1042 at 5 % level).

Biodegradability in co-fermentation with and without ash

The degradation in anaerobic fermentation of odm is influenced by the kind and composition of input substrate, and the reaction conditions. To determine the rate of degradation effluent samples were taken at five-day intervals to determine the odm concentration. The average odm values of the effluent after digestion are also presented graphically in Figure 30.

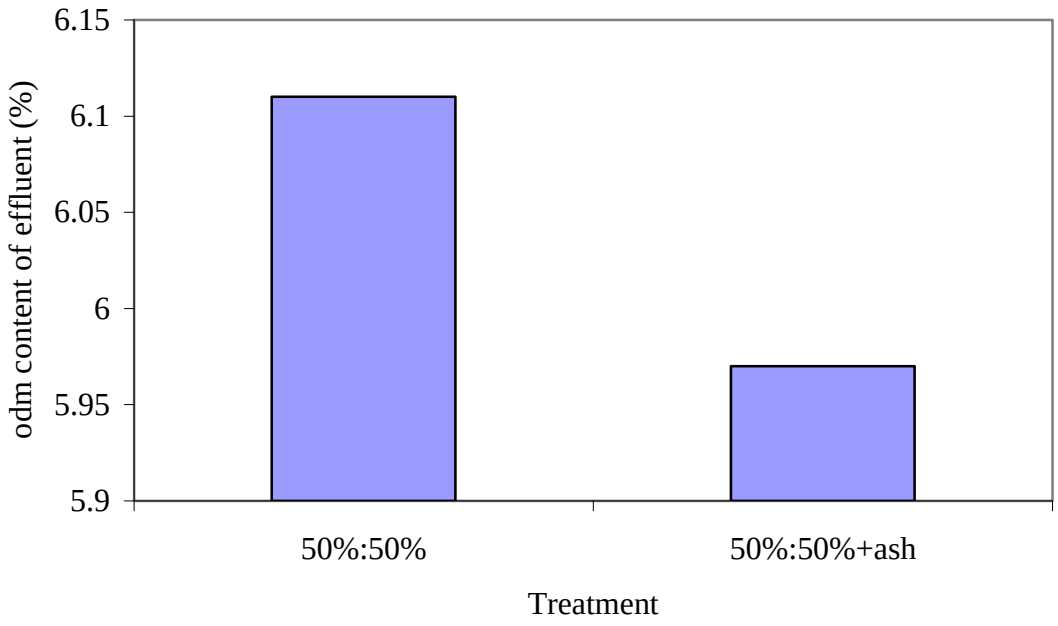

Figure 30: Average odm content of effluent in co-fermentation with and without ash

A test mean difference using ANOVA indicates that there is no significant difference between the co-fermentation treatment without ash (with mean odm = 6.11 %) and the co-fermentation treatment with ash (with mean odm = 5.97 %) at p = 0.196 (LSD = 0.2225 at 5 % level).

Figure 31 shows the average degradation of the two treatments during the 27-day fermentation period. Degradation of the mix 50:50 at the end of fermentation period was found to be 11.07 % at the operating temperatures and HRT of 20 days, whilst the mix 50:50+ash showed 14.09 % degradation. A test mean difference using ANOVA indicates that there is no significant difference between the co-fermentation treatment with ash (with mean degradation = 14.09 %) and the co-fermentation treatment without ash (with mean degradation = 11.07 %) at p = 0.096 (LSD = 3.619 at 5 % level).

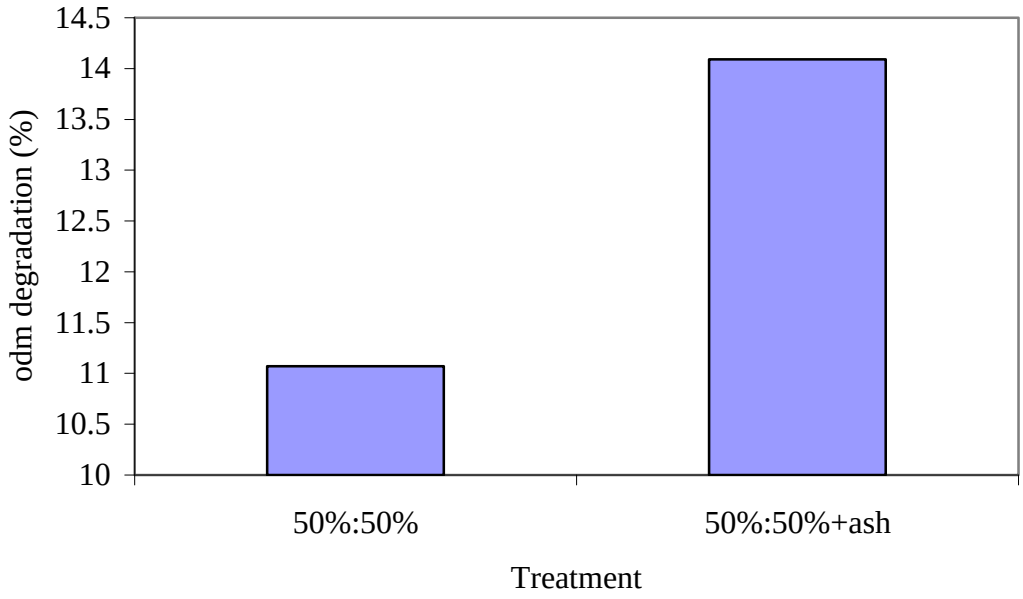

Figure 31: Average degradation of degradation of odm content in co-fermentation with and without ash

Main experiment

Co-fermentation of shea waste with cow dung and the fermentation of pure cow dung as control at 30 days HRT

Methane content in main experiment

The methane content of biogas from the co-fermentation of shea waste with cow dung (50:50) at the operating temperatures and retention time ranged from 57.33 to 64.00 % volume, whilst that from the pure cow dung fermentation (control) ranged from 60.00 to 64.33 % by volume as presented in Appendix B-1.

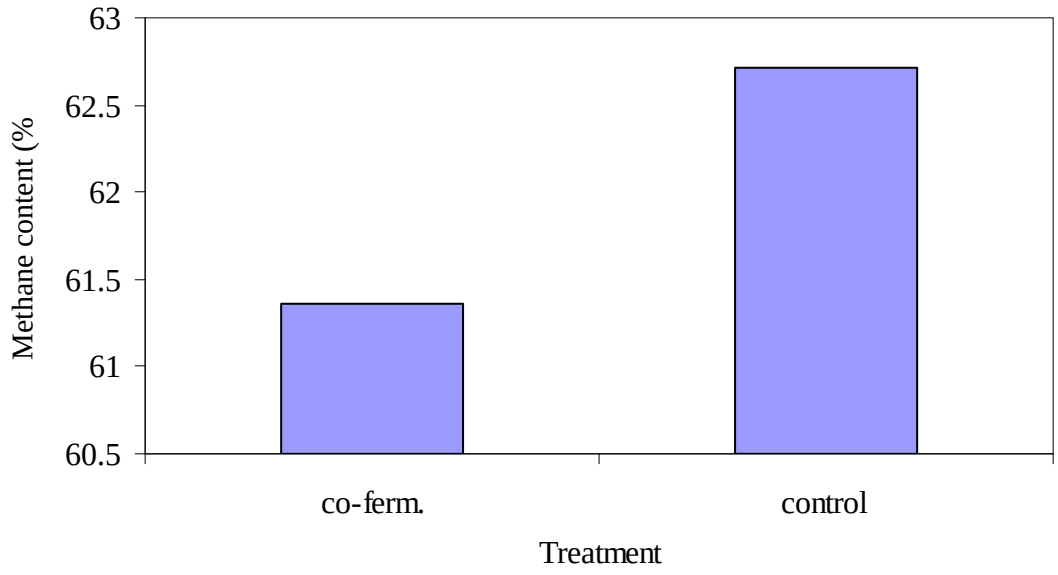

Figure 32: Average methane content in biogas from co-fermentation of shea waste and control

The average methane content in biogas from the co-fermentation of the shea waste with cow dung was 61.36 % volume, whilst the average methane content from the cow dung fermentation was 62.71 % volume. Figure 32 shows the average values of the methane contents in the two experimental treatments in

graphical form. A test mean difference using ANOVA indicated that the control treatment (cow dung fermentation) was significantly higher than the co-fermentation treatment at $p < 0.001$ (LSD = 0.3589 at 5 % level).

Carbon dioxide content in main experiment

The carbon dioxide content in the biogas in the co-fermentation of shea waste with cow dung (50:50) at the operating temperatures and retention time ranged from 36.00 to 42.67 % by volume, whilst the carbon dioxide content in biogas from the digestion of pure cow dung ranged from 35.67 to 40.00 % volume.

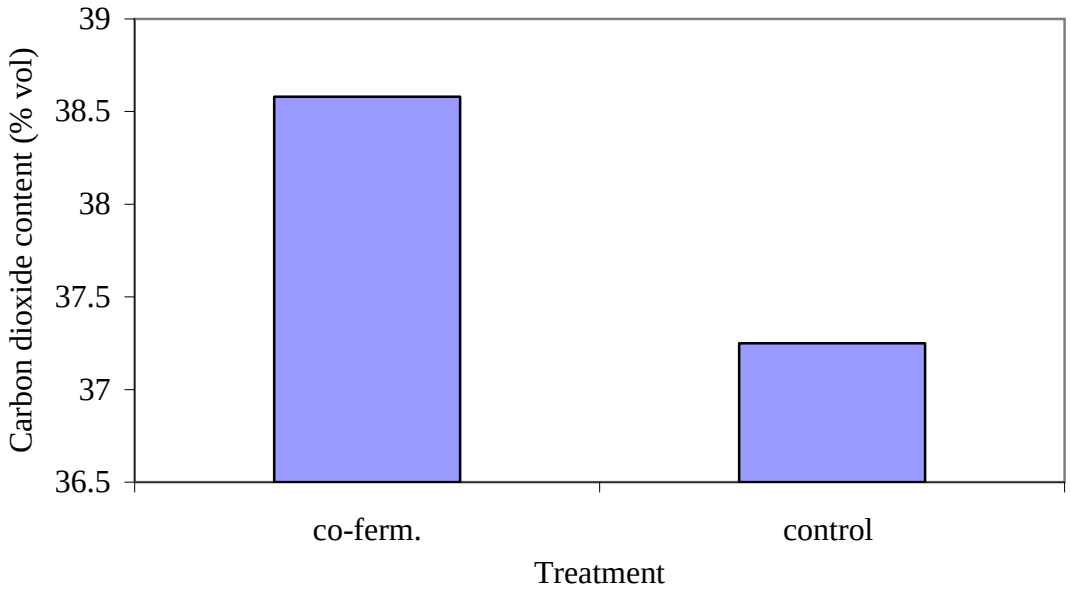

Figure 33: Average carbon dioxide content in biogas from co-fermentation of shea waste and control

The average values of the carbon dioxide content in the biogas from the co-fermentation of shea waste with cow dung and from the digestion of 100 % cow dung are shown in Figure 33. The test mean difference using ANOVA indicated

that the co-fermentation treatment (with mean CO_2 content 38.59 %) was significantly higher than the control treatment (with mean CO_2 content 37.25 %) at $p < 0.001$ (LSD = 0.3636 at 5 % level).

Reactor specific gas yield in main experiment

The experimental result for the co-fermentation of shea waste with cow dung gave mean values of reactor specific biogas and methane yields as 0.49 l/l*d and 0.30 l/l*d respectively, whilst for the digestion of pure cow dung as control the values were 0.28 l/l*d and 0.17 l/l*d respectively.

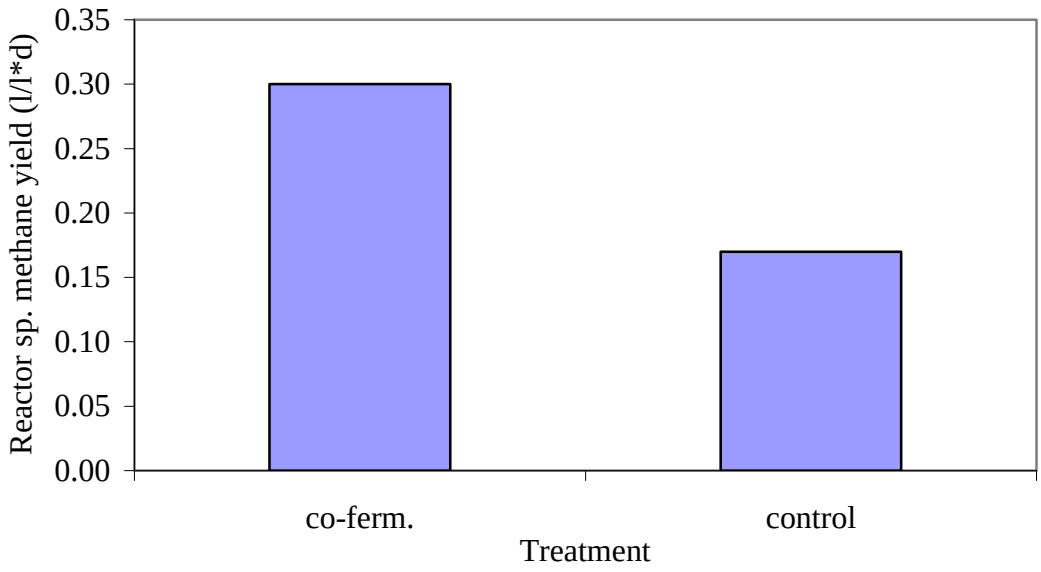

Figure 34: Average reactor specific methane yields from co-fermentation of shea waste and control

Figure 34 show the reactor specific methane yield for the two treatments. The value of the reactor specific methane yield depicts the efficiency of the reactor volumes in the digestion process. A test mean difference using ANOVA indicates

that co-fermentation treatment (with mean 0.2979) was significantly greater than the control treatment (with mean 0.1748) at $p<0.001$. (LSD = 0.00681 at 5 % level).

Substrate specific gas yield in main experiment

Biogas production from co-fermentation over the entire fermentation period of 57 days showed almost two times as much as the production from pure cow dung as shown in Appendix B-2. The average substrate specific biogas and methane yields from the co-fermentation of shea waste with cow dung were 0.21 l/g odm and 0.13 l/g odm respectively, whilst for the control the mean values were 0.12 l/g odm and 0.07 l/g odm respectively. Figure 35 shows the substrate specific methane yield in graphical form.

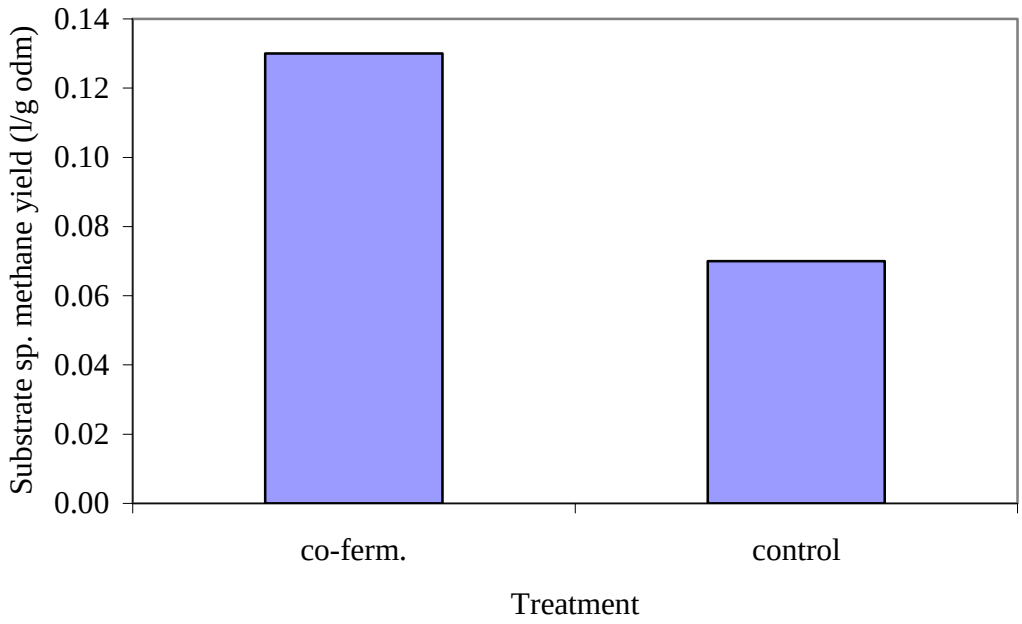

Figure 35: Average substrate specific methane yields from the co-fermentation of shea waste and control

A test mean difference using ANOVA indicates that co-fermentation treatment (with mean 0.1296) was significantly greater than the control treatment (with mean 0.0737) at $p<0.001$ (LSD = 0.0054 at 5 % level).

pH-values in main experiment

The pH-values for the reactor contents during the investigation are presented in graphical form in Appendix B-3. Figure 36 shows the graphical presentation of the average pH-values of the experiments from three replications in the co-fermentation of shea waste with cow dung and the fermentation of pure cow-dung. The test mean difference using ANOVA indicated that the control treatment (with mean 7.12) was significantly greater than co-fermentation treatment (with mean 6.93) at $p< 0.001$ (LSD = 0.02031 at 5 % level).

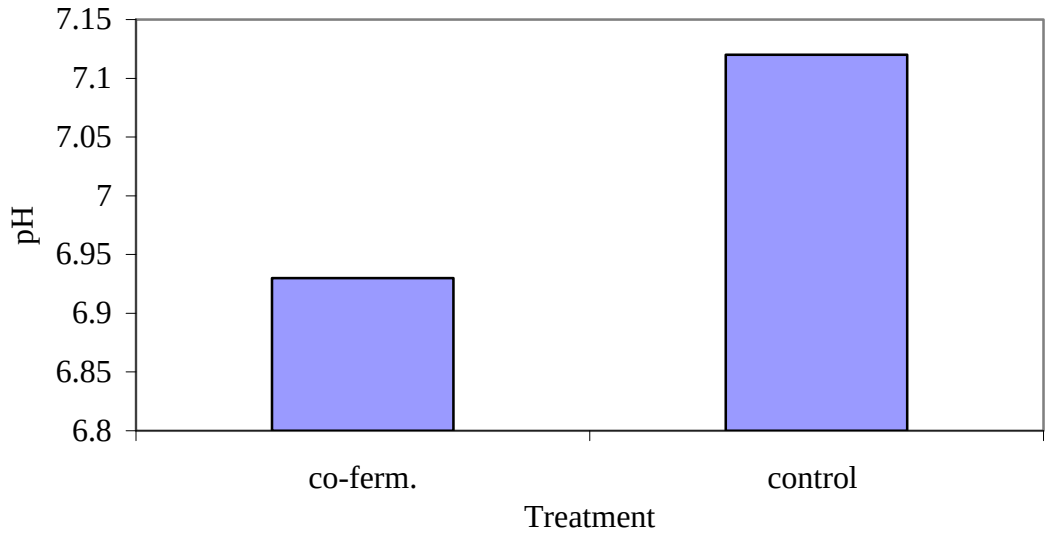

Figure 36: Average pH-values of reactor content in co-fermentation of shea waste and control

Biodegradability of substrates in main experiment

The average odm values of the effluent from the co-fermentation of shea waste with cow dung, and from the digestion of pure cow dung as control are presented in Figure 37. A test mean difference using ANOVA indicates that the odm values of effluent from the control treatment (with mean 6.238) was significantly higher than the co-fermentation treatment (with mean 5.927) at $p<0.001$ (LSD = 0.1332 at 5 % level).

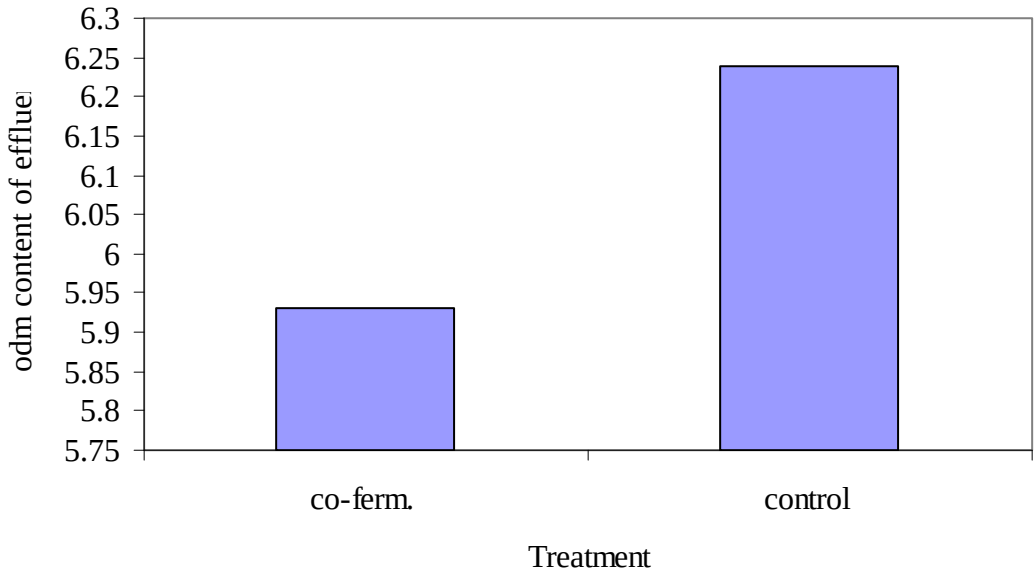

Figure 37: Average odm of effluent in co-fermentation of shea waste and control

The average degradation of the odm content during the co-fermentation of shea waste with cow dung after the retention period was found to be 12.16 % at the operating temperatures and HRT of 30 days, whilst the pure cow dung fermentation showed 7.74 % degradation as represented in Figure 38. The test mean difference using ANOVA indicated that the degradation from the co-

fermentation treatment (with mean 12.16) was significantly greater than the control treatment (with mean 7.74) at p< 0.009 (LSD = 3.126 at 5 % level).

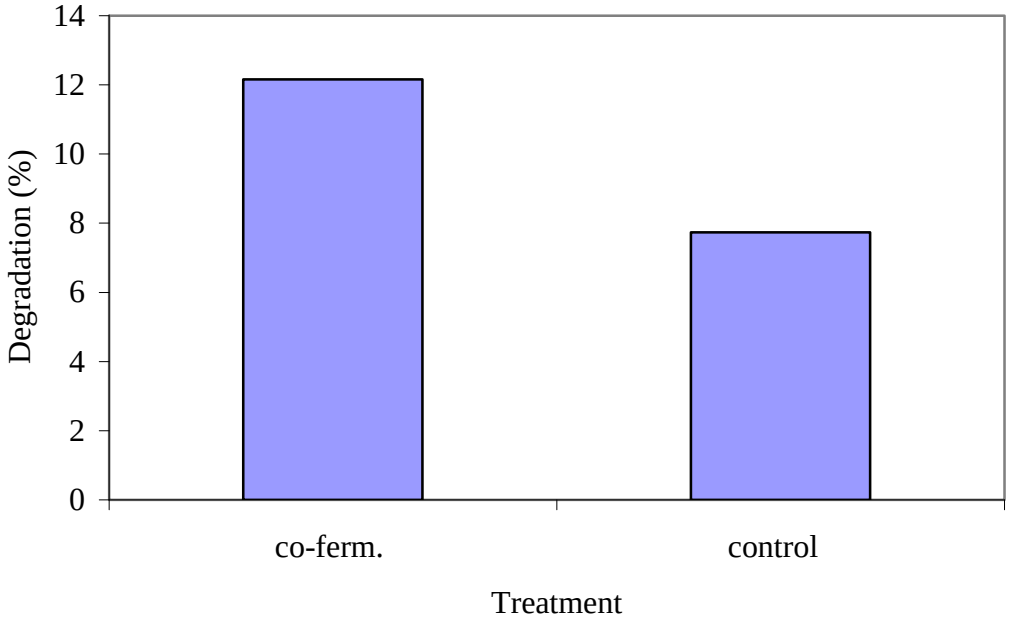

Figure 38: Average degradation of degradation of odm content in co-fermentation of shea waste and control

CHAPTER 5

DISCUSSIONS

Introduction

Biogas is a mixture of gases comprising principally combustible methane (CH_4) and incombustible carbon dioxide (CO_2). The quality of biogas is determined by the composition of methane and carbon dioxide, and is therefore a crucial factor in determining the viability of the biogas AD process. The biogas quality also depends on the composition and the appropriate amount of organic waste used. Care must be taken in the AD process not to compromise on the biogas quality, and to ensure that the safe operation of the biogas plant is guaranteed. It is therefore important to have information on the amount and the composition of the organic waste, the co-substrate addition if necessary, as well as the HRT that is needed to guarantee process stability and to ensure adequate degradation of the organic matter. It is in this context that the findings of the present study are discussed.

Biogas production and quality under mono-fermentation

In the trial run to test the viability of mono-fermentation of shea waste as an option in AD, none of the treatments undertaken in the investigation proved to be stable in terms of sustainable biogas production. In all treatments there was an

initial increase in biogas production at the starting phase till production got to a peak, and thereafter production began to decrease continuously to levels nearing zero. Decreasing biogas production paralleled with deteriorating methane content of the gas to levels below 50 %. No steady phase was attained in any of the treatments under mono-fermentation during the period of the experiments. The rate of decline in biogas production was influenced by the odm concentration of the substrate as well as the HRT, which is correlated to the quantity of substrate fed to the digester in a day. It was observed that biogas production from substrates at 7 % odm declined faster than at 3 % odm, whilst production trend from 5 % odm is found in-between 7 % odm and 3 % odm. Biogas production also dropped faster at 30 days HRT than at 60 days HRT, whilst production trends from 45 days HRT fit in-between 30 days and 60 days HRTs (Figures 17a, b and c). This agrees with the findings of Powers *et al.* (1997) which states that generally, reduction of HRT resulted in increased rate of instability of the system leading to decreased performance of the digesters in terms of rate of gas production and TS and VS destruction.

The level of pH of the digester content influenced the rate of decline in biogas production. The higher the acidity of the digester contents the faster the decline in biogas production. It has been confirmed that methanogenic bacteria are very sensitive to pH and do not thrive below a value of 6.5 (FAO, 1997). The higher the odm concentration, the lower the pH-value. Pure shea waste substrates at 7 % odm had a pH range of 5.32 - 5.52, whilst at 3 % odm the range was 5.54 – 5.69. The pH values for 5 % odm ranged between the values for 7 % odm and 3 % odm, that is in the range 5.47 – 5.60 (Table 10). The optimum biogas production is

achieved when the pH value of input mixture in the digester is between 6 and 7 (FAO, 1997). The pH values during the tests were mostly below 6 placing the process in a situation not to give optimum biogas production. During the starting phase of 7 % odm at 60 days HRT for example, the pH of the digester content was 6.76 due to the presence of substantial amount of the inoculum in the digester, but at the time of termination of the experiment the pH of the digester content had dropped to 5.66. This explains the increasing biogas production in the beginning of the AD and the subsequent reduction towards the time of termination, as it has been observed that high fat contents of substrate increase volatile fatty acids (VFA) considerably (Steffen *et al*., 1999).

The experiments under mono-fermentation of shea waste were terminated for two reasons: firstly, when biogas production declined to near-zero levels and secondly, when the methane content declined below 50 % by volume of biogas because it has been determined that biogas with less than 50 % methane content is not combustible (Sasse, 1988). An interesting observation however was the potential of the shea waste to generate substantial amount of methane. The raw material contained approximately 86 % of volatile solids (Table 7). At the peak of production for 60 days HRT, substrate specific biogas yield of 610 l/kg odm was attained at 3 % odm shea substrate with methane component of 66 % by volume of biogas; 510 l/kg odm at 5 % odm shea substrate with methane component of 63 % by volume of biogas, whilst the substrate specific biogas yield of 580 l/kg odm was attained at 7 % odm of substrate with methane share of 62 % by volume of biogas (Figures 15a and 17a). It is the potential of the shea waste to generate

substantial amount and high quality methane that prompted the co-fermentation option.

Comparing the process performance in mono-fermentation of shea waste with and without ash in the substrate, it was evident that the addition of ash was not adequate to ensure process stability in the production of methane and biogas, and also to ensure optimum pH throughout the fermentation period. However, the addition of ash to the shea waste substrate improved the pH from 5.50 to 6.98 (Table 8). It was also observed that the biogas and methane production from the treatment with ash over the fermentation period decreased more slowly than from the treatment without ash (Figures 19a and b), compelling the termination of the treatment without ash earlier than that with ash.

The instability of the mono-fermentation process is attributed to high volatile fatty acids due to the presence of fats or oils (lipids) in the shea waste leading to low pH, agreeing with Steffen *et al.* (1999) observation that high fat contents of substrate increase volatile fatty acids (VFA) considerably of the substrate. Lipids are known to be attractive for biogas production due to the fact that they are reduced organic materials and have high theoretical methane potential (Fernandez *et al*., 2005). However, anaerobic treatment of organic wastes with high lipid content presents problems, as it has been widely reported that high LCFA concentrations can destabilize anaerobic digesters due to inhibition of methanogenic bacteria by possible damage to cellular membrane (Hanaki *et al*., 1981). To have a relatively stable process the option was therefore co-digestion or co-fermentation of the waste with cattle manure. It has also been shown that the performance of digesters could be considerably improved by means of co-substrate

addition (Steffen *et al*., 1999) and this is as a result of the improvement of the buffer capacity, which gives a positive effect in the co-fermentation process (Mshandete *et al*., 2004).

Biogas production and quality under co-fermentation

Co-fermentation of shea waste with cow dung was shown to be a viable option, exhibiting appreciable process stability. Steffen *et al*. (1999) stated that up to 80 % co-substrate addition could be applied in some cases in agricultural digesters. The present investigation, however, showed that cattle manure addition of 10 % and 25 % was inadequate to ensure process stability. The shea waste substrate with cattle manure addition of 10 % had an input pH-value of 6.09, which dropped to 5.6 after 17 days fermentation period, whilst the treatment with the cattle manure addition of 25 % had an input pH of 6.37 and this value dropped to 5.73 after 23 days digestion period. The shea waste substrate with cattle manure addition of 50 % had mean input pH-value of 6.68, but rose to 6.78 after 33 days of digestion. This is in conformity with Abdel-Hadi (2003) finding that in co-fermentation the greater the cattle manure addition the higher the process stability, and the closer the pH value of substrate to the optimal value of 6.8-7.2.

In spite of the fact that cattle manure addition of 50 % by volume achieved process stability for anaerobic digestion of the waste at 30 days HRT, co-fermentation of the shea waste with cow-dung at 20 days HRT at the same mixture ratio showed instability. Reduction of HRT to 20 days amounted to increase in the daily digester feeding, which resulted in instability of the system. The instability in the performance may be attributed to either a partial bacteria washout or

unfavourable substrate pH and temperature for accelerated production and growth of methanogens. Generally, bacteria require suitable conditions of pH and temperature to grow optimally (Hobson and Wheatley, 1993).

With increase in the loading rate or overfeeding of the digester with raw materials, volatile fatty acids may accumulate with a concurrent drop in pH and a consequent inhibition of methane production (FAO, 1997). When the substrate was buffered with 10 g of ash per daily feed, the pH of input substrate increased from an average value of 6.74 to 7.16, stabilizing the pH of the digester content at a mean value of 6.75, compared with the average value for digester contents without ash, which is 6.51. Marchaim (1992) states that the addition of chemicals to raise the pH and to provide additional buffer capacity has the advantage of stabilizing the pH immediately, and allowing the unbalanced methanogenic populations to correct themselves more quickly.

The buffered substrate, which achieved a comparatively higher pH of digester content invariably, supported the growth and activity of the methanogens. Methanogenic bacteria are very sensitive to pH and their growth can be inhibited by acidic conditions (FAO, 1997). This study showed that co-fermentation of shea waste with cow dung is feasible at 30 days HRT and at the loading rate of 2.38 g odm/l*d. Shortening the HRT, the optimum shea waste and cow dung mixture would require a buffering agent to improve the pH of the substrate to the optimal pH range of 6.8-7.2. Shortening the HRT may also depend on temperature, as within the mesophilic range and up to 35 ^{o}C, the higher the temperature, the lower the retention time (Lagrange, 1979). If higher and uniform temperature regimes can be assured, the retention time could be lowered as metabolic activity of the

bacteria increases with temperature and organic material degrades more rapidly at higher temperatures (Hohlfeld and Sasse, 1985).

The biogas yield in the co-fermentation treatment increased immediately after the addition of the co-substrates. The starting phase lasted for about 7 days and then the biogas production stabilized. The methane content of biogas from the co-fermentation of shea waste and cow dung showed an interesting trend. As shown in Appendix B-1, the methane content in the biogas declined from 61.7 % in the starting phase to 57.3 % and began to pick up gradually to 64 %. Thereafter the methane content varied, apparently based on the temperature fluctuations. It is worthy to note that despite the initial decline, the methane content from the co-fermentation process rose higher than that of the control experiment after the 44th day up to the end of the experiment. This trend of fall and rise in methane content levels in co-fermentation of organic wastes with cattle manure appears to be peculiar with fatty substrates as is evident in the work of Amon *et al*. (2002).

Two temperature regimes were experienced (as shown in Appendix B-4) in the course of the experiment. This observation is attributed to seasonal changes in temperature. The period around day 32 was expected to be the commencement of the harmattan season as lower temperatures characterized it at early hours of the day with about 19 ^{o}C (room temperature) recorded at 7.00 a.m. From the starting phase up to day 32, the daily temperatures of the laboratory ranged from 23–29.5 ^{o}C and thereafter, the temperatures declined slightly ranging from 19–27 ^{o}C. The temperature of the effluent in the anaerobic digester ranged from 24.9-28.9 ^{o}C. The measured temperature of the digester contents was always higher than the ambient temperature by a margin of between 1.5 and 5 ^{o}C as shown in Appendix

B-5. Biogas production was influenced by the temperature regimes (Appendix B-4), more specifically by the daily temperature fluctuations within the laboratory because variations of 1 ^{o}C in a day may force the methane-producing organisms into periods of dormancy (Mattocks, 1984). General observation over the entire fermentation period of 57 days was a systematic decrease in ambient temperatures as shown in Appendix B-4. Daily ambient temperature variations recorded were between 6.5 ^{o}C and 9 ^{o}C. Its been emphasized that seasonal and diurnal temperature fluctuations significantly affect anaerobic digestion and the quantity of gas produced (Burke, 2001). Marchaim (1992) has also stressed the point that temperature variations can have adverse effects on anaerobic digestion. The results obtained agree with these references.

Methanogenic bacteria are more sensitive to changes in temperature than other organisms present in digesters (Marchaim, 1992); this was attributed to the faster growth rate of the other groups, such as the acetogens, which can achieve substantial catabolism even at low temperatures. It was also emphasized that all bacterial populations in digesters are fairly resistant to short-temperature upsets, up to about two hours, and return to normal gas production rates when the temperature is restored (Marchaim, 1992). The concern, however was that numerous and prolonged temperature drops can result in unbalanced bacteria populations, and lead to low pH problems. According to Fulford (1988), a sudden change of more than 5 ^{o}C in a day can cause methanogens to stop working temporarily; resulting in a build-up of undigested volatile acid and hence making the plant go ‘sour’.

The differences in the two temperature regimes led to differences in levels in biogas production, subsequently affecting the parameters of the gas as shown in Appendix A-10, which shows the substrate and reactor specifics of the biogas yield under the two temperature regimes in the co-fermentation of shea waste with cow dung. The difference of 1.8 ^{o}C between the mean substrate temperatures led to differences in substrate and reactor specific values as well as in methane content. It is expected that the design and construction of biogas digesters located below ground level will promote a higher and less fluctuating temperature regime to enhance the substrate and reactor specific methane yield of the process than the case in the laboratory setting.

pH is the vital determinant parameter for the biogas process and the percentage of the shea waste in the substrate-mix influenced the pH-value. The addition of cow dung improved the substrate pH in the co-fermentation. This observation is consistent with the results of Mshandete *et al*. (2004). The digester content pH was measured in the range of 6.95–7.1, and despite the initial drop in pH to 6.72, it later on began to rise. This observation is confirmed by the fact that as the digestion process continues, concentration of ammonia increases due to digestion of nitrogen resulting in increase in pH (FAO, 1997).

No literature has been found on the AD of shea waste up to date so there are no figures or values to compare with. It is interesting, however to note that the results obtained provide a connection with other substrates. The substrate and reactor specific biogas yields therefore offer considerations to compare the shea waste with other substrates as shown in Table 11.

From the comparison with other organic wastes, it is evident that shea waste has the characteristics of a good raw material for the generation of high quality methane if the AD process is handled with due diligence. Process stability in AD of the shea waste could only be achieved through co-fermentation with cow dung, whilst having in mind that the recommended maximum organic loading rate is not exceeded. To ensure stability it was also evident that the HRT must not be shorter than 30 days. Lower values obtained for the substrate and reactor specific yields from the present work were attributed to the fluctuating and lower temperature regimes under which the experiments were conducted. The average methane content of 61.4 % however, was quite appreciable.

Table 11: Substrate and reactor specific biogas yields of selected organic wastes in co-fermentation.

Source	Substrate	T	HRT	L_D	CH_4	Biogas yield	
						substrate specific	reactor specific
		^oC	d	g odm/l*d	%	l/g odm	l/l*d
1	Shea waste + cow dung	27.5	30	2.38	61.4	0.21	0.49
2	Fodder beet + cow dung	35	25	3.10	69	0.90	2.20
3	Food waste + cow dung	37	30	3.08	57.6	0.50	1.50
4	Food waste + cow dung	55	24	4.42	56.3	0.71	2.54

where source: 1 – present study; 2 – Linke (2001b); 3 – Kraschinski (1995); 4 – Oeschsner (1995).

Analysis of the effluent to determine the odm showed low level of degradation at 30 days HRT. Though, co-fermentation process under ambient conditions was stable at 30 days HRT, the HRT for shea waste digestion need to be extended beyond 30 days to guarantee the degradation of this organic substance to a high degree as proposed by Amon *et al.* (2002). This is also ascertained in the work of Steffen *et al*. (1999), where it is reported that although fat provides the highest biogas yield, it requires the highest retention times due to its poor bioavailability.

Cow dung as control

Numerous experiments have been conducted with respect to the fermentation of cow-dung. The result of the control obtained in this investigation is compared to other research work as shown in Table 12. The differences in results are attributed to different laboratory conditions. Whilst this investigation was carried out under ambient conditions, results from other researchers were obtained from studies carried out under temperature-controlled conditions. Temperature fluctuations apparently have contributed to the relatively lower values for this investigation. In temperature-controlled or less fluctuating temperature regimes it is expected that the biogas output would be improved. It is expected that the design and construction of the biogas digester located below ground will promote a higher and an even temperature regime to enhance the

substrate and reactor specific methane yields of the process than the case in the laboratory.

Table 12: Comparison on mean temperature, odm, HRT, L_D, methane and biogas yield from cow dung fermentation obtained from present study with other available results

Source	Temp.	odm	HRT	L_D	CH_4	Biogas yield	
						substrate specific	reactor specific
	^oC	%	d	g odm/l*d	%	l/g odm	l/l*d
1	30	7	32	2.40	60.8	0.30	0.72
	26	7	28	2.45	61.6	0.23	0.56
2	26	7	35	2.00	69.1	0.30	0.60
	26	7	45	1.56	70.2	0.31	0.48
3	55	5.7	24	2.34	56.4	0.25	0.57
4	27.2	6.76	30	2.38	62.7	0.12	0.28

where source: 1 – Yaldiz (1987); 2 – Shan (1992); 3 – Oeschsner (1995);
4 – present study

Digestion at 7 % odm and 30 days HRT

The 7 % odm was chosen as the optimum option for the fermentation of the subtrates for two reasons:

a. In the preparation of substrates for digestion less water is used in the 7 % odm than the 3 %. Therefore there is saving in water use at 7 % odm.

b. More biogas per organic matter input is achieved at 7 % odm than at 3 %. Production of combustible biogas is of paramount concern in this study and effort was geared toward achieving this goal.

The HRT of 30 days was chosen, for the digestion of the shea substrate at this HRT was found to be stable. It is at this minimum HRT that anaerobic process stability was achieved. The reduction of HRT to 20 days showed process stability only when the substrate was buffered with ash. Therefore to ensure high digester specific biogas production for the anaerobic digestion of shea waste for energy production, the digestion option of 7 % odm and 30 days HRT were chosen.

Fertilizer value of the slurry

This is the effluent from the outlet of the digester after the substrate is subjected to anaerobic conditions. The anaerobic digestion process converts the plant nutrients into a form that can easily be absorbed by plants (Fulford, 1998). Thy *et al.* (2003) confirmed that biodigester effluent is potentially superior to raw manure fertilizer because the anaerobic digestion process results in conversion of organic nitrogen in the manure to ionised ammonia (NH_4^+), which can be used directly by plant roots. Comparing the fertilizer value in the raw substrate to the effluent slurry from the co-fermentation of shea waste and the control, an increase in the nitrogen content was observed from the effluent in both the mixed substrate and pure cow-dung. However, the nitrogen content in the effluent from co-

fermentation was higher than in the pure cow dung (Table 13). The slurry from the anaerobic digestion process would be used as farm manure to boost crop production.

Table 13: Comparison of nutrient value of effluent obtained from present study with other available results.

No.	Source	Material	Nitrogen %	Phosphorus %	Potassium %
1	Fulford, 1998	Buffalo dung	1.01	1.11	0.92
2	Present study	Cow dung	1.75	0.34	0.39
3	Present study	SH+CD	2.19	0.29	0.71

SH- shea waste; CD- cow dung

Table 13 shows the comparison of nutrient value of effluent obtained from present study with other available results. The nutrient content from effluent from the mixed substrate of co-fermentation had the highest percentage nitrogen value. The percentage phosphorus and potassium from cow dung fermentation and from the mixed substrate however were found to be lower than that shown by Fulford (1998). The results correspond well with values from Fulford (1998), with the percentage nitrogen values being even better in the present study.

Implications of findings for the design of biogas digester

Observations made from the study show that the shea substrate in AD process possesses the potential to form scum. Scum is usually described as one of the main operational problems of anaerobic digesters (Pagilla *et al*., 1997). Scum formation has been attributed to insufficient mixing and heating, high grease content in the influent, severe temperature fluctuations, high or poorly controlled loading rates, and high concentrations of fatty acids (Lemmer and Baumann, 1988; Pagilla *et al*., 1997).

Literature shows that both HRT and temperature affect the scum-forming potential (SFP). Increasing HRT and temperature resulted in significantly lower SFP of sludge, whilst the SFP also decreased when the extent of digestion increased, due to increased temperature or HRT (Halalsheh *et al*., 2005). They showed that SFP increases with decrease in pH of the solution, and further comparing with the effects of the digestion, which showed that SFP was higher for the reactor operated at 15 days than at 75 days HRT for the same pH value. It is imperative therefore that the characteristic of the input substrate (shea waste) must be considered in the design and construction of the biogas digester.

Economic analysis

The evaluation of biogas plants does not include only the monetary cost and benefit factors, but also of the nonpecuniary and unquantified factors. The basic investment-cost factors depend on the design of the biogas plant. The cost of material for building the digester, gasholder and displacement pit constitute the biggest cost item. In Ghana, two 40 m^3 digesters, Indian-type plant cost $15,000 to

build in 1999/2000, giving about \$187.5 per m^3 digester cost (Aklaku *et al*., 2006). While the average plant has a service life of 10-15 years (Sasse, 1988), other costs may arise on a recurrent basis, for example painting the drum of a floating-drum plant and replacing it after 4-5 years. At least 3 % of the initial investment costs is assumed for maintenance and repair of the plant (Sasse, 1988).

The main benefits of a biogas plant include:

- savings attributable to less or no consumption of conventional energy for cooking and lighting,
- the excess energy potential which could be exploited commercially,
- substitution of digested slurry for chemical fertilizer with noticeable increases in crop yield, and
- savings on time if one has to look for firewood.

A biogas plant is profitable in terms of money if it yields considerable savings on conventional sources of energy like firewood, kerosene or liquefied petroleum gas (LPG).

The gross energy content of the biogas produced from the co-fermentation of shea waste with cattle manure is estimated to be 5.73 and 6.40 kWh/m^3 (1 m^3 CH_4 has calorific value of approximately 10 kWh, quoted from Sasse (1988)). From Shebu Industries processing 9000 metric tons of nuts per year, an estimated amount of 5400 metric tonnes of shea cake are generated as a by-product. This quantity of shea by-product has the potential to generate 975.2 m^3 of biogas or 598.8 m^3 of methane with a calorific value of about 5988 kWh, which is equivalent to 487.6 litres of diesel oil (Sasse, 1988) or 5.42 metric tonnes of firewood, applying that the calorific value of 1 m^3 of biogas is equivalent to 5.56

kg of firewood (Sasse, 1988). This quantity of energy would save the company of some cost in purchased energy.

The shea waste, apart from being a source of pollution to the environment, will reduce the rate of deforestation, if firewood is used as the energy source. As the annual productivity of savannah vegetation in Ghana is 6 to 12 metric tonnes of wood per hectare (Aklaku *et al*., 2006), biogas generated from shea waste would potentially save 3.4 to 6.9 hectares of savannah vegetation of the country annually.

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Introduction

This chapter summarizes the purpose of the study, the methodology used, and the results and discussion. It also presents the conclusions arrived at, and the recommendations derived from the conclusions made.

Summary

With the estimated shea nut yield of 100,000 metric tonnes per annum, and based on the current estimation of 60 % of this yield which is processed locally, it is expected that about 39,000 metric tonnes of shea waste are produced annually. In order to utilize the waste in an appropriate way and to reduce its negative impact on the environment, there is the need for research in the field of shea waste treatment. For the purpose of understanding the characteristics in performance of the shea waste and to provide the necessary input parameters towards the design of biogas plants, various process and biogas production parameters of anaerobic digestion have been investigated.

A number of experiments were performed using six horizontal reactors with a liquid volume of 74 litres in the laboratory. The reactors were equipped

with a mechanical agitator and were fed once daily. The ambient temperatures in the laboratory dictated the temperature of the substrate in the reactors. The biogas generated in the reactors was collected daily in water-sealed gasholders, with the volume of the gas determined and the quality of the gas analysed on daily basis.

Experiments on pure cow dung (cattle manure) digestion were performed among nine variables to determine the optimum levels in biogas production. Mono-fermentation of shea waste was undertaken to determine its viability as an option in waste treatment. Three experimental treatments in co-fermentation of shea waste with cow dung, in the volume ratios 50:50, 75:25 and 90:10, were performed to determine the optimum as an option in anaerobic digestion. The hydraulic retention times (HRT) of 20 and 30 days were investigated under the optimum co-fermentation treatment of 50:50 by volume. The addition of ash to raise the pH and to improve the buffer capacity of substrates was undertaken in some treatments. The final experimental series performed were the co-fermentation of shea waste with cow dung in the ratio 50:50 by volume at 7 % odm content, which were run parallel with a pure cow dung digestion as control. All experiments proceeded at ambient temperatures in the laboratory.

It was found out that mono-fermentation of shea-waste is not a viable option in anaerobic digestion. Irrespective of the volatile solids content or odm concentration of the substrates the experiments under mono-fermentation showed process instability. In all instances the experiments were terminated due to decreasing pH-values of substrate and near-zero biogas production.

Amongst the experimental treatments in co-fermentation of shea waste with cow dung, only 50:50 by volume was found to be a viable option and showed

process stability at HRT of 30 days. When the HRT was reduced to 20 days, the anaerobic digestion of the substrate of the same shea waste to cow dung ratio was unstable, whilst its counterpart which was buffered daily with 10 g ash per input substrate feeding showed process stability.

The methane content in the biogas generated from the co-fermentation of shea waste with cow dung at 30 day HRT was higher than at 20 days, meaning that at increased organic loading rate the methane content decreased. However, the average methane content in biogas from the co-fermentation of shea waste with cow dung and from digestion of pure cow dung was 61.36 % and 62.71 % respectively. The hydraulic retention time for the experiments was 30 days.

The reactor specific methane yield from the co-fermentation of shea waste with cow dung in the main experiment was 0.30 l/l*d, whilst with the fermentation of pure cow dung a value of 0.17 l/l*d was obtained. The substrate specific methane yield from the co-fermentation of shea waste with cow dung was 0.13 l/g odm, whilst that from the digestion of pure cow dung was 0.07 l/g odm.

The rate of degradation of volatile solids or odm is an indication of the digestion efficiency of the biogas process. The rate of degradation however, depends on the feedstock and the fermentation conditions. The degree of degradation at the operating ambient temperatures at 30 days HRT in the co-fermentation of shea waste with cow dung was 12.16 %, whilst that for the control was 7.74 %.

Findings of the study showed that:

a. Amongst the experimental treatments co-fermentation of shea waste with cow dung in the ratio 50:50 by volume was found to be a viable option and showed

process stability at 30 days HRT. The null hypothesis, which states that there is no option under AD for the treatment of shea waste, is therefore rejected.

b. The results of the experiments showed that the digestion potential depended on the substrate characteristics. The shea waste contained 86 % volatile solids. According to Steffen *et al.* (1999) wastes containing less than 60 % volatile solids are not considered as valuable substrates for AD. The pH of pure shea waste substrate at 7 % odm was 5.50, which proved inappropriate for AD. With the addition of cow dung, the substrate pH was increased to 6.68, which fell closer to the optimum range of 6.8 – 7.2, therefore facilitating digestion with sustainable methane production. The null hypothesis, which states that AD does not depend on the characteristics of the substrate, was therefore not valid.

c. The results have shown that production of biogas/methane vary with HRT and odm concentration of the substrate. At HRT of 30 days and varying odm concentration of substrates, biogas and methane production levels varied in cow dung fermentation as well as in mono-fermentation of shea waste. Co-fermentation of shea waste with cow dung at 7 % odm and at 20 days HRT showed process instability with unsustainable gas production, whilst at 7 % odm and 30 days HRT the AD performance was viable and stable. The results therefore indicated that the null hypothesis did not hold and was rejected.

d. The results obtained in biogas/methane yield compared favourably with the works of other researchers. The average methane content from the co-fermentation of shea waste with cattle slurry was 61.4 % with a substrate specific biogas yield of 210 l/kg odm. These values are appreciable especially when they were achieved

at a mean ambient temperature of 27.5 ^{o}C. This finding of the study was inconsistent with the null hypothesis and was rejected.

e. The quantitative and chemical composition of the biogas obtained in the main experiment was 61.4 % methane from co-fermentation of shea waste with cow dung. The mean methane content from pure cow dung as control for the experiment was 62.7 %. These values are adequate and quite acceptable as they are above the 50 % threshold for combustibility, thus making the null hypothesis invalid.

f. The results obtained showed that AD increases the fertilizer value of agricultural waste as shown in Table 9. The null hypothesis, which states that there is no difference in the nutrient value between the raw and the digested substrate, was therefore rejected.

From the findings of the study all the null hypotheses stated were not valid and therefore the alternate hypotheses were accepted in each case.

The results of the experiments showed that the digestion potential of shea waste depended on the substrate characteristics and the fermentation parameters. The reactor and substrate specific energy yield in the co-fermentation process also depended on the substrate characteristics and the fermentation parameters. To ensure process stability in anaerobic digestion of shea waste, it was observed that the buffering capacity of the process had to be improved by the addition of cow dung (cattle manure) to at least 50 % by volume of the total shea waste mix.

Conclusions

Shea waste is biodegradable organic material with high volatile solids content and has shown to have the potential to produce biogas with high methane content. Co-fermentation of shea waste with cattle manure was found to be a feasible anaerobic digestion option in the generation of methane and also in the treatment of shea waste prior to disposal in an effort to reduce its pollution potential on the environment. The production of biogas from anaerobic digestion of shea waste provides an important energy potential, which should be of value in improving the economics of shea processing.

Recommendations

From the results, findings and conclusions made it is recommended that the design and construction of the biogas digester must be located below ground level to promote a higher and an even temperature regime to enhance the substrate specific methane yield of the process than the case in the laboratory.

Further research is recommended to explore and to exploit other co-substrates and energy crops, which will boost the specific biogas yields. It is also recommended that further investigation be carried out into the nutrient value of the effluent as well as its effect on the growth rate of plants.

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APPENDICES

A-1. Average methane content in biogas from the fermentation of cow dung (mean values for the entire fermentation period ranging from 30 to 60 days)

Retention time HRT (d)	odm (%)	Mean temp. T (^{o}C)	Loading rate, L_D (g odm/l*d)	CH_4-content X (%)	Standard deviation ±S, (CH_4%)	Coef. of variation (%)	n
60	3	29.8	0.54	60.27	4.51	7.48	60
	5	29.8	0.92	60.55	4.39	7.25	62
	7	30.0	1.33	58.50	4.13	7.06	62
45	3	29.1	0.71	61.88	4.06	6.56	45
	5	29.2	1.23	59.73	5.09	8.52	48
	7	31.3	1.70	55.82	1.28	2.29	61
30	3	28.3	1.08	60.40	3.68	6.09	30
	5	32.0	1.68	58.05	1.27	2.19	43
	7	32.3	2.40	58.40	0.90	1.54	43

A-2. Average digester content pH-values for cow dung fermentation (mean values for the entire fermentation period ranging from 30 to 60 days)

Retention time HRT (d)	Organic dry mat. odm (%)	Temp. T ^{o}C	Loading rate, L_D (g odm/l*d)	Reactor pH-value X_{mean}	Standard deviation ± S (pH)	Coef. of variation (%)	n
60	3.08	29.8	0.54	6.82	0.26	3.81	60
	5.16	29.8	0.92	6.78	0.17	2.51	62
	7.32	30.0	1.33	6.81	0.14	2.06	62
45	3.11	29.1	0.71	6.80	0.25	3.68	45
	5.27	29.2	1.23	6.80	0.20	2.94	48
	7.14	31.3	1.70	6.58	0.12	1.82	61
30	3.19	28.3	1.08	6.83	0.25	3.66	30
	4.94	32.0	1.68	6.63	0.07	1.06	43
	7.00	32.3	2.40	6.58	0.12	1.82	43

A-3. Average degradation of degradation of odm in the digestion of cow dung (mean values for the entire fermentation period ranging from 30 to 60days)

Retention time HRT (d)	Organic dry mat. odm (%)	Temp. T ^{o}C	Loading rate, L_D (g odm/l*d)	Degrad. R X (%)	Standard deviation ± S (R%)	Coef. of variation (%)	n
60	7.32	30.0	1.33	7.65	3.35	43.79	6
45	7.14	31.3	1.70	5.65	2.79	49.38	6
30	7.00	32.3	2.40	4.71	2.09	44.37	4

Input substrates at odm 7 %

A-4. Average methane content in biogas from the mono-fermentation of shea waste (mean values for the entire fermentation period ranging from12 to 50 days)

Retention time HRT (d)	Organic dry mat. odm (%)	Mean temp. T (^oC)	Loading rate, L_D (g odm/l*d)	CH_4-content X (%)	Standard deviation ±S, (CH_4%)	Coef. of variation (%)	n
60	3	31.2	0.500	62.76	3.33	5.30	50
	5	31.3	0.863	61.14	2.90	4.74	50
	7	31.6	1.223	61.84	3.64	5.89	50
45	3	28.9	0.683	58.07	0.79	1.36	30
	5	28.9	1.177	55.63	1.19	2.14	30
	7	29.2	1.666	56.80	1.86	3.33	30
30	3	28.2	1.019	53.75	1.55	2.88	12
	5	28.2	1.690	53.92	2.31	4.28	12
	7	28.2	2.350	48.67	5.53	11.36	12

A-5. Average substrate specific biogas and methane yield (G_{odm} , M_{odm}) from the mono-fermentation of shea waste (mean values for the entire fermentation period ranging from 12 - 50 days)

Retention time HRT (d)	Organic dry mat. odm (%)	Mean temp. T (^{o}C)	Loading rate, L_D (g odm/l*d)	substrate spec. biogas yield, G_{odm} X (l/g odm)	substrate spec. methane yield, M_{odm} X (l/g odm)	n
60	3	31.2	0.500	0.40	0.25	50
	5	31.3	0.863	0.29	0.18	50
	7	31.6	1.223	0.35	0.22	50
45	3	28.9	0.683	0.35	0.20	30
	5	28.9	1.177	0.27	0.15	30
	7	29.2	1.666	0.23	0.13	30
30	3	28.2	1.019	0.29	0.16	12
	5	28.2	1.690	0.20	0.11	12
	7	28.2	2.350	0.10	0.05	12

A-6. Average pH-values of reactor contents during the mono-fermentation of shea waste (mean values for the entire fermentation period ranging from 12 - 50 days)

Retention time HRT (d)	Mean temp. T (^oC)	Loading rate, L_D (g odm/l*d)	Reactor pH-value X	Standard deviation ±S, (pH-value)	Coef. of variation (%)	n
60	31.2	0.500	6.28	0.23	3.66	50
	31.3	0.863	6.25	0.39	6.24	50
	31.6	1.223	6.41	0.29	4.52	50
45	28.9	0.683	6.34	0.24	3.79	30
	28.9	1.177	6.35	0.30	4.72	30
	29.2	1.666	6.23	0.36	5.78	30
30	28.2	1.019	6.61	0.14	2.12	12
	28.2	1.690	6.58	0.20	3.04	12
	28.2	2.350	6.27	0.42	6.70	12

A-7. Average methane content in biogas from co-fermentation of shea waste with cow dung (mean values from 2 replications over retention period of 17 to 33 days)

Treatment	Mean temp. T ^oC	Loading rate, L_D (g odm/l*d)	CH_4-content X (%)	Standard deviation ±S, (CH_4%)	Coef of variation (%)	n
50:50	28.4	2.279	60.88	2.10	3.45	66
75:25	28.0	2.364	51.48	4.97	9.65	50
90:10	27.8	2.353	49.88	5.62	11.27	34

A-8. Average substrate specific- biogas and methane yield (G_{odm}, M_{odm}) from the co-fermentation of shea waste with cow dung (mean values from 2 replications over retention period of 17 to 33 days) at 30 days HRT

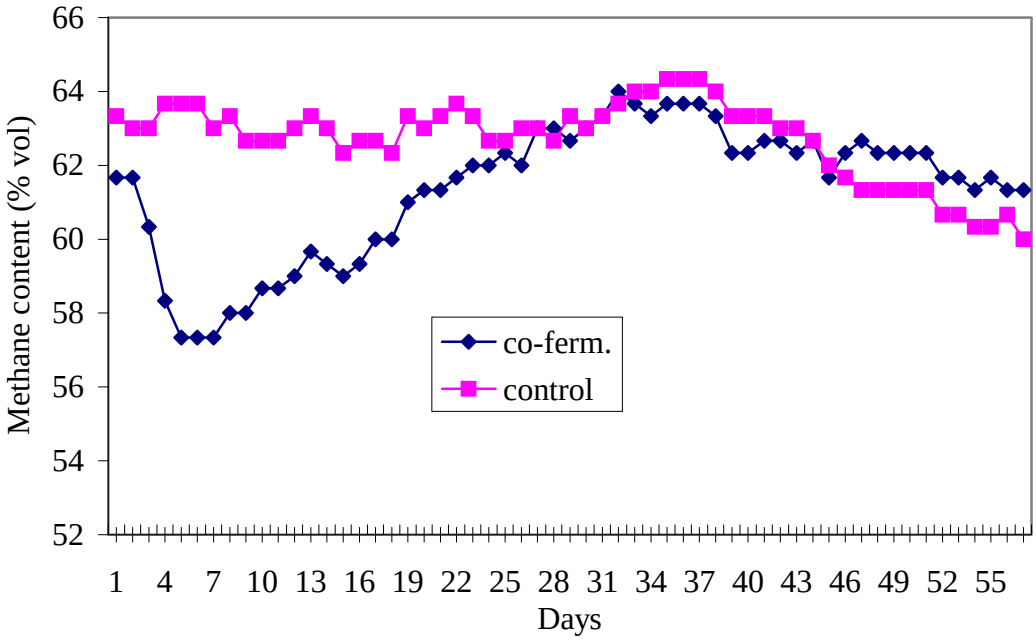
Treatment	Mean temp. T ^oC	Loading rate, L_D (g odm/l*d)	Substrate sp. biogas yield,X G_{odm} (l/g odm)	Substrate sp. methane yield X M_{odm} (l/g odm)	n
50:50	28.4	2.279	0.24	0.15	66
75:25	28.0	2.364	0.15	0.08	50
90:10	27.8	2.353	0.13	0.07	34

A-9. Average methane content in biogas from co-fermentation of shea waste with cow dung, and with and without ash (mean values from 2 replications over retention period of 27 days)

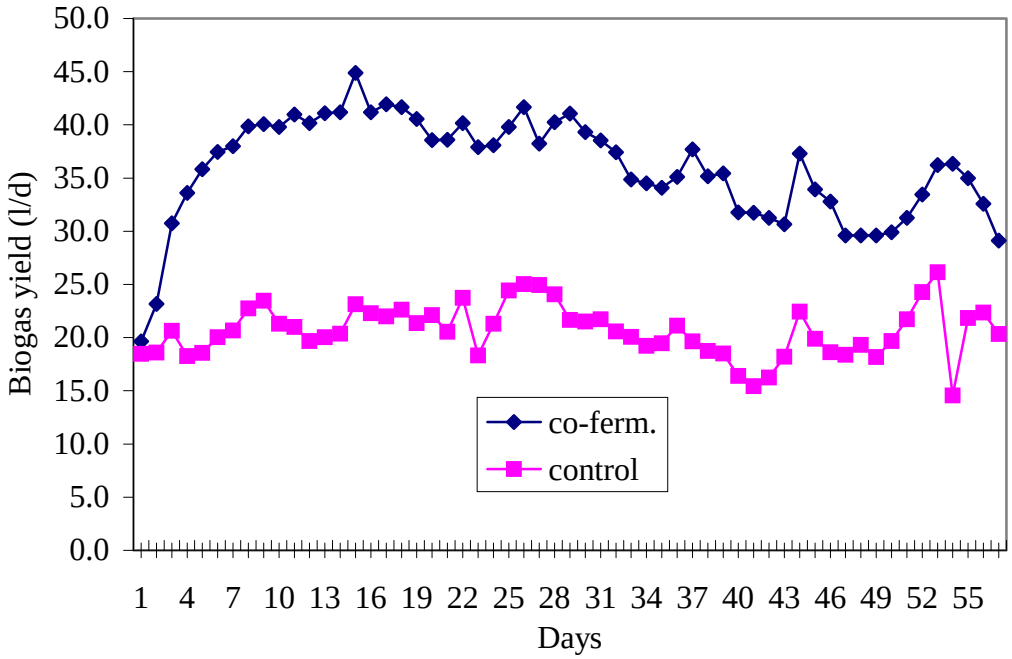
Treatment	Mean temp. T ^oC	Loading rate, L_D (g odm/l*d)	CH_4-content X (%)	Standard deviation ±S, (CH_4%)	Coef of variation (%)	n
50:50	27.0	3.651	50.91	5.10	10.02	54
50:50 + ash	26.9	3.651	54.31	3.94	7.25	54

A-10. Temperature regimes on biogas yield from co-fermentation of substrate

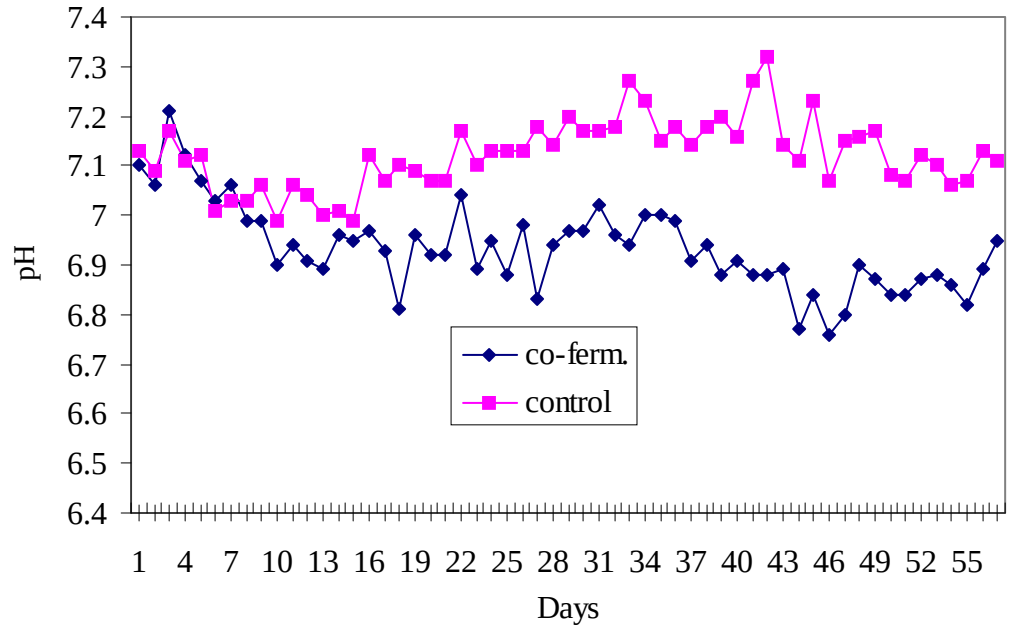
Temperature regime	T (mean) (^{o}C)	HRT (d)	L_D (g odm/l*d)	CH_4 (%)	Biogas yield Substrate specific (l/g odm)	Biogas yield reactor-specific (l/l*d)
I	28.3	30	2.39	61.0	0.23	0.54
II	26.5	30	2.31	62.4	0.19	0.45



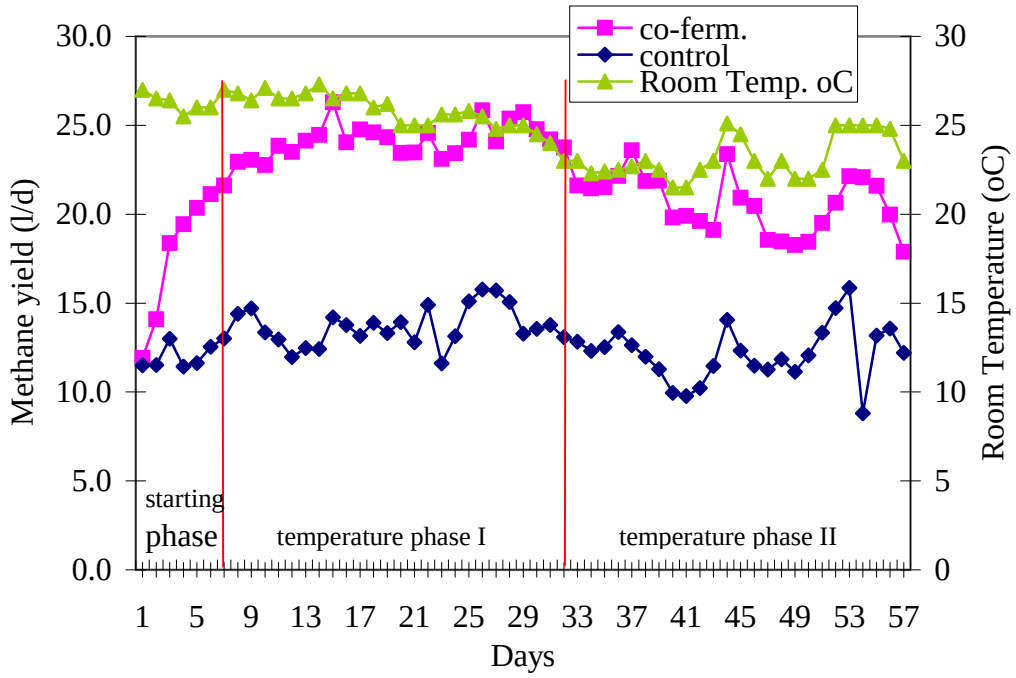
B-1: Average methane content in biogas from co-fermentation of shea waste with cow dung and the control at 30d HRT



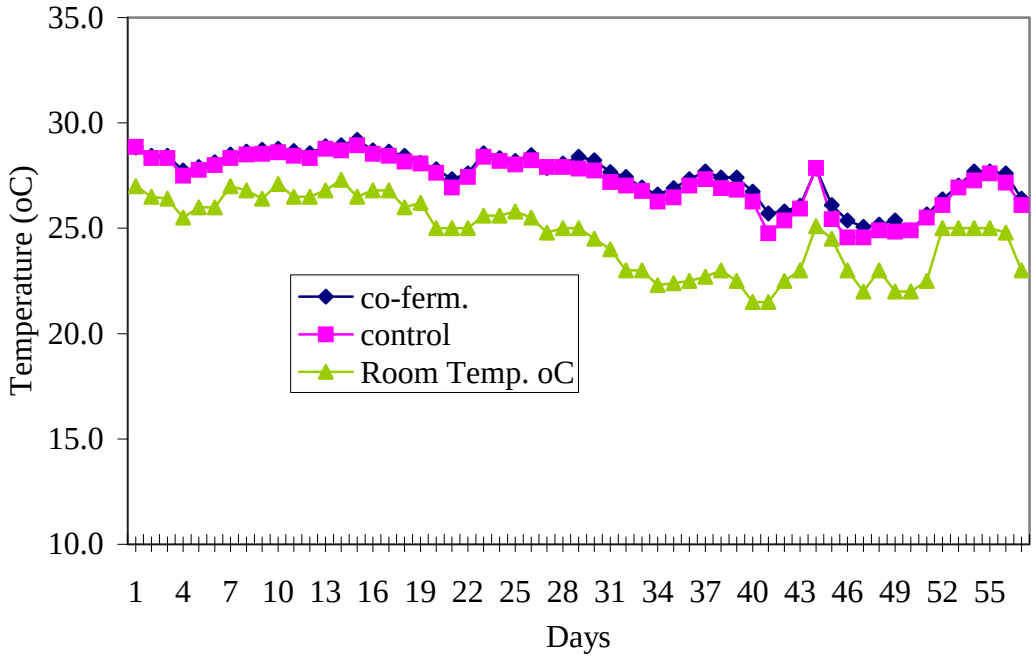
B-2: Daily biogas yield from co-fermentation of shea waste with cow dung and control



B-3: pH-values of reactor content in co-fermentation of shea waste with cow dung and the fermentation of pure cow dung as control



B-4: Effect of ambient temperature on methane production



B-5: Influence of ambient temperature on substrate temperature