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RESEARCH ON ANAEROBIC DIGESTION OF ORGANIC SOLID WASTE AT HOUSEHOLD LEVEL IN DAR ES SALAAM, TANZANIA

Bachelor Thesis

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Abstract

Rapid urbanisation and population growth have magnified the necessity for adequate solid waste management throughout the world. In order to minimise the risk to the environment and human health, economically feasible solutions are sought for the treatment of solid waste, particularly in urban areas of low- and middle-income countries.

This paper evaluates the suitability of the ARTI Compact biogas system (CBS) as a decentralised low-tech treatment option for the organic fraction of household waste in Dar es Salaam (DSM), Tanzania. A literature review about solid waste and energy management in DSM was followed by the installation and monitoring of a research CBS with the aim of obtaining precise data concerning the performance of the digester as well as quantity and quality of the biogas and effluent. The unstirred floating-dome digester (capacity 850l, pH: 6.5, Temp.: 30°C) was fed with two substrates: Food waste (FW: 24% TS, 91% VS) and market waste (MW: 10% TS, 88% VS). The daily load of 2kg waste (diluted with 18l of water) was based on literary findings and represents a realistic figure of generated waste quantity per Tanzanian household of 5 members. The reduction of waste volume (FW: TS reduction by 84.9%, MW: TS reduction by 72.8%) and organic load (FW: VS reduction by 92.2% and COD reduction by 83.1%; MW: VS reduction by 85.3% and COD reduction by 84.2%) were substantial and illustrate the effectiveness of the digester. Through the anaerobic process, the ammonia concentration (NH_4-N) was raised by 134.5% to 74.1mg/l (FW) and 206.5% to 27.9mg/l (MW), which enhances the usefulness of the effluent as an organic fertilizer. On average, the anaerobic digestion of food waste resulted in 640l (574Nl) biogas per kg VS with methane content of 56.8%. 700l (628Nl) biogas per kg VS with 66.4% CH_4 were produced from market waste (hydraulic retention time for both feedstocks: 42.5 days). Kitchen waste in DSM consists of an equal mix of these two substrates and was found out to produce approximately 200l of biogas which is sufficient for 45min of cooking on a gas stove (equivalent to 1/3 of the daily cooking time per average household). A family with 5 members can hence save 28kg of charcoal per months (23'000 TZS) which defines the amortisation period of a CBS (price 850'000 TZS) as 3 years.
An inspection tour to the 12 installed CBS at household level in DSM revealed that only 4 systems were in operation. Although the consequential efforts by ARTI-TZ resulted in an increase to 10 CBS being in operation 5 weeks later, these findings underline the importance of an adequate follow-up strategy to guarantee a high percentage of well maintained ARTI Compact biogas systems.

The final evaluation regarding the suitability of the CBS (technical, economical, environmental, socio-cultural and political, as well as safety aspects) was assessed as good. However, as the high investment cost presents the highest barrier for wide dissemination of the ARTI technology in Tanzania, economical adjustments should be taken into consideration. This study includes various recommendations regarding technical adaptations, operational enhancements, rebate system and after-sales services.

Zusammenfassung

Anhaltende Verstädterung und starkes Bevölkerungswachstum verstärken weltweit die Dringlichkeit für eine angemessene Abfallwirtschaft (Solid Waste Management). Um die Risiken für Umwelt und Gesundheit zu minimieren, werden speziell für urbane Zentren in Entwicklungsländern zunehmend alternative Lösungen zur sinnvollen Abfallbehandlung gesucht.

Die vorliegende Arbeit beurteilt die Eignung des ARTI Compact Biogas Systems als dezentrale low-tech Möglichkeit, den organischen Anteil von Haushaltsabfällen in Dar es Salaam (DSM), Tansania zu behandeln. Einer Literaturstudie über Energieverbrauch und Abfallwirtschaft in DSM folgte Installation, Betrieb und Überwachung einer ARTI Forschungsanlage. Ziel dabei war, präzise Daten zur Effizienz der Anlage zu generieren, Aussagen zur Menge und Zusammensetzung des produzierten Biogases zu ermöglichen und die Qualität des Effluents zu bestimmen. Der ungerührte, floating-dome Fermenter (Kapazität 850l, pH: 6.5, Temp: 30°C) wurde mit zwei Substraten gefüttert: Speise-Abfälle (SA: 24% TR, 91% oTR) und Markt-Abfälle (MA: 10% TR, 88% oTR). Die täglich zugeführte Abfallmenge von 2kg (verdünnt mit ca.18l Wasser) repräsentiert eine realistische Abfallmenge pro 5-köpfigen Haushalt. Die Reduktion des Abfallvolumens war beträchtlich (SA: TR-Abnahme um 84.9%, MA: TR-Abnahme um 72.8%), ebenso verdeutlicht die Reduktion des organischen Anteils (SA: oTR-Abnahme um 92.2%, CSB-Abnahme um 83.1%; MA: oTR-Abnahme um 85.3%, CSB-Abnahme um 84.2%) die Wirksamkeit der Anlage. Aufgrund der anaeroben Vergärung stieg die Ammoniumkonzentration (NH_4-N) um 134.5% auf 74.1mg/l (SA), resp. um 206.5% auf 27.9% (MA), was eine verbesserte Düngequalität aufgrund rasch verfügbarer Pflanzennährstoffe darstellt. Durchschnittlich resultierte aus der Vergärung der Speise-Abfälle 640l (574Nl) Biogas/kg oTR, bei einem Methangehalt von 56.8%. Die Vergärung der Markt-Abfälle ergab eine Menge von 700l (628Nl) Biogas/kg oTR mit einem CH_4-Anteil von 66.4%. Die Aufenthaltszeit betrug bei beiden Substraten 42.5 Tage. Ein gleichwertiges Gemisch dieser zwei Substrate ergab eine ungefähre Gasproduktion von 200l in DSM, was einer Kochdauer von 45min auf einem Gasherd entspricht. Dies wiederum entspricht 1/3 der durchschnittlichen Kochzeit eines tansanischen Haushalts pro Tag. Eine 5-köpfige Familie kann daher 28kg Holzkohle pro Monat einsparen (23'000 TZS), was eine Amortisationszeit der ARTI-Anlage (850'000 TZS = ca.550 €) von 3 Jahren ergibt.
Die Besichtigung von 12 installierten ARTI-Haushaltsanlagen in DSM deckte gravierende Unterhaltsmängel auf: Nur 4 der Anlagen waren in Betrieb. Die nachfolgenden Anstrengungen von ARTI-TZ verfehlten die angestrebte Wirkung nicht: 5 Wochen später stieg der Anteil der funktionierenden Anlagen auf 10. Trotzdem verdeutlichen diese Resultate, dass eine angemessene Nachverkaufsunterstützung unbedingt erforderlich ist.

Die Schlussbeurteilung der ARTI-CBS Eignung beinhaltet technische, ökonomische, ökologische, soziokulturelle und politische Kriterien sowie Sicherheitsaspekte und ergab ein positives Resultat. Nichtsdestotrotz sollten ökonomische Anpassungen ins Auge gefasst werden, da die hohen Investitionskosten das Haupthindernis für eine weite Verbreitung der Technologie darstellen. Die Arbeit listet abschliessend Empfehlungen auf bezüglich technischen Anpassungen, Unterhaltsbetrieb, Rabattsystem und Kundendienst.

Table of Contents

Abbreviations

AD	Anaerobic Digestion
ARTI	Appropriate Rural Technology Institute
A/TIC	Acids / Total Inorganic Carbon
CBS	Compact Biogas System
COD	Chemical Oxygen Demand
DCC	Dar es Salaam City Council
DSM	Dar es Salaam
FW	Food Waste
GPR	Gas Production Rate
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit GmbH
HH	Household
HRT	Hydraulic Retention Time
JICA	Japan International Cooperation Agency
LPG	Liquid Petroleum Gas
MSW	Municipal Solid Waste
MW	Market Waste
OLR	Organic Loading Rate
SGP	Specific Gas Production
SRT	Solid Retention Time
SW	Solid Waste
SWM	Solid Waste Management
TS	Total Solids
TZ	Tanzania
VS	Volatile Solids
WW	Wet Weight

1 Introduction

On a worldwide scale, rapid population growth and urbanisation have led to an enormous increase of solid waste generation per unit area. Particularly urban- and peri-urban areas of low- and middle-income-countries are confronted with great challenges concerning appropriate Solid Waste Management (SWM) in order to minimise the risk to human health and avoid environmental degradation. However, most municipalities struggle to provide sufficient and adequate SWM services (Kassim & Ali, 2006). Considering the fact that the largest fraction of waste in developing countries is of organic nature and therefore amendable to anaerobic digestion, it makes environmental and economic sense to survey this option (Mbuligwe & Kassenga, 2004).

1.1 General Background

Urban solid waste management in general and inadequate disposal in particular are considered to be of the most immediate and serious environmental problems in urban areas of developing countries (Zurbrügg, 2002). The present SWM systems are predominantly based on an "end of pipe" solution, i.e. collection-transport-dumping of waste with limited recycling of inorganic waste, mainly done by the informal sector. In most cities of low- and middle-income countries the physical composition of solid waste consists mostly of organic, hence biodegradable matter (Troschinetz et al., 2008), yet less than 50% of the total waste generated is collected and disposed of in sanitary manner (Parrot et al., 2008). Inadequate management like uncontrolled dumping bears several adverse consequences: It not only leads to an uglification of the living area, but also to a high risk of polluting surface and groundwater through leachate and furthermore promotes the breeding of flies, mosquitoes, rats and other disease vectors. In addition, it emits unpleasant odours and methane, a major greenhouse gas contributing to global warming (Yhdego, 1995).

Figure 1: Uncontrolled dumping in Dar es Salaam, Tanzania

Besides composting and direct animal feeding, anaerobic digestion (AD) is a promising method to treat the particular fraction of organic solid waste. While AD for the treatment of animal dung is fairly common in rural areas of developing countries, information on technical and operational feasibilities concerning the treatment of organic solid waste is limited. Regarding the enormous waste problems in the urban areas of these countries, the question arises whether AD could be an appropriate and sustainable method to treat organic household waste as well as wastes from markets and restaurants.

The ARTI Compact Biogas Plant, developed in India, is a small-scale system based on anaerobic technology that combines organic solid waste treatment with the production of cooking energy and liquid fertilizer. Already widespread in India on household (HH) level, it is now being promoted in Tanzania.

1.2 Objectives

The overall objective of this study is to assess the suitability of the ARTI Compact biogas plant as a treatment option for organic solid waste on household level in urban areas of developing countries.

The installation, operation and monitoring of an ARTI biogas plant at ARDHI University in Dar es Salaam (DSM), Tanzania, shall give precise and reliable data regarding the daily gas production and its composition, the reduction of the organic load and the quality of the effluent for different feedstock. In addition, the hazard imposed on the health of the operator through toxic substances produced by the anaerobic process is assessed as well as the risk of attracting disease vectors by the system. All these information are evaluated on the socio-cultural, economical and traditional waste management background of urban households in DSM. Interviews with users of existing ARTI biogas plants in Tanzania shall furthermore provide information concerning the convenience of operation and the economic efficiency of the system. The household survey aims to compare the results from the research plant run under controlled conditions with the performance of plants operating under real conditions in private HHs.

Combining these results with literary findings about the SWM on household level in DSM will indicate whether the ARTI-technology can be regarded as appropriate to treat organic household waste or how to devise strategies for enhancing the performance of ARTI-biogas plants.

1.3 Methodologies

- Literature review

An extensive literature review on solid waste management and energy utilization in DSM, specifically for cooking purpose, is conducted. Moreover research reports and general literature on anaerobic digestion of organic materials are reviewed.

- Installation, start-up and operation of ARTI Biogas Plant at ARDHI University DSM

The installation and start-up of a research-plant is followed by continuous measuring on site of the gas production and gas composition resulting from canteen food waste and vegetable/fruit market waste. Temperature, pH and Redox-Potential of the effluent are additionally measured on a daily basis.

- Laboratory analysis

Laboratory analyses are completed for determining various parameters of the feedstock (TS, VS, COD_{total}, $COD_{dissolved}$, N_{total}, NH_4-N, P_{total}) and effluent (TS, VS, COD_{total}, $COD_{dissolved}$, N_{total}, NH_4-N, P_{total}, PO_4, Pb, Cu, Cd) in the Laboratory of Environmental Engineering at ARDHI University DSM.

- Inspection of ARTI biogas plants in Dar es Salaam and interviews with operators

Visits to 17 ARTI biogas units in DSM are conducted to assess the performance of these plants. Additionally, interviews with the owner and operator about their experiences are accomplished.

2 Background Information

Figure 2: Map of Tanzania [1]

2.1 Tanzania

2.1.1 General facts and figures

Land area:	881.289 km^2	
Total population:	34.6 Millions (2002)	
Population growth:	2.9% (2007)	
Urban population:	23% (2007)	
Capital:	Dodoma	
Average urban household size:	4.9 persons (2000)	
Life expectancy:	52 years (2006)	
Estimated per capita income:	349 US$ (2005)	
Below basic needs poverty line:	35.7% (2000/01)	
Below food poverty line:	18.7% (2000/01)	
Unemployment rate:	12.9% (in urban higher than in rural areas)	
Total adult literacy rate:	69% (2000-2005)	
Electrification rate:	11% (2007)	
Currency:	Tanzanian Shilling (TZS)	
Exchange rate (November 2008):	1'000 TZS	= 0.987 CHF
		= 0.649 EUR
		= 0.811 US$
Main languages:	Swahili, English	
Climate:	Tropical on the coast, semi-temperate inland	
Political system:	Multiparty parliamentary democracy	

2.1.2 Dar es Salaam

Dar es Salaam (DSM) is the principal city and administrative, commercial and industrial centre in Tanzania. It is located on the eastern coast of the country along the Indian Ocean and in 2005 had a total area of 1393km^2. The whole city is politically and administratively divided into three Municipalities (Temeke, Ilala and Kinondoni). The city area is growing at a rate of 7% per year and it is estimated that roughly 70% of the population in the city live in informal or unplanned settlements (Kaseva & Mbuligwe, 2005). The estimated population of DSM is between 2.5 and 3.4 million, the population density is 1793 persons per km^2 and the average population growth rate is 4.3% per annum (Kassim & Ali, 2006).

DSM has a warm, moist monsoon climate: relatively cold and dry from April to October, hot and humid from November to March. The average annual precipitation in Dar is over 1000mm due to the long rains between March and May, when rainfall is about 150-300mm. The temperature average is 24°C, whereas the maximum temperature is 35°C in the afternoon and the minimum 13°C at dawn.

2.1.3 Solid waste management in Dar es Salaam

The rapid increase of population in Dar es Salaam, coupled with the increasing growth of commerce and trades has increased the solid waste generation at a rapid rate. SWM in DSM is administered by the three municipalities under the Dar es Salaam City Council (DCC). In 1994 the DCC acknowledged the difficulty of providing adequate SWM and hence decided to involve the private sector as a partner in SW collection services: While the private sector (community-based organisations and local companies) acts as a collector, the City Council remains as the principal and overall responsible for provision of the service (Kassim & Ali, 2006). The estimated annual budget devoted to MSW in DSM is 10million US$ (Parrot et al., 2008).

SWM in DSM at household level is generally considered to be housekeeping and thus usually falls to women and house servants as practised in many African countries (Kassim & Ali, 2006).

Solid waste generation

The total quantity of solid waste generated in Dar es Salaam City was found to be between 1800t/d (Mbuligwe & Kassenga, 2004) and 2500t/d (Kaseva & Mbuligwe, 2005). However, recent findings of the DCC estimate the total waste to be as high as 3500t/d (Oral information Mkumba, 26.11.2008). Table 1 reveals that households alone generate about 56% of this total waste.

Table 1: Solid waste generation in DSM city (Kaseva & Mbuligwe, 2005)

Waste source	*Total waste generated [t/d]*	*% of total*
Households	1360	56.1
Commercial establishments	80	3.3
Institutions	185	7.6
Markets	375	15.5
Others including industrial	425	17.5
Total	**2425**	**100**

The study on waste generation in DSM by Kaseva & Mbuligwe (2005) concluded average domestic waste generation in unplanned, low-income areas of 0.34kg/capita/day (Buguruni), 0.39kg/c/d (Kariakoo) and in planned areas 0.43kg/c/d (Upanga), 0.44 (City centre). These results are comparable to an older study conducted by Ame in 1993, which established waste generation rates for high income group of households in DSM city to be 0.45kg/c/d, for medium-income group 0.38kg/c/d and for low-income group to be 0.34kg/c/d. In 1996, JICA reported a fairly high domestic waste generation rate of 0.7kg/c/d in DSM (Kaseva & Mbuligwe, 2005). All the information found are quite in line with World Bank Standard for developing countries which is between 0.3 and 0.6kg/c/d.

Solid Waste composition on household level

The composition of household waste in DSM is similar to that of most developing countries, with organic waste (in Table 2 listed as kitchen waste, grass and wood) around 67% being the biggest component. Other authors estimated the total organic fraction of MSW in DSM city to be 71% (Mbuligwe & Kassenga, 1998) and 78% (Chaggu et al., 1998).

Table 2: Composition of household waste in DSM
(Mbuligwe & Kassenga, 2004; Source JICA, 1997)

Waste category	*Low-income [%]*	*Middle-income [%]*	*High-income [%]*	*Weighted Average [%]*
Kitchen waste	39.8	41.9	44.5	42.0
Grass and wood	15.0	30.9	19.8	25.3
Paper	3.3	3.0	3.1	3.1
Plastic	1.9	1.9	3.4	2.2
Glass	1.3	2.4	8.8	3.5
Metal	1.8	2.1	1.8	2.0
Textile	0.6	0.5	3.8	1.2
Leather and rubber	1.2	1.0	0.3	0.9
Ceramic and stone	0.4	0.3	0.5	0.4
Other waste types	34.7	16.0	14.0	19.4
Total	**100**	**100**	**100**	**100**
Moisture content	30.6	31.1	31.5	31.1

It is worth noting that differences in household waste composition among different income groups with respect to kitchen waste are negligibly small. Institutional solid waste constitutes 56-64% organic waste (Mbuligwe, 2002).

Existing Solid Waste practices

As shown in Table 3, the majority of waste generated by households in DSM city is either self-disposed close to the site where it was produced or illegally dumped in a prohibited area such as at the roadside, in open spaces or drains (Figure 3).

Figure 3: Illegally dumped waste in Dar es Salaam

Table 3: Quantities of waste disposed of [t/d] by different methods in TZ, 1997 (Mbuligwe & Kassenga, 2004)

Type of waste	*Self-disposal*	*Discharge/ Collection*	*Illegal dumping*	*Recycling*	*Total*
Household	651.3	172.9	478.1	114	1416.3
Commercial					
Restaurant	0	12.7	0	1	13.7
Guesthouse/hotel	0	1.6	0	0.2	1.8
Other	0	11.8	0	0	11.8
Institutional	2.1	8.6	0	0	10.7
Market	0	33.9	0	0	33.9
Street weeping	0	1.3	0	0	1.3
Informal sector	0	56.5	226.2	0	282.7
Total	**653.4**	**299.3**	**704.3**	**115.2**	**1772.2**

As the current disposal facility is not environmentally suitable and its capacity exhausted, the most problematic functional element of solid waste management in DSM has been identified as disposal (Mbuligwe & Kassenga, 2004).

Collection service

Managed in a top-down approach, the design and operation of SW collection in DSM shows activity at City Council and municipal level. Poor flow of information to households (HH) and low level of involvement have resulted in low participation in the scheme. In addition, due to the mismatch between the amount of waste generated and the capacity of the service providers, approximately 52% of SW generated in DSM still remains uncollected. Only 44 of 73 wards are currently covered to some extent by collection services (Kassim & Ali, 2006). Generally, the high-income and planned areas receive better services than others because of the good waste storage, payment habit and accessibility for the collection trucks (Kaseva & Mbuligwe, 2005).

Figure 4: Waste pushcart, waste truck and waste collection point in Dar es Salaam

The charge for SW collection in DSM was set by DSM City Council (DCC) according to income level. However, every municipality has its own by-laws and charges for solid waste collection. The monthly payment for the SW collection range between 200 and 3'000 TZS according to income-areas. Yet many of the contractors manage to collect less than 50% of the service charge (Kassim & Ali, 2006). A great number of HHs is reluctant to pay for a variety of reasons including: priority set, low income level and especially lack of awareness. As many HHs are not aware about their service providers and privatisation as a whole, they do not know if the service provider is from the private sector, public sector or an agent who is already paid by the City Council.

Nevertheless, it is generally acknowledged that privatisation of SW collection in DSM has brought several advantages like creating employment among DSM residents and by increasing the collection from 10% in 1994 to 40% of the total waste generated in 2001, also significantly improving the cleanliness of the city (Kaseva & Mbuligwe, 2005).

2.1.4 Energy management

Table 4: Primary energy consumption in TZ 1999 by source (Schmitz, 2007):

Energy consumption by source	*[TJ]*	*[%]*
Total energy consumption 1999	629'402	100.0
Total fossil fuels	31'903	5.1
Coal and coal products	126	0.0
Crude Oil and natural gas liquids	26'293	4.2
Others	5485	0.9
Hydroelectric	7'829	1.2
Total renewables, excluding hydroelectric	589'460	93.7
Primary solid biomass (incl. fuel wood)	589'446	93.7
Biogas and liquid biomass	14	0.0

The Census 2005 presented biomass still to be 92.1% of total primary energy supply. Domestic energy accounts to 78.8% of total nation-wide energy consumption. Nation-wide electrification is about 10% (urban 39% and rural 2%). The electricity consumption per capita in 2002 was 84kWh (Schmitz, 2007).

Table 5: Household (HH) energy sources and utilization (Mwakaje, 2007)

Type of energy used in HH sector	*% of total HH energy consumption*	*Purpose of energy used*
Biomass fuels (charcoal&firewood)	97.7	Cooking, heating, lighting
Petroleum fuels	2.0	Kerosene for lighting and cooking
Electricity	0.3	Lighting, powering the radio and in a few cases cooking
Solar, biogas, wind	0	Lighting, cooking

In 2007 the major source of energy for cooking nationwide was wood (60%) followed by charcoal (35%). In rural areas, firewood with 87% is the major source of cooking-energy. Urban areas predominantly use wood for cooking (57%) with the exception of DSM, where mainly charcoal is used (Human Development Report 2007).

The majority of homes in Dar es Salaam use more than one kind of cooking fuel. As mentioned above and presented in Table 6, charcoal is the most preferred cooking fuel in DSM, as it is considered to be a modern source, unlike firewood, agricultural residues and dung (Sanga, 2003). 470'000t of charcoal are consumed in DSM per year (Costech, 2006).

Table 6: Preferences in the use of cooking fuels in DSM in 2001 (Sanga, 2003)

Kind of fuel	*First choice [% of homes]*	*Second choice [% of homes]*	*Third choice [% of homes]*
Charcoal	69	25	3
Kerosene	25	53	5
Electrical power	4	6	17
LPG	1	2	0
Others	1	14	75

The production, distribution and sale of charcoal constitute one of the largest industries in the informal sector, offering employment and income for people in rural and urban areas. The kilns used in Tanzania have a yield of roughly 1kg of charcoal for every 6kg of wood used. Due to deforestation in the outlying areas of the city, the distance from the points of charcoal production to the city increased from 50km in the 1970s, to 200km in the nineties (Sanga, 2003), to 2000km (Costech, 2006). Daily consumption for a family of five persons is around 2.8kg. Thus the per capita consumption is approximately 0.6kg/d. Considering the average efficiency of the charcoal stoves at 20%, and the lower heating value of charcoal being equal to 30.8 MJ/kg, consumption per capita of useful energy is approximately 1.35 GJ/year (Sanga, 2003).

Currently, the price in Dar es Salaam for one bag of charcoal (60-70kg, of which only 40-50kg are usable) ranges between TZS 30'000-35'000. For an average family of 5 members, one bag lasts for approximately 2 weeks (Oral information Ndimbo 10.9.08, Mkumba 26.11.08), which adds up to an annual spending between 720'000 and 840'000 TZS for charcoal only.

2.1.5 Deforestation and Health

In 2005 the forest area in Tanzania covered 352'600km^2 which is 39.9% of the total land. Dependence on fuelwood and charcoal as listed in 2.1.4 lead to an estimated annual per capita firewood consumption of 1m^3 per year, resulting in 7kg per rural household per day (Schmitz, 2007). Hence between 1990 and 2005, 62'800km^2 of forest area have been destroyed, resulting in a nationwide average annual change of forest area of minus 1% (Human Development Report 2007). The greatest part of wood harvested is used for the production of charcoal (75%), followed by logging (12%), agricultural activities (7%) and others (6%). Only one third of all the woods consumed annually is recovered through reforestation, and thus the use of wood for charcoal production is not sustainable (Sanga, 2003). As a consequence of deforestation, erosion is leading to diminished fertility of land, which is assumed to result in a 0.5 to 1.5% reduction annually in the gross national product (Schmitz, 2007).

Smoke emissions in the households stemming from the use of firewood, dung and straw as energy for cooking on open fireplaces are showing undesirable side-effects on the health of women and children. Indoor air pollution is taken far more serious than increasing air pollution in cities (Schmitz, 2007). In Dar es Salaam, acute respiratory infections occupy second place in all doctor's appointments at 13%, right behind malaria which leads with 50% (Sanga, 2003).

2.1.6 Fertilizer demand

In 1999 Tanzania consumed 21'000t of industrial fertilizer, resulting in an intensity of 5kg per hectare cropland (Schmitz, 2007). Other sources describe the fertilizer demand for Tanzania as 1.79kg/ha. Between 1970 and 2002, fertilizer demand decreased on average and annually by 4.18% per year even with regional subsidies. Currently, the use of artificial fertilizer by smallholders in TZ can be described as "virtual absence".
The number of households in Tanzania using organic fertilizer in 2002 was 1'270'272, 26% of all crop growing households. The total area of organic fertilizer application was 2'334'188ha, 33% of total planted area. Of all organic fertilizer, 88% is farm yard manure and 12% compost (Schmitz, 2007). These facts imply that even though organic fertilizer is used by the producer, they have not been commercialised yet.

2.1.7 History of domestic biogas dissemination in Tanzania

Biogas technology was introduced in Tanzania in 1975 by the Small Industries Development Organisation (SIDO). These early biogas plants adopted the floating drum technology from India and were mainly introduced in primary and secondary schools, rural health centres and other institutions.

In 1982, the Ministry of Industries and Trade through its parastatal organisation Centre for Agriculture Mechanisation and Rural Technology (CAMARTEC) initiated a biogas development programme in the Arusha area which was supported by the German Agency for Technical Cooperation (GTZ). Under this programme, the Chinese dome biogas plant was adapted to local conditions and standardised into biogas units of 16, 30 and 50m^3. Technical Cooperation between Tanzania and Germany led in 1983 to the introduction of the Biogas Extension Service (BES) in which CAMARTEC and GTZ were in charge of implementing the project in TZ. Dissemination strategy and project structures underwent decisive changes mainly around 1990. These were chiefly a result of financial and personnel withdrawal of the GTZ from the BES and the subsequent extensive transfer of the project to the counterpart organisation (Schmitz, 2007). Between 1983 and 2005, a total of 707 biogas units have been constructed by CAMARTEC (Costech, 2003). Other institutions involved in biogas development/popularisation include MIGESADO, Tanzanian Traditional Energy Development and Environmental Organisation (TaTEDO), Evangelical Lutheran Church in Tanzania (ELCT), Ministry of Energy and Minerals (MEM) and Tanzania Commission for Science and Technology (COSTECH).

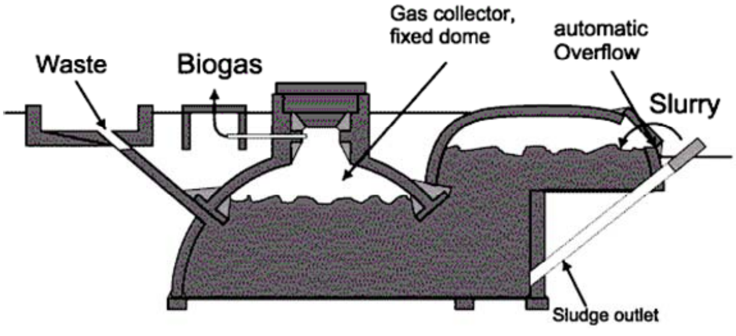

Figure 5: CAMARTEC fixed-dome plant [2]

Over the period of 1997 to 2007, some 2900 biogas installations have been reported, 120 of the floating drum design and 430 plastic bag plants. Out of these, some 1900 are expected to still be in operation (SNV, 2008).

As a consequence of the "Biogas for better life, An African Initiative" (www.biogasafrica.org), which has been initiated in May 2006 in Nairobi, Kenya, various Tanzanian biogas stakeholders launched a National Initiative in 2007 under the supervision of the Netherlands organization SNV. The objective is to further develop and disseminate domestic biogas in rural areas with the ultimate goal to establish a sustainable and commercial biogas sector in Tanzania. The Initiative aims to install 12'000 new biogas plants (modified CAMARTEC fix-dome design) during the next five years.

2.1.8 Policy and plans in regard to biogas

Tanzanian energy policies do not specifically promote biogas, as only "alternative" energy sources are broadly promoted in policy. Recently, though, the Government established the Rural Energy Agency (REA) under the Ministry of Energy and Minerals (MEM). It is the objective of REA to stimulate access to energy in rural areas, to which extent a Rural Energy Fund was established.

The National Strategy for Growth and Reduction of Poverty states that by 2010 at least 10% of the population shall be using alternative power to wood fuels for cooking (SNV, 2008).

2.2 Anaerobic Digestion

Anaerobic Digestion (AD), also referred to as biomethanization, is a natural process that takes place in the absence of oxygen. It involves the biochemical decomposition of complex organic material by various bacterial processes with the release of an energy rich biogas and the production of a nutritious effluent. Digesters or reactors are physical structures that facilitate anaerobic digestion by providing an anaerobic environment for the organisms responsible for digestion.

2.2.1 Biological process

The biological conversion of organic material under anaerobic conditions can be described by the following four stages (see Figure 6):

1 Hydrolysis
The first step involves the extracellular enzyme-mediated transformation of higher-molecular-mass organic polymers and lipids into basic structural building blocks such as fatty acids, monosaccharides, amino acids, and related compounds which are suitable for use as a source of energy and cell tissue.

2 Acidification
The fermentative bacteria degrade the soluble organic monomers of sugars and amino acids, producing volatile fatty acids (propionic, butyric and valeric acids), acetate, H_2 and CO_2. Ammonia is also produced by the degradation of amino acids.

3 Acidogenesis
Both long chain fatty acids and volatile fatty acids (VFA) are degraded generating acetate, carbon dioxide and hydrogen.

4 Methanogenesis
The forth and last step involves the bacterial conversion of hydrogen and acetic acid formed by the acid formers to methane gas and carbon dioxide. The bacteria responsible for this conversion are strict anaerobes, called methanogenic. Due to their very slow growth rates, their metabolism is usually considered rate-limiting in the anaerobic treatment of organic waste (Mata-Alvarez, 2003).

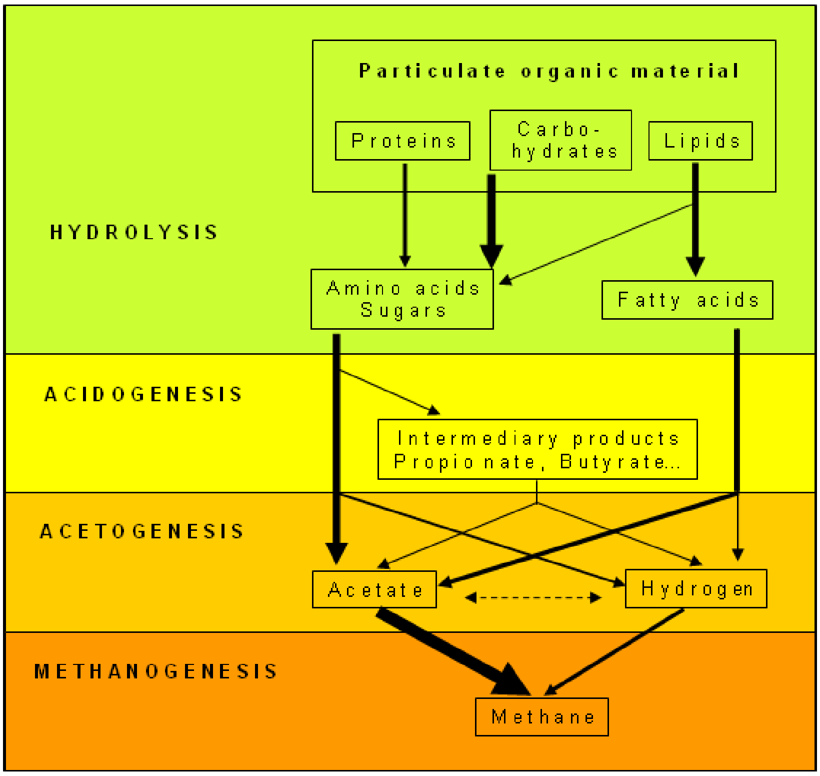

Figure 6: Scheme of the biodegradation steps of complex matter (Mata-Alvarez, 2003)

In one-stage systems, the above described reactions occur simultaneously in a single reactor, whereas in two- or multi-stage systems, the reactions take place sequentially in at least two reactors with the second stage consisting of the conversion to methane.

Another differentiation in systems is related to its dry matter content:
Wet-systems: TS<15%
Dry systems: TS=20-50%

A major danger for overall anaerobic conversions is presented when microorganism populations are not balanced. This can be a result of an overload, which is defined as either an excess of biodegradable organic matter for the active population capable of digesting it, or any circumstances that produce a decrease in active microorganism concentration (abrupt change of temperature, accumulation of toxic substances, flow rate increase etc.). These disturbances mainly affect methanogenic bacteria, whereas the much more tolerant acidogenic bacteria continue to work, producing more acids, which in return inhibit the activity of methane-formers. This imbalance can eventually result in a digester failure (Mata-Alvarez, 2003).

2.2.2 Substrates/Feedstock

In general, all types of biomass can be used as substrates as long as they contain carbohydrates, proteins, fats, cellulose and hemicellulose as main components. Lignin, the main constituent of wood can not be degraded under anaerobic conditions (Mata-Alvarez, 2003). The performance of digesters operating on solid wastes is dependent on the particle size of the influent. Therefore, size reduction of the particles and the resulting increase of the available specific surface, represents an option for increasing degradation yields and accelerating the digestion process (Mata-Alvarez, 2003).

Table 7: The maximum gas yield per kg VS of different organic waste substrates (+cow manure) found in literature.

Substrate	*TS [%]*	*VS [%]*	*Retention time [days]*	*Biogas yield [m^3/kg VS]*	*Source*
Spent fruits	25-45	90-95		0.4-0.7	Deublein
Vegetable wastes	5-20	76-90	8-20	0.4	“
Market wastes	8-20	75-90	30	0.4-0.6	“
Leftovers (Canteen)	9-37	75-98		0.4-1.0	“
Bio waste (HH)	40-75	30-70	27	0.3-1.0	“
Overstored Food	14-18	81-97	10-40	0.2-0.5	“
Fruit wastes				0.2-0.7	Gunaseelan
Banana peels		86-94		0.2	“
Citrus waste		89-97		0.4-0.5	“
Vegetable wastes				0.2-0.3	“
Mixed food waste (Korea)	26	90-95		0.3-0.5	Lee et al.
Bio waste	60-75	50-70		0.2-0.6	Eder&Schulz
Kitchen waste	9-37	50-70		0.2-0.5	“
Market waste	28-45	50-80		0.45	“
Liquid manure from cattle	6-11	68-85		0.35-0.55	Schilling& Tijmensen
Excreta from cattle (fresh)	25-30	80		0.6-0.8	Deublein

2.2.3 Biogas

Biogas consists primarily of utilizable methane (CH_4) and inert carbon dioxide (CO_2), which are both colourless and odourless. It also contains several impurities as listed in Table 8. Biogas with methane content higher than 45% is combustible and burns with a blue flame. The explosive limits of CH_4 in air are 6 to 12% by volume (Deublein, 2008).

Table 8: Typical biogas components from organic fraction of MSW (Mata-Alvarez, 2003)

Components	*Concentration (by volume)*
Methane (CH_4)	55-60%
Carbon dioxide (CO_2)	35-40%
Water	2% (20°C) – 7% (40°C)
Hydrogen Sulphide (H_2S)	20-20’000ppm (2%)
Ammonia (NH_3)	0-0.05%
Nitrogen (N_2)	0-2%
Oxygen (O_2)	0-2%
Hydrogen (H_2)	0-1%

Table 9: General features of biogas (Deublein, 2008)

Energy content	6.0 – 6.5 kWh/m^3
Fuel equivalent	0.60 – 0.65L oil/m^3 biogas
Explosion limits	6 -12% biogas in air
Ignition temperature	650 -750°C
Theoretical air demand	5.7m^3 air/m^3 burning gas
Critical pressure	75-89bar
Critical temperature	-82.5°C
Normal density	1.2kg/m^3
Molar mass	16.043g/mol
Smell	Bad eggs (the smell of desulfurized biogas is hardly noticeable)

Use of biogas

Biogas can principally be used like other fuel gas. For domestic purposes it is most suitable for cooking, heating water and lighting. The following are some approximate quantities of gas for these different uses (Koottatep et al., year unknown):

- Domestic cooking: 2m^3 per day for a family of five or six people
- Water heating: 3m^3 per day for a 100-litre tank or 0.6m^3 for a tub bath and 0.35m^3 for a shower bath
- Lighting: 0.1-150m^3 per hour per light

The gas demand can be defined on the basis of energy consumed previously. For example, 1kg firewood corresponds to 200l biogas, 1kg dried cow dung corresponds to 100l biogas and 1kg charcoal corresponds to 500l biogas. The gas demand can also be defined using the daily cooking times. The gas consumption per person and meal lies between 150 and 300l biogas. For one litre water to be cooked 30-40l biogas are required, for 1/2kg rice 120-140l and for 1/2kg vegetables 160-190l. (Kossmann et al., year unknown).

The critical temperature of methane is around -82.5°C; even with very high pressure it is not possible to liquefy methane at higher temperature, which is probably the most important bottleneck of biogas utilization. As a consequence, biogas cannot be stored over long periods at reasonable costs, but has to be used immediately or within a few hours (Mata-Alvarez, 2003). On a larger scale, biogas can be converted into electricity. Thus this solution needs a gas storage capacity of about half a day to store the night production and requires the cleaning of gas.

Hydrogen sulphide

Hydrogen sulphide (H_2S) is an aggressive gas mainly responsible for corrosion. As shown in Table 10, H_2S is already hazardous to human health in small quantities.

Table 10: Effects of H2S (adopted from Eder & Schulz, 2006)

Concentration in the air in ppm (parts per million) 1ppm=0.0001%	*Effects*
0.03-0.15	Threshold of perception, Odour of rotten eggs
15-75	Irritation of eyes and respiratory passages, nausea, vomiting, headache, unconsciousness
150-330	Paralysation of olfactory nerves
>375	Death through intoxication (after several hours)
>750	Unconsciousness and death through still stand of breathing in 30-40 minutes
>1000	Rapid death through respiratory paralysis in few minutes

The hydrogen sulphide content in the biogas is subject to considerable unexplainable variation in the course of the day (Deublein, 2007). In general, gas cleaning for combustion in burners is only necessary at a H_2S content of more than 0.1% (1'000ppm) (Mata-Alvarez, 2003)

Water vapour

Water vapour creates condensation in the tubing. To prevent blocking and corrosion, it has to be condensed in water traps, especially when higher amounts of corrosive components, such as CO_2 and H_2S are dissolved, making the gas more aggressive.

2.2.4 Effluent

Due to the decomposition and breakdown of its organic content, the residue of the biomethanization process, also called slurry, normally gets rid of smell and provides fast-acting nutrients (mainly NH_4-N) which easily enter into the soil solution, thus becoming immediately available to the plants. Hence digested sludge can increase agricultural yields according to its nutrients.

The pathogenic organisms present in the digesters raw influent (or inoculum) from animal faeces get eliminated during the mesophilic digester process at 35°C. Tests showed a complete elimination after 3 months of all harmful pathogens like Enteric virus, Salmonella, Shigellas, Vibrio Cholera, Pathogenic Escheria coli, Trichuris and Hookworms (Costech, 2006). Even more important for agricultural use is the fact that all plant-pathogenic germs are completely destroyed during the anaerobic digestion process (Wellinger et al., 1991).

2.3 ARTI Compact Biogas System

The ARTI Compact biogas system (CBS) was developed in 2003 by Appropriate Rural Technology Institute (ARTI) India, an NGO based in Pune (Maharashtra state, South India) and founded in 1996 by a group of scientists, technologists and social workers. About 2500 ARTI-plants are currently in use both in urban and rural households in Maharashtra (Müller, 2007). The design and development of this technology using organic waste rather than manure as feedstock has won the 'Ashden Award for Sustainable Energy 2006' in the food security category [3].

2.3.1 ARTI-TZ

Appropriate Rural Technology Institute Tanzania (ARTI-TZ) is a Tanzanian registered non-political, non-profit organization founded in 2007. Its mission is to serve Tanzania as an instrument of development through the dissemination and application of scientific knowledge and sustainable technologies for energy production, environmental protection, employment and income generating opportunities.
ARTI-TZ derives its technologies from ARTI-India under a technology transfer agreement. It provides promotion and training of the ARTI Compact biogas plant, a charcoal kiln for producing briquettes made from agricultural waste and the ARTI Sarai Cooker Systems for reduced Indoor Air Pollution and charcoal consumption.

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Contact: arti.tanzania@gmail.com
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+255 (0) 713 234 604 (Joy Desai, Operation Director)

JET (Joint Environmental Techniques) was founded in 2008 to manufacture, sell and install the products of ARTI-TZ as well as provide technical support.

2.3.2 Design and Technology of ARTI Compact Biogas System

The ARTI Compact biogas system (CBS) is made from two cut-down standard high density polyethylene (HDPE) water tanks and standard plumber piping. The larger tank acts as the digester while the smaller one is inverted and telescoped into the digester and serves as a floating gas holder, which raises proportional to the produced gas and acts as a store room of the biogas. The CBS is designed for treating 1-2kg (dry weight) of kitchen waste per day [4]. The gas can directly be used for cooking on an adjustable gas stove whereas the liquid effluent can be applied as nutrient fertilizer in the garden. Space of about 2 m^2 and 2.5 m height is needed for a CBS of 1000l.

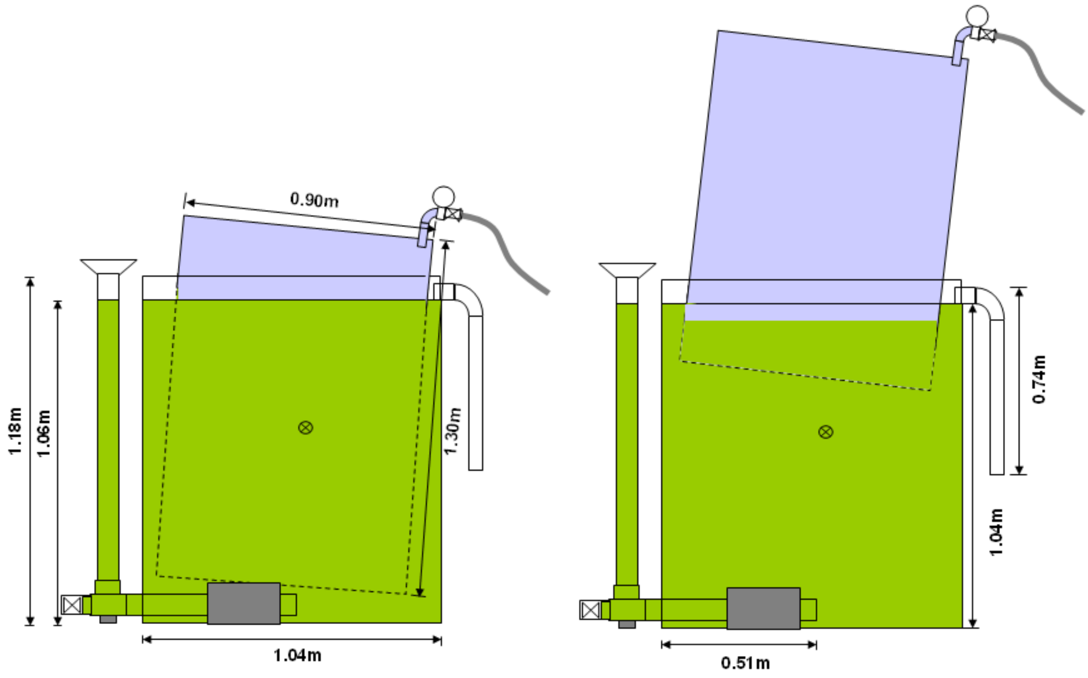

Figure 7: ARTI Compact biogas plant scheme (gasholder empty and gas-filled)

The effective volume of the digester is approximately 850l, given by the dimension of the 1000l-water tank (inner radius: 51.5cm) and the position of the overflow-pipe (1.04 m above ground level). The total surface area of the digester (0.83m^2) is covered by roughly 0.65m^2 (78%), in other words the gas released through 22% of the digester surface is lost to the atmosphere without utilization. The usable gas volume of the 750l-gasholder is 400l (see Figure 14**Error! Reference source not found.**).

The Hydraulic Retention Time (HRT) suggested by ARTI-TZ, which describes the ratio of the reactor volume (0.85m^3) to the flow rate of the influent substrate (0.02m^3/day), is 42.5 days. The seemingly rather long period of time that digester liquid spends in the reactor is justified by the appearances of sinking and floating layers.

2.3.3 Dissemination and costs

Since ARTI-TZ started disseminating CBS in November 2006 until November 2008, 31 ARTI Compact biogas units have been installed in Tanzania and Uganda (Table 11).

Table 11: ARTI-CBS installed by 30 November 2008

Country	*Digester size*	*Quantity*	*Location*	*Level*
Tanzania	1.0m3	10	9 in DSM, 1 in Mbeya	Household
	1.5m3	1	Kyela	Household
	2.0m3	3	DSM	Household
	3.0m3	2	Saadani (Safari Lodge), Mbagala (Kinasi Lodge)	Institutional
	2.0m3	4	2 on Mafia Island (Kinasi Lodge) 2 in DSM (army campus)	Institutional
	3.0m3	3	DSM (Azania Secondary School)	Institutional
	4.0m3	1	DSM (Bethsaida Sec. School)	Institutional
	1.0m3	1	DSM (ARTI-office)	Demonstration
	1.0m3	1	DSM (ARDHI-university)	Research
Uganda	2.5m3 5.0m3	2 1	Kitende (St.Mary's Sec. School)	Institutional
	1.0m3	2	Kampala (JET-office, ARTI-office)	Demonstration

Table 12: Costs of the ARTI-biogas plants (November 2008)

Size of digester [l]	*Size of Gasholder [l]*	*Price [TZS]*	*Price [EUR]*
1000	750	850'000	550
1500	1000	1'100'000	715
2500	2000	1'500'000	975
4000	3000	1'850'000	1200

It is worth noting that ARTI-TZ ceases to recommend the 1000l-digester (with 750l gasholder) as ideal household plant and will in the near future advise customers to purchase the larger model consisting of a 1500l-digester and 1000l-gasholder (oral information Potnis, 18.10.08).

3 Materials and Methods

3.1 Research-plant at ARDHI University

To conduct a detailed monitoring of the ARTI system, an ARTI Compact biogas plant was installed and operated on the campus of ARDHI University. This allowed great flexibility in terms of substrate changes and on-site measurements of the gas production and composition. The analyses were accomplished in the nearby Environmental Engineering Laboratory of ARDHI University.

3.1.1 Installation

The installation of the ARTI Compact biogas system (digester size: 1000l, gasholder: 750l) was carried out on 30 July 2008 by an ARTI-Technician at the waste water treatment experiment-site of ARDHI-University (Figure 8). The fenced and guarded location was chosen due to security consideration and good accessibility of water. To guarantee direct sunlight (7.5h from 9:00 to 16:30) and hence high temperature inside the digester, three medium-sized trees surrounding the digester had to be cut down previous to the installation. The digester was put on a wooden pallet.

Figure 8: Experimental site

Table 13: List of materials and prices used for the installation of ARTI plant

Pieces	Product	Price [TZS]	Price [Euro]
1	HDPE (High-density polyethylene) Water tank 1000l (Simtank): Ø1.04m, height 1.25m	152'000	98.6
1	HDPE-watertank 750l (Simtank) Ø1.30m, height 0.90m	110'000	71.4
1	T-Connector 3"	3500	2.3
1	Male Socket 3"	4500	2.9
1	Female Socket 3"	4500	2.9
1	Male Socket 2"	3000	1.9
1	Bucknut 2"	1800	1.2
1	Elbow 2"	1500	1.0
1	Tank Connector ¾"	3500	2.3
1	Bush ¾" * ½"	600	0.4
1	Nipple ½"	600	0.4
1	Elbow ½"	500	0.3
1	Cock ½"	2000	1.3
2	Solid Tape	2000	1.3
2	Tangit Clue	3000	1.9
1	2-Component Epoxy (M-Seal)	3000	1.9
1	Pipe 3" (length 180 cm) [6m = 12'000 TZS]	4000	2.6
1	Pipe 2" (length 100 cm) [6m = 10'500 TZS]	2000	1.3
1	Hose (5m)	5000	3.2
1	Gasstove	50'000	32.5
	Labor	100'000	64.9
	Total	**457'000**	**295.6**

The following additional parts were used exclusively for the research plant:
1 PVC plug 2”, 1 PVC Socket 3” * 2”, 1 Ball Valve 2”, 1 Tank Connector ¾”, 1 Bucknut ¾” * ½“, 1 PVC Cock ½, 1 manometer (0-60mbar) to measure the gas pressure inside the digester.

Procedure

A detailed description of the installation procedure together with a photo-documentation is attached in Appendix B2. A DVD produced by ARTI-India includes a visual “do-it-yourself” instruction and can be ordered from ARTI-India. The whole installation including the inoculation of the ARDHI plant was carried out by one person and was completed within 3.5 hours.

Inoculum and start-up

60kg of dried cow dung (TS: 23%, VS: 74%) were gradually mixed by hand with water in 25l buckets and straw material was removed (Figure 9). The homogenous mass was then poured into the digester. Approximately 300l of effluent (pH: 6.38, Redox-Potential: -238mV, TS: 0.12%, VS: 12%, COD: 842mg/l) from the existing plant at ARTI-office was added to the digester and served as part of the inoculum. This effluent had previously been enriched with a special powder-mix, which includes flour and yeast bacteria. According to the ARTI director, this step is done to create a secret about the start-up and prevents users from doing the installation without support of ARTI-TZ (Oral information Potnis, 6.8.08). Following the installation and inoculation, the digester was left without feeding for 10 days, in which the change in gas composition was recorded and the gas released on a daily basis.

Figure 9: Preparing of cow dung

3.1.2 Feedstock and feeding plan

Organic household waste in DSM mainly consists of kitchen waste, which can be divided into food leftovers and peelings or pieces of vegetables and fruits. It was therefore decided to test two different substrates in the research plant, both representing typical parts of household kitchen waste: Food waste (FW) and waste from the vegetable/fruit market (MW).

Figure 10: Food waste (FW, left) and market waste (MW, right)

The food remains were collected from the student's canteen at ARDHI-University. These leftovers consisted of stiff maize porridge (*Ugali*), rice, vegetable (beans and spinach), potato chips, pieces of meat with sauce and fish residue (Figure 10). Orange and banana peelings were also merged into the food remains. Soda caps, tooth picks and meat bones were frequently among the food waste and had to be removed.

Fruit- and vegetable waste was obtained from Mwenge market. Its composition was spoiled fruits (papaya, orange, banana, avocado, pineapple, passion fruit), spoiled vegetables (tomato, eggplant, pepperoni, carrot, potato, cucumber, onion, spinach, plantain, okra, broccoli) and vegetable peelings (cabbage, bean, cassava) (Figure 10). All wastes were stored in closed buckets and used within a maximum of 4 days.

Pre-treatment and dilution of feedstock

The objective of pre-treatment is to reduce the size of substrate particles in order to meet the basic requirement of fitting into the 3"- inlet-pipe. In addition, increasing the surface of the feedstock allows better digestion for the bacteria responsible for the hydrolysis. The pieces of both substrates were treated previous to the feeding to attain a particle size of less than 1cm.

Figure 11: Food waste raw, mashed, minced (left to right)

Figure 11 shows that pre-treatment of food waste was only needed for the meat, fish and fruit pieces. They were either cut up with a kitchen knife or minced with a manual meat-mincer. The large quantity and fibrous texture of the market waste, combined with the small size of the meat-mincer and the repeated bluntness of its knives, resulted in a low convenience for the operator. As a consequence, the fruit and vegetable waste were cut up manually and then prepared with an electric kitchen blender (Philips, HR2810/A, 400W) (Figure 12).

Figure 12: Market waste raw, manually cut, blended and diluted (left to right)

Feeding plan

The experimental design in terms of feeding was divided into three phases (Table 14):

- Phase 1: Start-up

The quantity of feedstock during the start-up period (first week) was continuously increased by 150g per feed until 1kg in the morning and 1kg in the evening was reached. Afterwards, canteen waste was fed for two weeks (2kg per day), according to the instructions of ARTI-TZ: The chopped feedstock (1kg twice a day) was given into the inlet pipe through a funnel (made of a cut-up 6l water bottle and a piece of pipe) and subsequently flushed with 10l of water. The effluent (10l) landed in the overflow bucket, which was emptied daily.

→ Aim of phase 1: Getting to know the system and finding adjustments of the feeding procedure to enhance the digestion process.

- Phase 2: Feeding strategy

The following minor adjustments of the feeding method were consequently applied when first feeding 2kg of canteen waste per day and afterwards 2kg of market waste: The cut up feedstock was mixed previous to the feeding by giving it into a bucket and filling it up to the 10l mark with water (stored in a container next to the digester to guarantee equal temperatures). The well stirred diluted feedstock was then poured as influent through the inlet-pipe to minimise the risk of blocking. The effluent in the overflow bucket was two to three times fed back for flushing the inlet pipe (20-30l), hereby mixing the bacteria of the effluent with the fresh influent. The amount of 2kg per day was chosen as it represents a realistic quantity of organic waste produced by an average household in Dar es Salaam (see 2.1.3).

→ Aim of phase 2: Obtaining and comparing the influent, gas production/composition and effluent over a period of constant feeding (reaching steady state conditions) for both substrates.

- Phase 3: Maximum load

After a break of one week, the feeding load of both substrates was increased up to 5kg/day to observe if the operational, biological or chemical-physical limit was reached.

→ Aim of phase 3: Testing the capacity of the system given by its size, construction or biology involved.

To attain comparable results, the time of feeding and measuring was attempted to be around 8:30 and 17:00 each day.

Table 14: Feeding plan of the ARTI research biogas plant at ARDHI University

Week	*Month*	*Phase*	*Topic/feedstock*	*Amount per feed [kg]*	*Total daily feed [kg/d]*	*Water/feed [l]*
31	July	Phase 1	installation & start-up			
32	August		start-up			
33			foodwaste	0.15 - 1.0	0.3 - 2.0	ca.9
34				1.0	2.0	
35						
36	September	Phase 2				
37				0.5	1.0	
38			marketwaste	0.5	1.0	ca.9
39				1.0	2.0	
40	October					
41			pause			
42		Phase 3	marketwaste (max)	0.5 - 1.5	1.0 - 3.0	ca.8
43				2.0 - 2.5	4.0 - 5.0	
44	November		foodwaste (max)	0.5 - 1.0	1.0 - 2.0	ca.8
45				1.5 - 2.0	3.0 - 4.0	
46				2.0 - 2.5	4.0 - 5.0	
47						
48		gasholder removal: examining sludge, stratification and exact digester volume				

Analyzed feedstock parameters

Table 15 presents the analysed parameters of the influent. The objectives of these analyses were to characterize the raw feedstock and diluted feedstock (influent) respectively and to compare these results afterwards with those of the effluent. This consequently allowed an evaluation regarding the efficiency of the AD process.

Table 15: Analysed feedstock parameters (TS, VS) and diluted influent parameters (all)

Parameter	*Explanation/ Relevance*	*Method & Instruments*	*Frequency (Phase 2)*
Total Solids (TS)	Residue upon water evaporation after 48 hours drying at 105°C represents the total solids and presents a raw estimation of all the organic and inorganic matter content in the original sample.	Oven (Toschnival) Precision Scale (Satorius 2355)	Twice per week
Total Volatile Solids (VS)	The fraction of solid matter that can be oxidised and driven off as gas at 550°C for 2 hours (constant weight) is an approximation of the organic fraction of the dry matter determined at 105°C (TS). The residue is the inert (mineral) fraction, mainly due to inorganic matter.	Muffel-Furnace (Vecstar, LF3) Precision Scale (Satorius 2355)	Twice per week
Total Chemical Oxygen Demand (CODtotal)	The oxygen equivalent of the organic matter that can be oxidised. CODtotal is a measure of all the organic matter in the sample.	Closed Reflux-Method Photospectrometer (Hach DR/2010)	Twice per week
Dissolved Chemical Oxygen Demand (CODdissolved)	The CODdissolved shows the amount of quickly digestible feedstock in the sample.	Closed Reflux-Method (Vacuum pump, membrane filter) Photospectrometer (Hach DR/2010)	Twice per week
Ammonium-Nitrogen (NH_4-N)	Anaerobic digestion of N-containing compounds release NH_4^+, which is used by the bacteria as their source of nitrogen. Optimal NH_4-N concentration in digester: <1000mg/l	Nessler Method (Filter paper) Photospectrometer (Hach DR/2010)	Twice per week

Total Nitrogen TKN (Ntot)	Essential nutrient to growth of organisms. Organic nitrogen and ammonia are together referred to as Kjeldahl nitrogen.	Semi-Micro-Kjeldahl Method (conducted by DSM University)	3 times per feedstock
Total Phosphorus (Ptot)	Essential nutrient to growth of organisms, include orthophosphates and organically bound phosphates.	Acid Persulfate-Digestion Method Photospectrometer (Hach DR/2010)	3 times per feedstock

The three samples per feedstock for Total Nitrogen analyses were stored in the fridge and lateron brought to the laboratory of DSM University. The pH value and Temperature of the diluted feedstock were measured sporadically (Hach-Lange Sension156). For detailed methodology description see Appendix A1.

3.1.3 Monitoring of digester activity

In order to monitor the biological performance of the different layers inside the unstirred digester, three sampling sources were chosen (Figure 13): At the height of the inlet pipe on the bottom of the digester (low), on medium height (middle: 0.62m above the ground) and at the height of the overflow pipe (high). Each time before feeding, 5l of digester liquid were released through the ball valve on the bottom to analyze the pH and temperature (low). The same was done with 1l off the tap at medium height (middle, each afternoon the Redox-Potential was additionally measured here) and afterwards the pH and Temperature were also analysed by dipping the electrode into the digester surface (high).

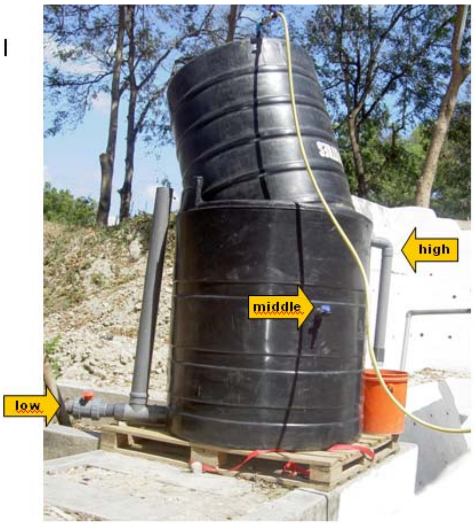

Figure 13: Sampling points

3.1.4 Gas measurements

The gas produced in the digester of the research plant at ARDHI University was released without utilization.

Gas production

Different methods were taken into consideration to measure the daily gas production (Liquid displacement, rocking displacement gasmeter, gasometer, flow-meter, Appendix C1 & C2). However, all of them require fixation of the floating drum and hence alter the system as a whole, e.g. the counter pressure caused by the attached instrument leads to a significant reduction of digester liquid before it is overcome. Liquid displacement was not suitable as it only represents the gas production over a short period of time and is therefore rather applicable for lab-scale reactors with batch-feeding. The extremely low gas production rate per time, which resulted in low flow rates was the main obstacle for flow-meter, rocking displacement gasmeter and gasometer. The gasometer (Schlumberger) for example requires a minimum flow rate or permanent gas production of 16l/h, which was not reached.

After numerous experiments, it was decided to apply a scaling on the gasholder. Hence the biogas produced was stored in the closed gasholder until the drum was lifted to maximal extent. Controlled by the Gasometer, 20l of gas was released. The tap was then closed and a white line drawn on the gasholder just above the surface of the digester liquid, using a Tipp-Ex marker. This procedure was repeated until all biogas (400l) was released. The scaling was controlled by calculation (Figure 14).

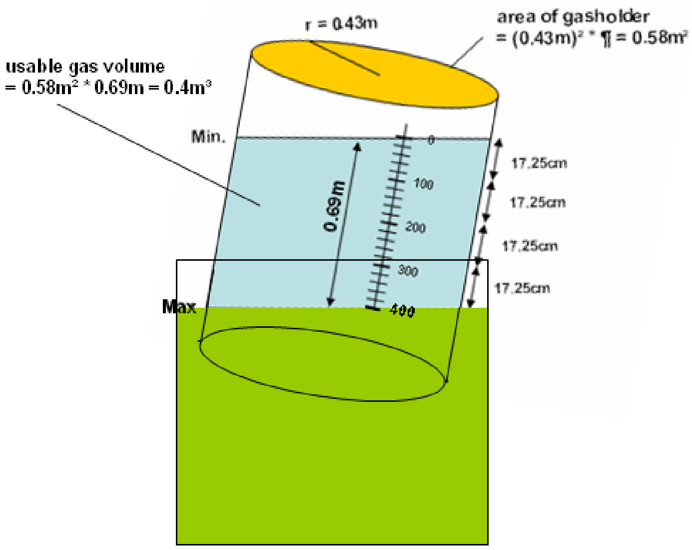

Figure 14: Scaling on gasholder

Starting on 17 August 2008, the amount of gas in the gasholder was recorded daily in the morning and afternoon before feeding.

Figure 15: Continuous rising of gasholder proportional to gas production

Gas composition

The Dräger X-am 7000 was used to measure the volume percentage of methane (CH_4), carbon dioxide (CO_2) and oxygen (O_2) in the biogas. Integrated sensors further reveal the content of hydrogen sulphide (H_2S) in the range of 0 – 100ppm and of ammonia (NH_3) between 0 and 200ppm. The gas composition was measured on a daily basis throughout phase 1 to 3 in the afternoon (before feeding) while releasing the gas.

3.1.5 Effluent

Table 16 presents the effluent parameters, explains their relevance and lists the method and frequency of analyses.

Table 16: Analyzed effluent parameters

Parameter	*Explanation / Relevance*	*Method & means*	*Frequency (Phase 2)*
pH	Indicates intensity of acidic or basic character of the solution at a given temp. Optimal pH-range for one-stage digester: 6.5-7.5	Sension 156 (Hach-Lange)	Daily before feeding (low,middle,high)
Temperature	Measure of the average kinetic energy of atoms or molecules. Optimal temp.-range for mesophilic bacteria: 35°C	Sension 156 (Hach-Lange)	Daily before feeding (low,middle,high)
Redox-Potential	Measure of the affinity of a substance for electrons. Optimal Redox-Potential for CH_4-production: <330mV	Sension 156 (Hach-Lange)	Daily before feeding in afternoon (middle)
Total Solids (TS)	See 3.1.2	See 3.1.2	Twice per week
Total Volatile Solids (VS)	See 3.1.2	See 3.1.2	Twice per week
Total Chemical Oxygen Demand (CODtotal)	See 3.1.2	See 3.1.2	Twice per week
Dissolved Chemical Oxygen Demand (CODdissolved)	See 3.1.2	See 3.1.2	Twice per week
Volatile Fatty Acids (VFA)	Fatty acids with a carbon chain of six carbons or fewer are produced in the first stage of the anaerobic digestion process. Inhibiting concentration: >3000mg/l (Eder &Schulz)	Nordmann-Titration (Phase 2&3) Kapp-Titration (Phase 3)	Twice per week
Ratio of Volatile Fatty Acids to Total Inorganic Carbon (A/TIC-ratio)	An increase in acids- (or proportional decrease in carbonate alkalinity-) concentration is the first practical measurable indication that an anaerobic treatment system is in a state of stress.	Nordmann-Titration (Phase 2), Kapp-Titration (Phase 3)	Twice per week
Total Nitrogen (N tot)	See 3.1.2	See 3.1.2	4 times per feedstock
Ammonium-Nitrogen (NH4-N)	See 3.1.2	See 3.1.2	Twice per week
Total Phosphorus (P tot)	See 3.1.2	See 3.1.2	4 times per feedstock
Phosphate (PO4)	Fraction of total phosphorus which is directly available to microorganisms	PhosVer3 Method (Filter paper) Photospectrometer (Hach DR/2010)	Twice per week
Heavy Metals (Cd, Cu, Pb)	Toxic effect (for AD): Pb: 340mg/l Cu: 170-300mg/l Cd: 20-600mg/l (Eder&Schulz, 2003)	Atomic Absorption Spectrometer (AAS)	4 times per feedstock

Detailed methodologies for TS, VS, Ammonium, Total Nitrogen, Phosphate, Total Phosphorus and Chemical Oxygen Demand are described in Appendix A1. The titration methodologies for VFA, alkalinity and A/TIC-ratio (according to Nordmann and Kapp) can be found in Appendix A2.

3.1.6 Calculations

The operational parameters commonly used to describe anaerobic processes are listed and explained underneath (Mata-Alvarez, 2003).

- <u>Hydraulic Retention Time (HRT)</u>

Describes the ratio of the reactor volume to the flow rate of the feed. It hence expresses the time a fluid element spends in the digester (strictly true for ideal reactors).

HRT = V / Q

HRT = hydraulic retention time [days]
V = reactor volume [m^3]
Q = flow rate [m^3/day]

- <u>Solid Retention Time (SRT)</u>

Describes the ratio between the content of total solids in the reactor and the solids flow rate of the effluent.

SRT = V*X/W

SRT = solid retention time [days]
V = reactor volume [m^3]
X = volatile solids concentration in the reactor [kg VS/m^3]
W = flow rate of the extracted volatile matter from the reactor [kg VS/day]

- <u>Organic Loading Rate (OLR)</u>

Describes the substrate quantity introduced into the reactor volume in a given time, whereby the substrate can be defined as TS, VS, COD or BOD.

OLR = Q*S/V

OLR = organic loading rate [kg feed/m^3 reactor day]
Q = substrate flow rate [m^3/day]
S = substrate concentration in the inflow [kg/m^3]
V = reactor volume [m^3]

- Gas Production Rate (GPR)

Describes the ratio between the produced biogas and reactor volume in a given time.

$$GPR = Q_{biogas}/V$$

GPR = gas production rate [m^3 gas/m^3 reactor day]
Q_{biogas} = biogas flow rate [m^3/day]
V = reactor volume [m^3]

- Specific Gas Production (SGP)

Indicates the biogas produced by a unit of mass of substrate, in terms of the total volatile solids in the feed, as $m^3_{biogas}/kg_{substrate\ fed}$. This index is strictly linked both to the biodegradability of the fed substrate and to the process attitude. The SGP value is often used to compare the performances of different anaerobic processes.

$$SGP = Q_{biogas}/Q*S$$

SPG = specific gas production [m^3 biogas/kg feed]
Q_{biogas} = biogas flow rate [m^3/day]
Q = inlet flow rate [m^3/day]
S = substrate concentration (VS) in the influent [kg substrate/ m^3]

- Substrate removal effectiveness

Also called substrate conversion, this parameter can be expressed in several ways and the substrate measured in terms of TS, VS or COD. Generally, the simplest and most used equation is:

$$\eta\% = (Q*S-Q*Se)/(Q*S)*100$$

η% = TS, VS or COD removed, as percentage [%]
Q = inlet and outletflow rate [m^3/day]
S = TS, VS or COD concentration in the inlet flow rate [kg/m^3]
Se = TS, VS or COD concentration in the effluent flow rate [kg/m^3]

- General gas equation

To be able to compare the gas production of the research plant in DSM with results from literature, the measured gas quantity needs to be converted into norm litres (norm conditions: 1.013bar, 0°C). Hence, the general gas equation is applied:

$$p * V = n * R * T$$

p	[bar = 105 N/m2]	Pressure of gas, norm conditions: pN = 1.013 bar
V	[l]	Volume of gas, quantity per time
n	[Mol]	Mol per gas, 1 Mol = 22.4 Nl
R	[N*m*mol-1K-1]	Universal gas constant, 8.31 N m mol-1K-1
T	[°K]	Absolute temperature, norm conditions: TN = 273 °K

- Conversion of gas quantity measured in Dar es salaam into norm liters:

Conditions TZ = Norm conditions

(p1 * V1)/T1 = n * R = (pN * VN)/TN = n * R

p1 = local pressure in system of which the measured gas V1 origins

V1 = measured gas quantity

T1 = temperature in °K

= (p1 * V1)/T1) = (pN * VN)/TN)

= VN = (p1 * V1)/T1) / (pN)/TN)

$$VN = (p1 * V1 * TN) / (pN * T1)$$

- Approximate maximum biogas yield

The following two steps enable the calculation of the approximate biogas potential:

1) COD → C

$$C + O_2 \rightarrow CO_2$$

12g + 32g (=COD) → CO_2

12g = 32 COD

→ 1g COD = 0.375g C

2) C → approximate maximum biogas yield

$$2C \rightarrow CO_2 + CH_4$$

2 * 12g → 1Mol + 1 Mol

24g = 24g = 2 * 22.4Nl = 44.8Nl

→ 1g C = 44.8/24

= 1.87 norm litres ‘gas’ maximum (50% CO_2, 50% CH_4)

3.2 Inspection of ARTI plants in Dar es Salaam

On 18 and 19 October 2008, 17 ARTI Compact biogas systems in DSM were visited during an inspection tour to document their status of functioning (12 at household level, 5 at institutional level). A list of the visited ARTI plants can be found in Appendix B1.
5½ weeks later, on 28 November 2008, a second inspection tour was done to observe the progress.

3.2.1 Analysed parameters

On the first tour, the on-site measurements were conducted on effluent-samples and included pH, temperature and Redox-potential. The gas composition was furthermore analysed using Dräger X-am 7000. 1.5l of effluent was taken from each plant and brought to the Environmental Engineering Laboratory of ARDHI-University where TS, VS, COD_{total}, NH_4-N, P_{total} and A/TIC (according to Nordmann), were analysed the following day. The concentration of heavy metals (Pb, Cd, Cu) was examined from 4 inspection sources. Samples which showed high quantity of invertebrate were taken to the zoology laboratory at DSM University and identified on 27.11.2008 (Identification key see Appendix C4).

On the second tour, the status of functioning was assessed and the combustibility of the biogas was tested. pH was furthermore measured using Litmus stripes (Merck "Neutralit" pH-indicator stripes pH 5.0-10.0).

3.2.2 Interviews

An interview with the person responsible for operation of the biogas plant was done on the first tour to learn more about the quality, quantity, pre-treatment method and dilution of the daily feedstock, the duration of daily gas use and the utilization of effluent. Additionally, emphasizes was laid on any problems that had occurred and room was given to suggest ideas for improvements (Questionnaire in Appendix B6)

4 Results

4.1 Research-plant at ARDHI University

All results from the research CBS at ARDHI University can be found in Appendix B5.

4.1.1 Influence of enhanced feeding procedure on process stability

As an indicator of the anaerobic process stability, Figure 16 presents the development of the pH inside the digester during phase 1 (neither previous mixing of feedstock with water nor feedback of effluent). The pH was measured twice per day before feeding in the morning (8:30) and evening (17:00) on three different reactor heights (low, middle, high). Generally, pH-values below 6 should be avoided as it restrains the activity of the methanogenic bacteria. The amount of daily feed (food waste) is shown as well as the digester temperature at medium height (average 27.8°C).

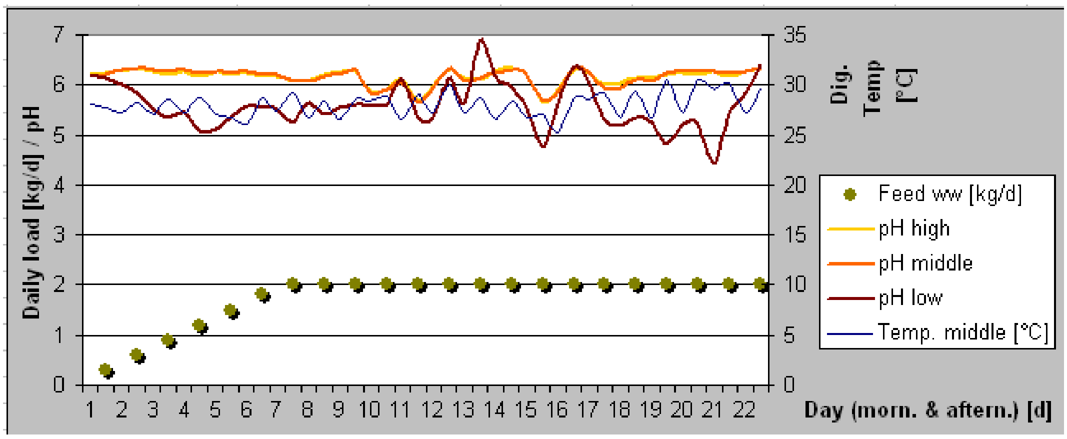

Figure 16: pH development inside digester during phase 1: start-up

As a comparison, Figure 17 reveals the development of the pH during phase 2 where emphasis was laid on enhanced mixing of the digester liquid. As a result, the pH values of all heights have stabilized around pH 6.5 and show less deviations. The average temperature inside the reactor (middle) was 28.8°C. The dark green spots represent kg wet weight (ww) of food waste (FW) as feedstock, whereas the light green spots stand for market waste (MW) of fruit and vegetables.

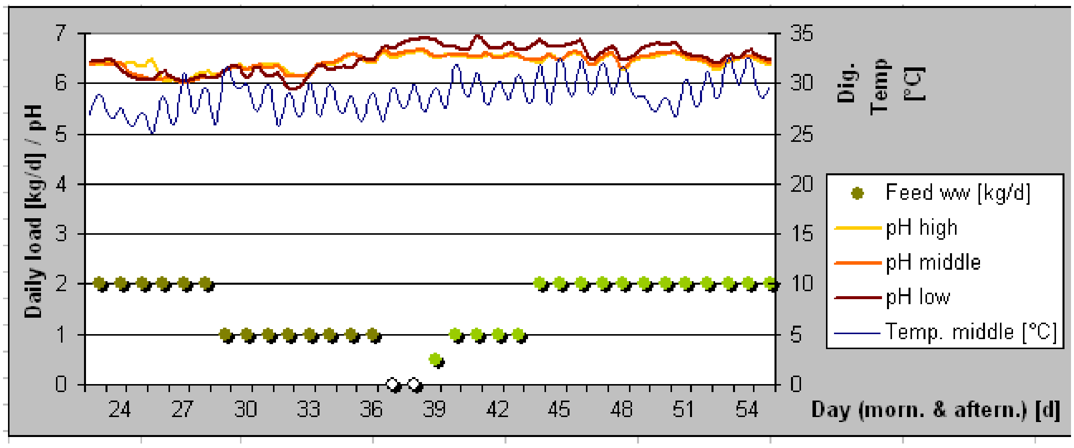

Figure 17: pH development inside digester during phase 2: feeding strategy

Figure 18 illustrates the stability of the digester during phase 3. Although the daily amount of feed was increased to 5kg/day, the reactor liquid did not show any alarming sign of disturbance, with pH only dropping slightly down to 6.2. As the average air temperature during this phase increased, so did the average digester temperature (30.9°C). It is conspicuous that due to the improved mixing of feedstock with water previous to the feeding and feedback of effluent, the pH values of low, middle and high reactor height are noticeably more congruent in phase 2 and 3 compared to phase 1.

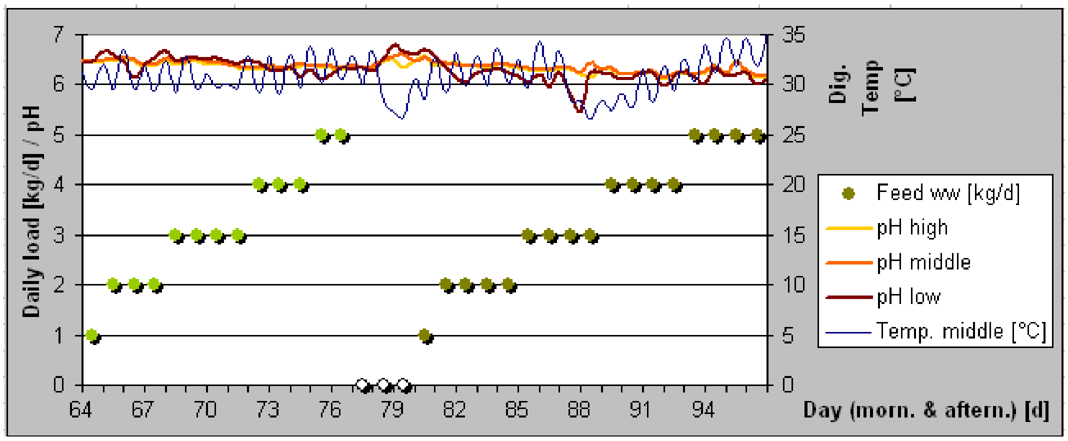

Figure 18: pH development inside digester during phase 3: maximum load

As the pH- value reacts with quite some delay to changes in quantity and quality of feeding substrate, the A/TIC-ratio provides valuable information in terms of immediate process stability. Figure 19 presents the course of A/TIC-ratio (Nordmann titration) while feeding both substrates. It is apparent that from the inoculum (cow dung), the amount of VFA was quite high in the beginning (day 8 & 11) compared to the alkalinity, which results in a high A/TIC value. After 25.08.08 (day 15), the A/TIC ratio was stabilized around 0.15 (feedstock: 2kg food waste/day). Following the change to 2kg market waste per day (day 46), the A/TIC-ratio was levelled around 0.08.

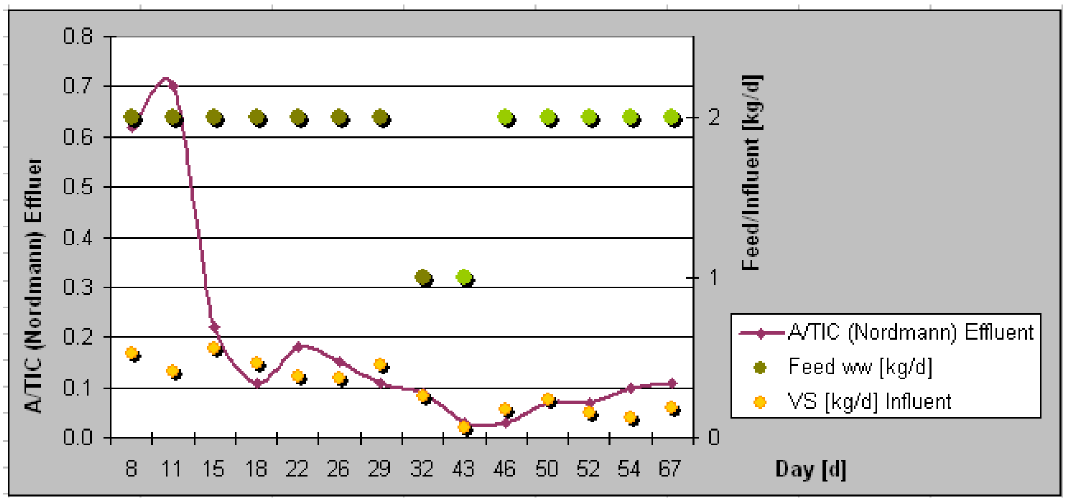

Figure 19: Development of A/TIC-ratio (Nordmann) while feeding FW (day 8-32) and MW (day 43-67)

4.1.2 Stratification inside digester in terms of TS, VS and COD

Figure 20, Figure 21 and Figure 22 present the different concentrations of TS, VS and COD inside the digester on the reactor bottom, at medium height and on the top layer (effluent) compared to the influent (FW until day 26, MW starting on day 46). A clear accumulation of solids and organic material can be observed on the ground of the digester due to sedimentation.

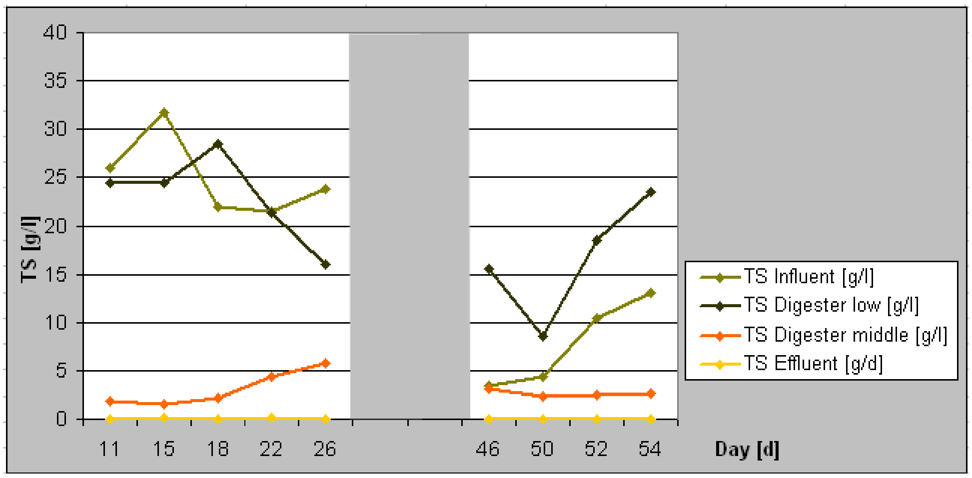

Figure 20: Comparison of TS concentration in influent, digester liquid and effluent

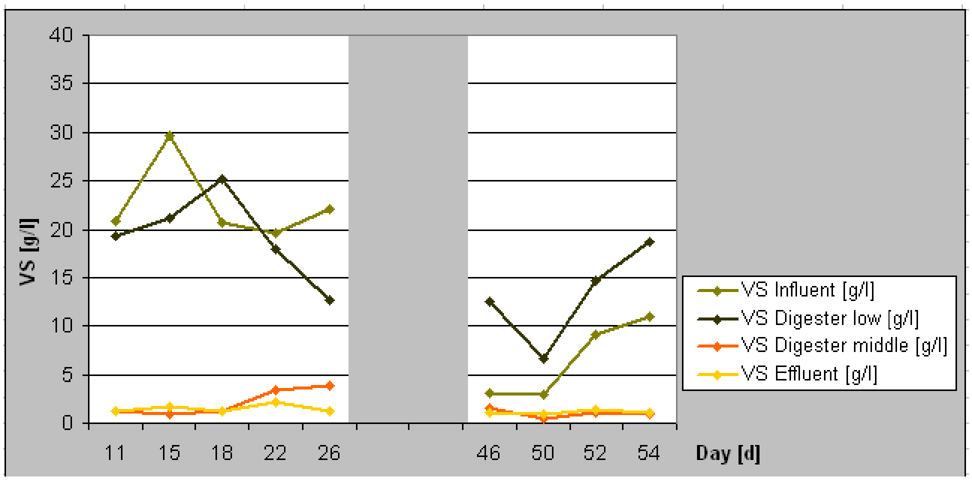

Figure 21: Comparison of VS concentration in influent, digester liquid and effluent

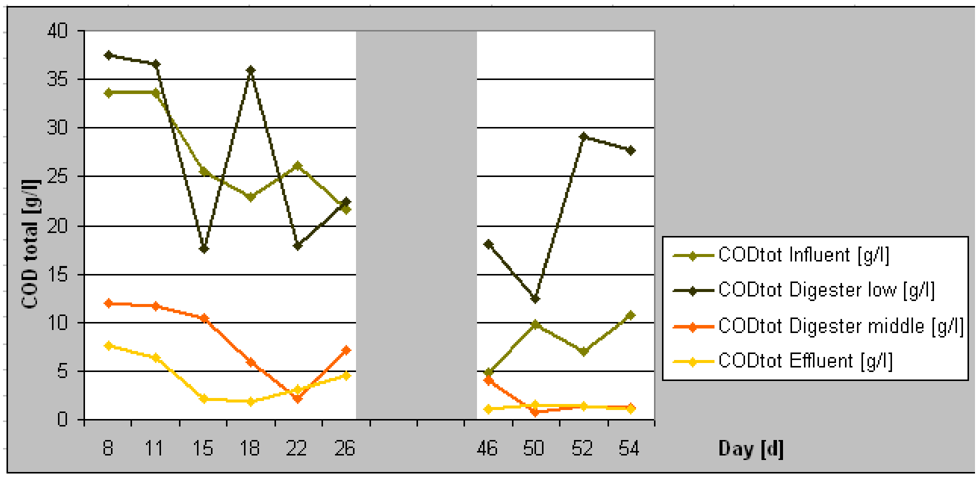

Figure 22: Comparison of COD concentration in influent, digester liquid and effluent

Figure 23 illustrates the stratification of the digester liquid which was analysed on 25.11.2008 after removing the gasholder and emptying the digester stepwise layer after layer (1 layer = 85l) with a hose using the cohesion force of water.

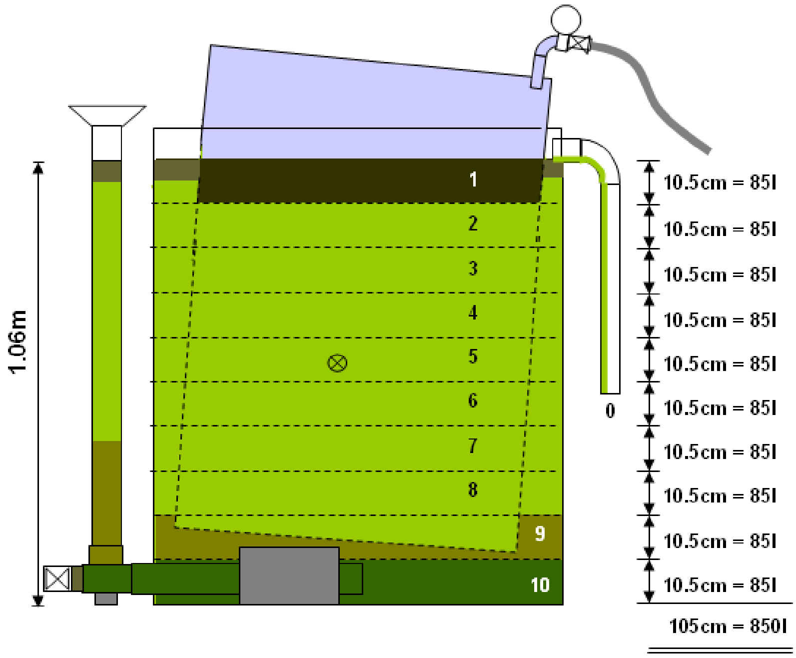

Figure 23: Stratification of digester liquid in ARDHI research plant

Table 17 reveals the detailed results of the TS and VS analyses. The majority of digester liquid (600l) as well as the effluent show similar TS and VS content, while the surface level (floating layer) inside the gasholder is characterized by a high TS and VS concentration.

Table 17: TS and VS of layers inside the digester (26.11.2008)

Height no.	*TS [g/l]*	*TS [%]*	*VS [g/l]*	*VS [%]*
0 effluent (high)	3.65	0.37	1.47	40.26
1 surface	74.11	7.41	60.58	81.75
2	3.33	0.33	1.42	42.74
3	3.37	0.34	1.30	38.71
4	3.62	0.36	1.41	38.85
5 middle	3.33	0.33	1.24	37.24
6	3.29	0.33	1.43	43.44
7	3.47	0.35	1.42	40.88
8	3.24	0.32	1.46	45.00
9	5.28	0.53	3.16	59.76
10 bottom (low)	41.17	4.12	32.68	79.36
Average (1-10)	**14.42**	**1.44**	**10.61**	**50.77**

4.1.3 Intense monitoring of VFA, alkalinity and A/TIC

Table 18 presents the VFA- and alkalinity concentration of the effluent as well as the A/TIC ratio over a period of 20 days while the amount of daily feedstock (food waste) was changed. Different pre-treatment methods and the titration according to Kapp were applied. Because of its time- and material-intensity, the membrane filtration was only conducted once per day. The results of both other pre-treatment methods (sieve/textile filtration and centrifugation) are mean values of two repetitions. The rather slow-acting pH values are listed as comparison.

Table 18: VFA, alkalinity and A/TIC results applying different pre-treatment methods (titration according to Kapp)

			sieve & textile filtered			centrifuged (10min/5000rpm)			membrane filtered		
Day	Feedstock FW [kg/d]	pH (effluent)	VFA (Kapp) [mg/l]	Alkalinity [mg/l] (Kapp)	**A/TIC (Kapp)**	VFA [mg/l] (Kapp)	Alkalini-ty [mg/l] (Kapp)	**A/TIC (Kapp)**	VFA [mg/l] (Kapp)	Alkalini-ty [mg/l] (Kapp)	**A/TIC (Kapp)**
86	3	6.29	61	884	**0.07**	55	880	**0.06**	45	869	**0.05**
88	3	6.16	58	851	**0.07**	32	867	**0.04**	30	828	**0.04**
90	4	6.23	123	797	**0.15**	121	811	**0.15**	78	803	**0.10**
92	4	6.24	124	845	**0.15**	158	771	**0.21**	106	761	**0.14**
94	5	6.35	124	845	**0.15**	89	835	**0.11**	84	813	**0.10**
96	5	6.15	193	804	**0.24**	195	855	**0.23**	164	793	**0.21**
98	0	6.43	52	981	**0.05**	46	1002	**0.05**	35	961	**0.04**
100	0	6.77	75	1121	**0.07**	83	1140	**0.07**	64	1136	**0.06**
103	2	6.39	132	1136	**0.12**	86	1168	**0.07**	63	1141	**0.06**
105	2	6.45	102	1129	**0.09**	67	1151	**0.06**	75	1161	**0.06**

To compare the accuracy of the method, the Nordmann titration was further applied over the same period of time (Table 19). The pre-treating method consisted of filtering the effluent samples first through a kitchen sieve and then through a textile mash. The presented results are again mean values of two repetitions.

Table 19: VFA, alkalinity and A/TIC results (titration according to Nordmann)

			sieve & textile filtered		
Day	Feedstock FW [kg/d]	pH (effluent)	VFA [mg/l] (Nordmann)	Alkalinity [mg/l] (Nordmann)	**A/TIC (Nord-mann)**
86	3	6.29	43	847	**0.05**
88	3	6.16	31	817	**0.04**
90	4	6.23	91	741	**0.12**
92	4	6.24	118	703	**0.17**
94	5	6.35	81	789	**0.10**
96	5	6.15	147	734	**0.20**
98	0	6.43	40	943	**0.04**
100	0	6.77	63	1028	**0.06**
103	2	6.39	121	1073	**0.11**
105	2	6.45	121	1069	**0.11**

It should be noted that previous to the analyses on day 94 (12.11.08), a heavy rain occurred. It eventually diluted the effluent sample to some extent.

Table 18 and Table 19 reveal that the influences of different titration and pre-treatment methods on alkalinity and A/TIC results are negligible. However, for measurements of the VFA concentration, the Kapp titration is strongly favoured over the Nordmann method because of its better accuracy.

All results of the various A/TIC analyses are presented in Figure 24, showing its developments and deviations. As far as statements in terms of process stability are concerned, both titrations (according to Kapp and Nordmann) and all pre-treatment methods are applicable, the simple 'sieve&textile' treatment being preferable due to its simplicity.

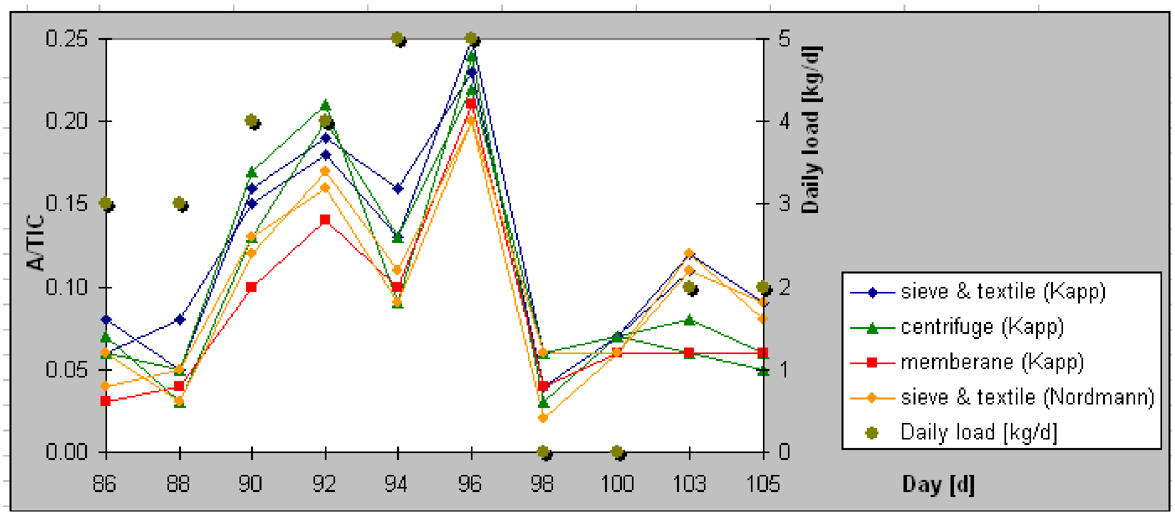

Figure 24: Results of A/TIC titrations (Kapp and Nordmann) with different pre-treatment

4.1.4 Operational parameters

Below are the calculated operational parameters of the research plant at ARDHI University, while constantly feeding 2kg of substrate over a defined period of time (Food waste: 18.08 – 08.09.2008, 7 samples, 2 repetitions), market waste: 25.09 – 16.10.2008, 5 samples, 2 repetitions).

- Hydraulic Retention Time (HRT) of ARDHI plant

Food waste and market waste: $0.85m^3$ / $0.02m^3$ = 42.5days

---

- Solid Retention Time (SRT) of ARDHI plant:

Food waste and market waste: $0.85m^3$ * 10.6kg VS/m^3 / 0.03kg VS/day = 300days

---

- Organic Loading Rate (OLR) of ARDHI plant:

Food waste	(TS)	$0.02m^3$/d * 26.7kg/m^3 / $0.85m^3$ = 0.628kg/m^3reactor d
	(VS)	$0.02m^3$/d * 22.6kg/m^3 / $0.85m^3$ = 0.532kg/m^3reactor d
	(COD)	$0.02m^3$/d * 28.3kg/m^3 / $0.85m^3$ = 0.666kg/m^3reactor d
Market waste	(TS)	$0.02m^3$/d * 8.2kg/m^3 / $0.85m^3$ = 0.193kg/m^3reactor d
	(VS)	$0.02m^3$/d * 7.0kg/m^3 / $0.85m^3$ = 0.165kg/m^3reactor d
	(COD)	$0.02m^3$/d * 8.6kg/m^3 / $0.85m^3$ = 0.202kg/m^3reactor d

---

- Gas Production Rate (GPR) of ARDHI plant:

Food waste: $0.234Nm^3$/d / $0.85m^3$ = $0.275Nm^3$ gas/m^3 reactor day

Market waste: $0.122Nm^3$/d / $0.85m^3$ = $0.144Nm^3$ gas/m^3 reactor day

---

- Specific Gas Production (SGP) of ARDHI plant:

Food waste: $0.234Nm^3$/d / $0.02m^3$/d * 22.6kg VS/m^3 = $264.4Nm^3$ biogas/kg feed

Market waste: $0.122Nm^3$/d / $0.02m^3$/d * 7.0kg VS/m^3 = $42.7Nm^3$ biogas/kg feed

- Substrate removal effectiveness (η%) of ARDHI plant:

Food waste: (TS) $(0.02m^3/d * 26.7kg/m^3 – 0.02m^3/d * 3.7kg/m^3) / (0.02m^3/d * 26.7kg/m^3) * 100 =$ 86.1%

(VS) $(0.02m^3/d * 22.6kg/m^3 – 0.02m^3/d * 1.7kg/m^3) / (0.02m^3/d * 22.6kg/m^3) * 100 =$ 92.5%

(COD) $(0.02m^3/d * 28.3kg/m^3 – 0.02m^3/d * 4.8kg/m^3) / (0.02m^3/d * 28.3kg/m^3) * 100 =$ 83.0%

Market waste (TS) $(0.02m^3/d * 8.2kg/m^3 – 0.02m^3/d * 2.7kg/m^3) / (0.02m^3/d * 8.2kg/m^3) * 100 =$ 67.1%

(VS) $(0.02m^3/d * 7.0kg/m^3 – 0.02m^3/d * 1.3kg/m^3) / (0.02m^3/d * 7.0kg/m^3) * 100 =$ 81.4%

(COD) $(0.02m^3/d * 8.6kg/m^3 – 0.02m^3/d * 1.2kg/m^3) / (0.02m^3/d * 8.6kg/m^3) * 100 =$ 86.0%

4.1.5 Reduction of waste volume and organic load

Figure 25 shows the degree of daily waste reduction (orange) by comparing TS concentration of the influent with TS of the effluent.

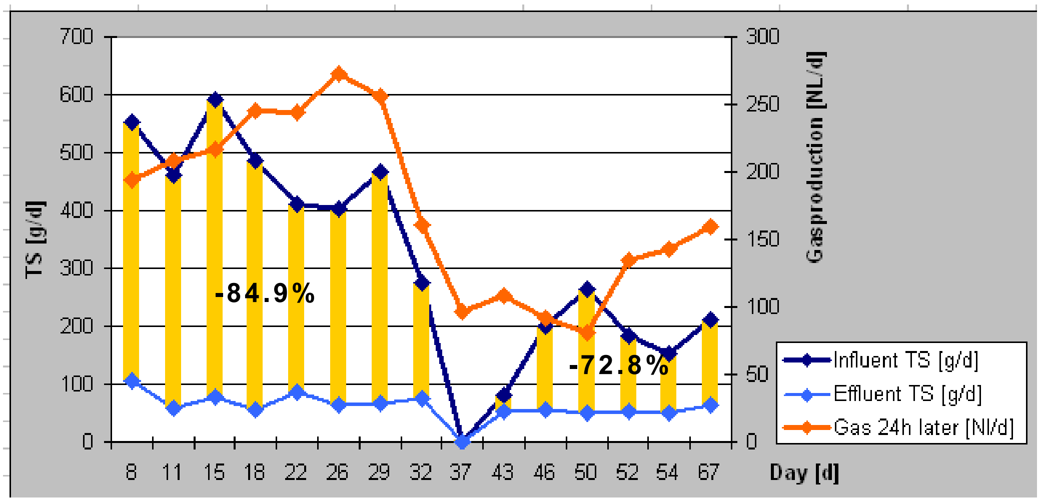

Figure 25: Reduction of waste volume (TS) when feeding FW (day 8-32) & MW (day 43-67)

One option to describe the reduction of organic load is given by measuring the VS of influent and effluent (Figure 26). The average VS of food waste influent is 451g/d and of its effluent 35g/d, which results in a reduction rate of 92.2%. The mean VS of market waste influent is 177g/d and of its effluent 26g/d, which leads to a reduction of 85.3%.

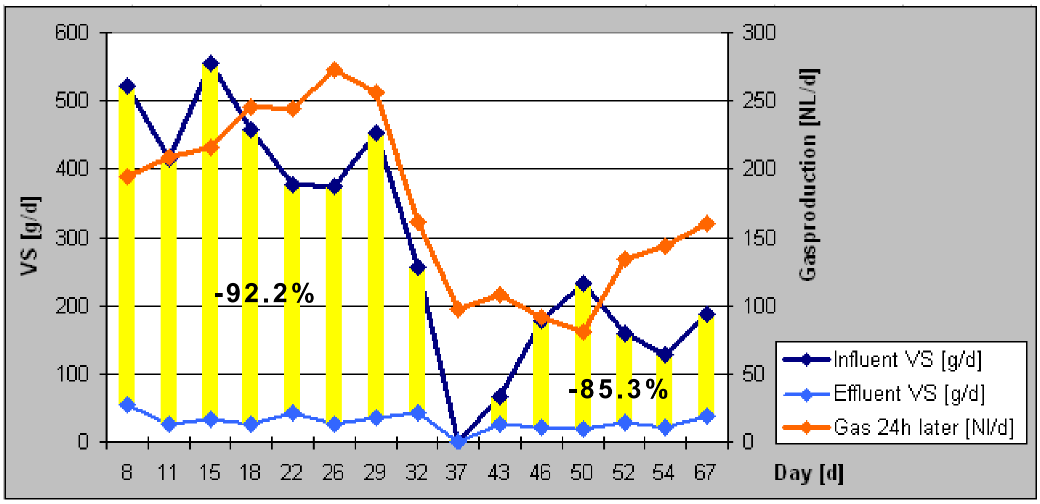

Figure 26: Reduction of VS content when feeding FW (day 8-32) and MW (day 43-67)

Another option to describe the reduction of organic load is through COD. As Figure 27 illustrates, the daily COD content of influent and effluent between FW (average influent 567g/d, average effluent 96g/d) and MW (average influent 152g/d, average effluent 24g/d) differ considerably. However, the reduction in term of COD for both substrates was found to be comparable at approximately 83%.

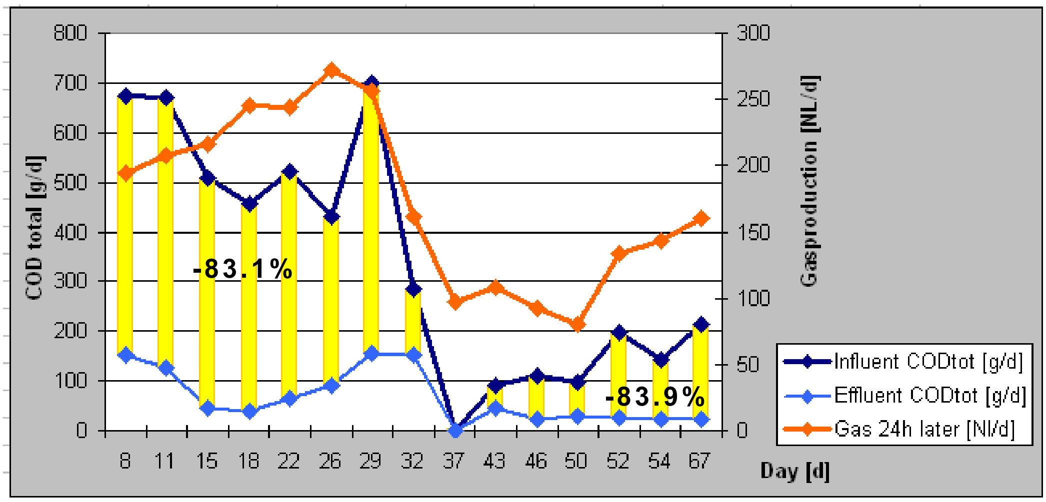

Figure 27: Reduction of COD content when feeding FW (day 8 -32) & MW (day 43 - 67)

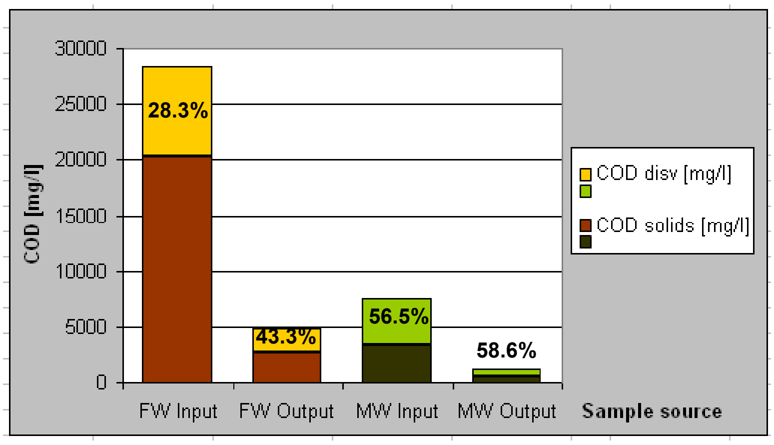

Figure 28: Comparison of COD solid and COD dissolved from FW and MW

Figure 28 reveals the percentage of COD dissolved compared to COD total from influent (2kg food waste & market waste) and effluent.

Figure 29 & 30 present an overview of TS, VS and COD reduction, both when feeding 2kg FW and MW per day.

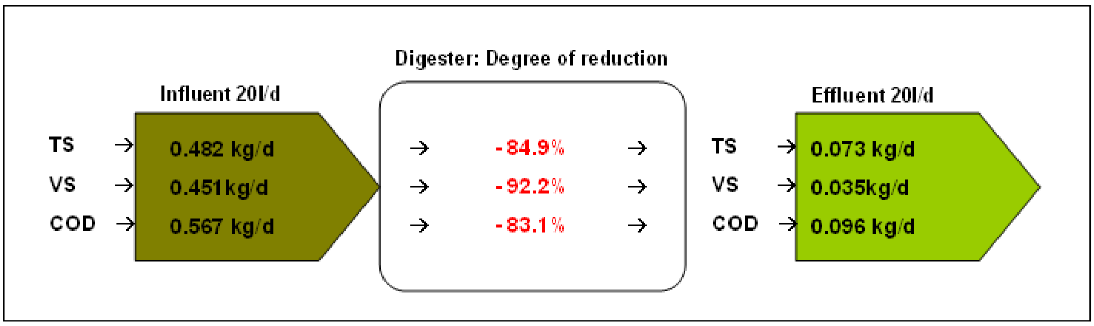

Figure 29: Input/Output with daily load of 2kg/d Food waste

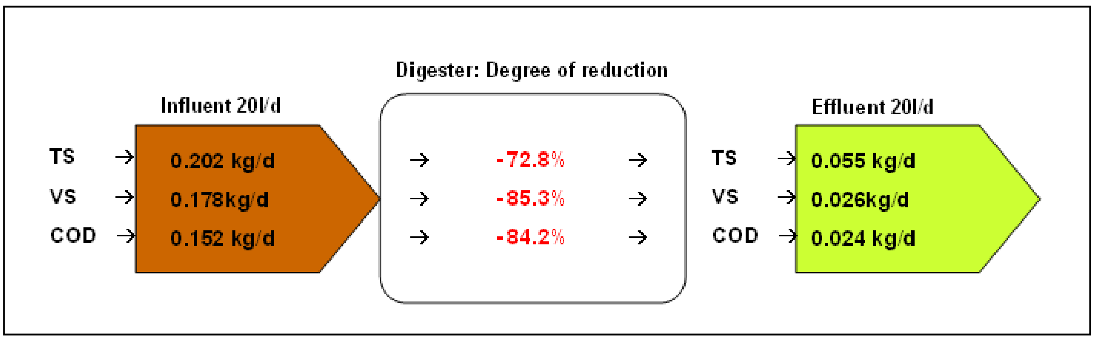

Figure 30: Input/Output with daily load of 2kg/d Marke twaste

4.1.6 Gas resulting from anaerobic digestion of food waste and market waste

After reaching a steady-state condition, the two feeding substrates were characterized and recorded in terms of wet weight, TS, VS and CODtotal over a period of 10 days: Food waste: 29.08.- 07.09.2008 (day 19 – 28); Market waste: 25.09 - 04.10.2008 (day 46 – 55). Table 20 presents the average values of these parameters and the quantity of the gas produced (measured on site and adjusted to norm conditions according to the general gas equation, see 3.1.6)

Table 20: Mean values during 10-day steady state conditions for both substrates

Feedstock (dilution 1:20)	Wet weight [kg/d]	TS [kg/d]	VS [kg/d]	CODtotal [kg/d]	Gas production DSM [l/d]	Gas production Norm [Nl/d]
Food waste	2	0.482	0.451	0.567	289	259
Market waste	2	0.202	0.180	0.172	126	113

Table 21 shows the average biogas production for the two different feed substrates per kg wet weight, TS, VS and COD. In brackets are the results transformed to norm conditions (0°C, 1013mbar).

Table 21: Gas production in dependence to daily wet weight, TS, VS and COD for both substrates (transformed to norm conditions)

Feedstock (dilution 1:20)	Average gas per kg wet weight [Nl/kg WW]	Average gas per kg TS [Nl/kg TS]	Average gas per kg VS [Nl/kg VS]	Average gas per kg COD [Nl/kg COD]
Foodwaste	144 (129)	599 (537)	640 (574)	509 (457)
Marketwaste	63 (57)	624 (559)	700 (628)	733 (657)

Figure 31 shows the daily gas production over 10 days of steady-state conditions resulting from 2kg FW (wet weight) and as comparison 2kg MW (ww). The daily VS average of FW was 0.451kg/d and 0.177kg/d for MW respectively and is marked as yellow spots. The average gas production during this period was 289l/d (259Nl/d) from FW and 126l/d (113Nl/d) from MW.

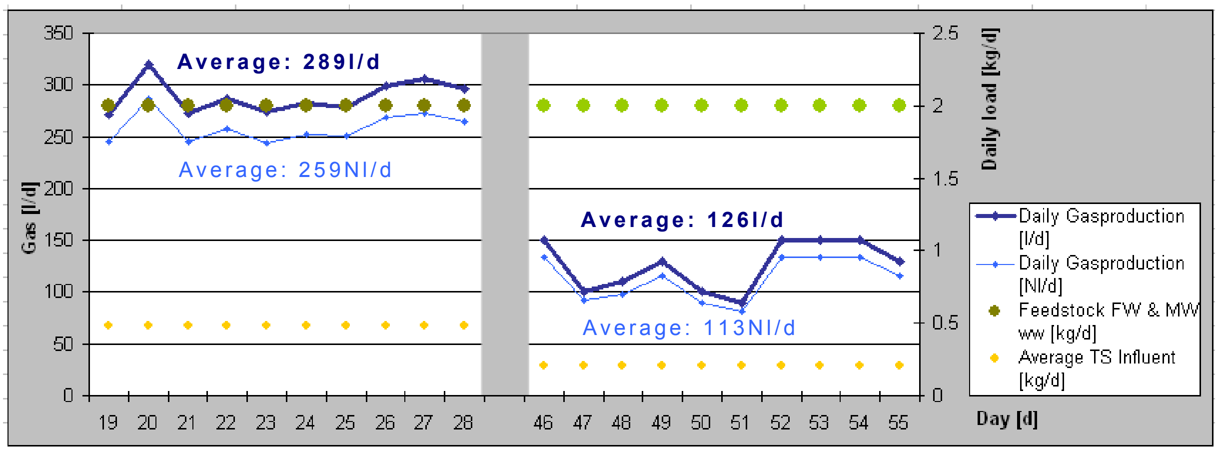

Figure 31: Comparison of daily gas production from FW and MW during 10 days of steady-state conditions

Figure 32 presents the development of daily gas production during phase 3, when daily feeding load was increased to 5kg/d wet weight MW (0.5kg/d TS) and subsequently 5kg/d FW (1.2kg/d TS). Between feeding MW and FW, a 3-day feeding break was intermitted in which the gas production dropped to 70Nl/d. For detailed gas productions see Appendix A3.

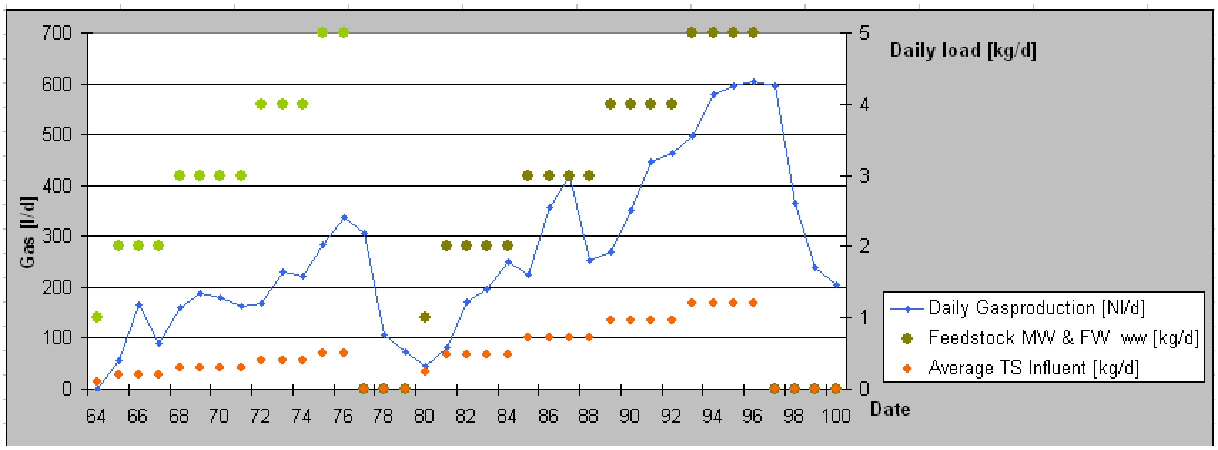

Figure 32: Gas production while increasing daily feed:MW (day 64-76), FW (day 80-100)

Figure 33 reveals the correlation between the daily feeding load and the consequential gas production. The gas quantity resulting from food waste (FW) is approximately double as high as from market waste (MW). While FW shows an almost linear increase in gas quantity, the relatively high gas amount resulting from 1kg MW can possibly be explained with the heterogeneity of the input material.

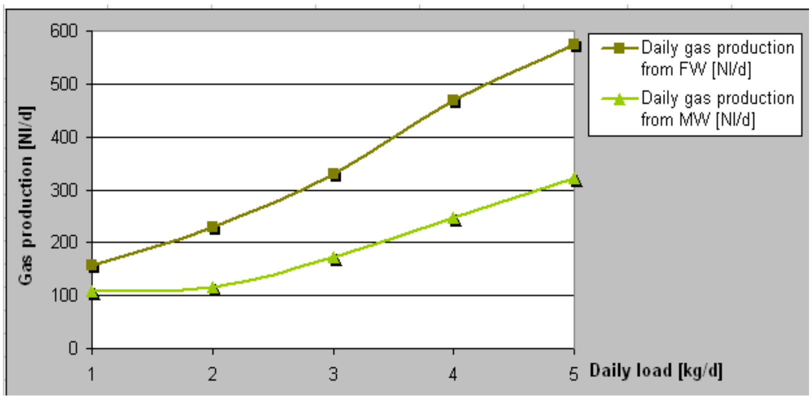

Figure 33: Gas production in dependence with daily feeding load

Approximate maximum biogas yield

As presented in Figure 29 and Figure 30, the average COD reduction was 470.6g/d (food waste) and 147.3g/d (market waste). This corresponds to the decomposition of 176.5g C per day and 55.2g C per day respectively. The calculated approximate maximum biogas potential is therefore 330Nl (FW) and 103Nl (MW) per day (Appendix A3), which is 78.6% and 109.6% of the measured gas production. The deviation between results from measurement and calculation can to some extent be explained by the inaccuracy of the conversion (COD → C) and the assumption that biogas consist of 50% CO_2 and 50% CH_4 (see 3.1.6).

Gas composition

The results of the daily gas composition measurements are shown in Figure 34 as average values recorded during the 10-days steady-state conditions (ww 2kg/d) each for FW and MW. The gas resulting from MW with 66.4% show a higher methane content compared to the gas from FW (56.8%).

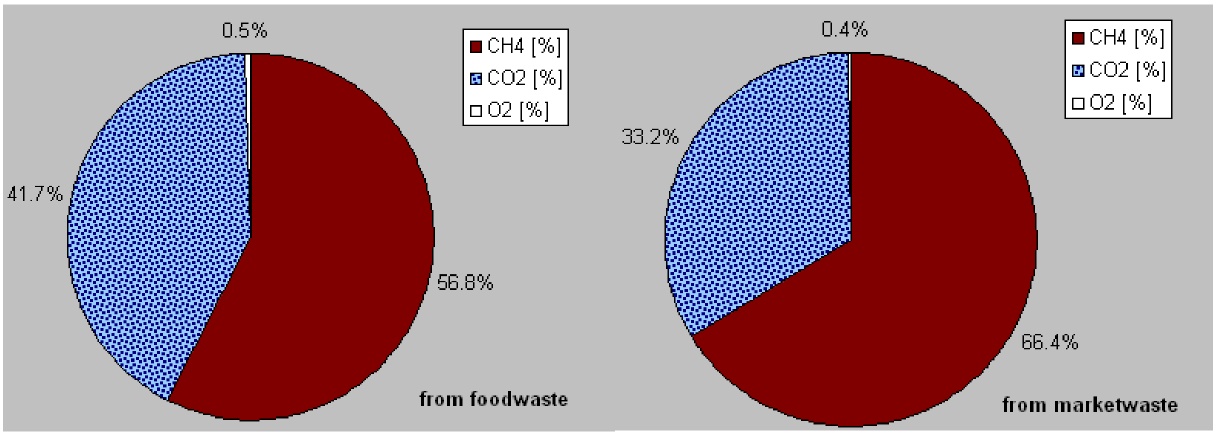

Figure 34: Average gas composition from 2kg/d FW (left) and MW (right), H_2S >100ppm and NH_3 >200ppm are not shown

Biogas utilization: Daily running time of burner

Numerous tests have been done to measure the burning period of 100l biogas produced at the research plant at ARDHI, using the biogas stove distributed by ARTI-TZ (Figure 35).

Table 22 presents the contents of methane and results of all tests when no weight was applied on the gasholder.

Figure 35: Gas stove attached on research CBS for burning tests

Table 22: Tests of burning duration for 100l biogas without weight on gasholder

Date	*Methane content [Vol-%]*	*Pressure in reactor [mbar] no weight on gasholder*	*Burning duration of 100l biogas [min]*
28.08.2008	60	2	25
	60	2	27
06.09.2008	62	2	24
10.09.2008	62	2	20.5
	62	2	22.5
	62	2	23
25.09.2008	70	2	19.5
15.11.2008	59	2	23
25.10.2008	56	2	19
03.11.2008	61	2	19.5
Average	**61.4**	**2**	**22.3**

Figure 36: Weight applied on gasholder

ARTI-TZ occasionally advises their customers to increase the gas pressure by permanently applying weight on the gasholder. Table 23 shows the test results, when ½ cement brick (approximately 12kg) was applied. The burning duration of biogas consequently decreases, yet the required cooking time for the same food also reduces.

Table 23: Tests of burning duration for 100l biogas with weight on gasholder

Date	*Methane content [Vol-%]*	*Pressure in reactor [mbar] 1/2brick (12kg) on gasholder*	*Burning duration of 100l biogas [min]*
06.09.2008	62	4	13.5
25.10.2008	56	4	9
03.11.2008	61	4	12
21.11.2008	68	4	12.5
	68	4	13.5
Average	**62.8**	**4**	**12.1**

4.1.7 Effluent quality

The average concentration of total phosphorus in the effluent samples while feeding food waste was 248mg/l (6.8% of TS), of which 171mg/l (69%) occurred as phosphate. After changing substrate to market waste, 147mg/l of phosphate were found, contributing 66% to the total phosphorus concentration of 225mg/l (8.2% of TS). As comparison, 162mg/l of total P were found in the influent consisting of diluted market waste.

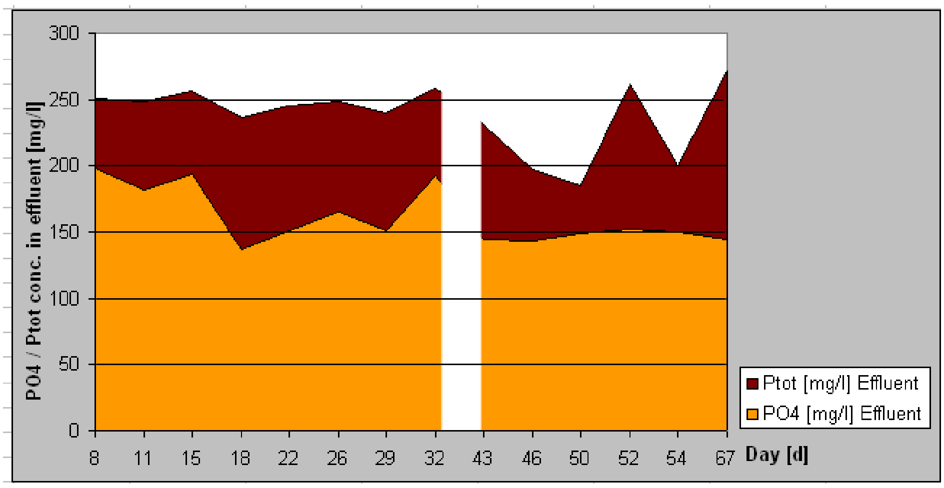

Figure 37: Concentration of Ptotal and PO4 in effluent while feeding FW (day 8-32) and MW (day 43-67)

While average ammonium-nitrogen concentration in the influent was found to be 31.6mg/l in food waste and 27.9mg/l in market waste, the NH_4-N concentration discovered in the effluent was 74.1mg/ (FW) and 85.5mg/l (MW). In other words, the bacterial activity resulted in an NH_4-N increase of 134.5% for FW, and 206.5% for MW respectively (Figure 38).

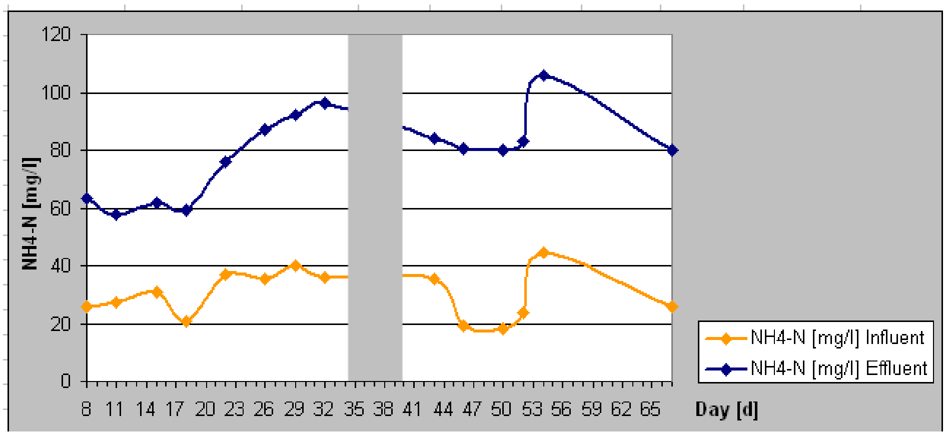

Figure 38: Ammonium-Nitrogen difference between influent and effluent

Heavy metals

The results of the Atomic Absorption Spectrophotometer (AAS) analyses for Lead (Pb), Copper (Cu) and Cadmium (Cd) are presented in Table 24.

Table 24: Heavy metal concentrations in effluents from research plant at ARDHI

Date	*Pb [mg/l]*	*Cu [mg/l]*	*Cd [mg/l]*
28.08.08	0.054	0.000	0.000
28.08.08	0.072	0.000	0.000
08.09.08	0.093	0.000	0.000
11.09.08	0.061	0.000	0.000
22.09.08	0.036	0.000	0.018
03.10.08	0.095	0.000	0.013
16.10.08	0.057	0.006	0.021
Average	**0.067**	**0.001**	**0.007**

It should be considered, that the range for inhibiting effects on anaerobic process (Cu: 40-250mg/l, Cd: 150-600mg/l) were by far not reached. On the other side, the requirement for Pb concentration (0.020-200mg/l) is fulfilled in all samples (Eder & Schulz, 2006).

The quality of the effluent as organic fertilizer can only to some limited extent be evaluated, as the suitability depends on the kind of plant it is applied. Furthermore, the content of Potassium (K), but also Fe, Ca, Mg and Zn are of vital interest because phosphate builds chelates with these essential trace elements which potentially prevent the reception of PO_4.

Comparison with Quality Standards of Compost is also of limited validity. Nevertheless, the measured heavy metal concentrations are far below the tolerated values for compost (see Appendix C5).

4.2 Inspection of installed ARTI-plants in DSM

4.2.1 Result overview of first inspection tour

Table 25 presents an overview of all visited ARTI plants during the first inspection tour. On 18/19 October 2008 out of 12 ARTI Compact biogas systems (CBS) at household level, 4 were in operation, whereas 8 were not in use due to various reasons, which are explained in 4.2.2. 5 additional CBS were furthermore visited on the first inspection tour to serve as comparison (marked grey in Table 25). These plants include the CBS at ARTI-office, which is used as demonstration plant and fed irregularly, the research plant at ARDHI University and the three recently installed 4000l-digesters of Azania Secondary School at institutional level (Appendix B7).

Table 26 reveals the gas composition of the inspected systems, which in general correspond well with the findings of the research plant at ARDHI. The high methane content of CBS #14 can be explained with the break-down and thus congested feeding. Because the CO_2-releasing process of hydrolysis became deactivated, the content of methane increased disproportionately. Contrarily, the low methane concentration of CBS #30 can be explained by its recent set-up (September 2008) and hence shows the predominant product of the hydrolysis (CO_2).

Table 25: Overview of effluent results from first ARTI inspection tour (18/19 October 2008)

			Effluent														
ARTI CSB-# (installation date)	*Size (dig./ gas-holder) [l]*	*Status*	*pH*	*Temp. [°C]*	*Redox [mV]*	*TS [%]*	*VS [%]*	*COD total [mg/l]*	*NH4-N [mg/l]*	*P total [mg/l]*	*Pb [mg/l]*	*Cu [mg/l]*	*Cd [mg/l]*	*VFA (Nordmann) [mg/l]*	*Alkalinity (Nordmann) [mg/l]*	*A/TIC (Nordmann)*	*Remarks*
2 (02/2007)	1000/ 750	In use	6.78	30.8	-270	0.37	61.3	3340	93.0	166	0.04	0.00	0.00	57.8	1200	0.05	Many invertebrate larvae
3 (04/2007)	1000/ 750	In use	6.47	28.6	-420	0.22	56.1	790	117.0	244	0.08	0.02	0.01	124.2	1180	0.11	For dog food H2O heater
4 (04/2007)	1000/ 750	Not in use	No digester liquid in CBS														Inlet ran down (by dogs)
5 (04/2007)	1000/ 750	Not in use	No digester liquid in CBS														Cause of breakdown unknown
6 (05/2007)	1000/ 750	Not in use	No digester liquid in CBS														Inlet pipe broken
7 (06/2007)	1000/ 750	Not in use	No digester liquid in CBS														4th breakdown
14 (03/2008)	1000/ 750	Not in use	7.60	36.0	+37				364.0					157.4	1780	0.09	Inlet blocked, not enough feed
15 (03/2008)	1000/ 750	Not in use	6.48	31.3	-312	0.24	54.6	2640	119.0	94	0.14	0.02	0.00	91	820	0.11	Gas tap broken
17 (05/2008)	2000/ 1500	Not in use	4.15	31.8	-182				63.5								Overfed
18 (05/2008)	2000/ 1500	In use	6.88	33.5	-437	1.75	63.7	5640	312.0	304				290.2	2410	0.12	Inlet slightly blocked
25 (08/2008)	1000/ 750	Not in use	6.61	31.3	-174	0.18	54.8	2020	67.5	368				124.2	810	0.15	Inlet blocked
30 (09/2008)	1000/ 750	In use	6.08	34.8	-60	0.23	62.7	3480	31.5	256	0.00	0.03	0.02	456.2	590	0.77	New (22.9.08)
1 (11/2006)	1000/ 750	In use	6.26	33.0	-503	0.16	59.3	3270	95.5	78				57.8	630	0.09	Demo-plant (ARTI-office)
24 (07/2008)	1000/ 750	In use	6.31	33.2	-455	0.31	58.6	1130	73.0	272				91.0	850	0.11	Research plant at ARDHI
26 (09/2008)	4000/ 3000	In use	6.46	31.2	-336	0.88	83.3	6100	45.0	314				423.0	650	0.65	Institutional New (1.9.08)
27 (09/2008)	4000/ 3000	In use	6.42	32.0	-347	0.47	75.8		45.0	328				223.8	750	0.30	Institutional New (1.9.08)
28 (09/2008)	4000/ 3000	In use	6.40	31.1	-366	1.37	83.8		48.0	320				655.4	800	0.82	Institutional-New, larvae

Table 26: Gas composition of inspected ARTI plants in DSM (18/19 October 2008)

		Gas composition				
ARTI CBS-#	*Status*	CH4 [Vol-%]	CO2 [Vol-%]	O2 [Vol-%]	H2S [ppm]	NH3 [ppm]
2	In use	68	32	0.2	72	167
3	In use	54	46	0	>100	>200
4	Not in use	no gas in gasholder				
5	Not in use	no gas in gasholder				
6	Not in use	no gas in gasholder				
7	Not in use	no gas in gasholder				
14	Not in use	80	11	0.3	>100	>200
15	Not in use	59	41	0.5	>100	>200
17	Not in use	52	48	0.2	>100	>200
18	In use	57	43	0.1	>100	>200
25	Not in use	53	33	0.5	>100	>200
30	In use	48	52	0.3	>100	>200
1	In use	59	41	0.2	>100	>200
24	In use	57	43	0.3	>100	>200
26	In use	55	45	0	>100	>200
27	In use	54	46	0	>100	>200
28	In use	56	44	0	>100	>200

4.2.2 Problems and consequences

The poor results of the first inspection tour in terms of functioning are mainly a consequence of

- Lack of proper instruction by ARTI-TZ (leads to low understanding of the operator)
- Poor maintenance by the operator (leads to inappropriate operation and damage of CBS)
- Lack of follow-up service by ARTI-TZ (leads to unidentified failures of CBS)

The concrete causes for the break-down of the 8 ARTI systems include breaking of inlet pipe, overfeeding, blocking of inlet pipe and broken gas tab. In some cases, the digester was not in use for several months and the real cause of the failure could not be determined. In general, the operators of the CBS did not seem well informed in terms of potential feedstock, quantity of water to dilute, feedback of effluent, correction of defects, etc. Considering the fact that even minor problems can lead to a complete standstill of the system (e.g condense water in the gas hose), the necessity of an accurate training and follow-up service is inevitable.

As a result of the above mentioned findings, the following improvements were strived:

- Employing an additional ARTI technician for fixing all damaged systems. He is furthermore responsible for the follow-up services, especially during the first months after the purchase of a new CBS until the daily operation becomes habitual.
- Conducting a workshop for the ARTI technicians to teach them how to inspect a CBS systematically by means of a check list (see Appendix B4).

- Creating a simple customer manual in English and Kiswahili which can be distributed as part of the instruction training. The illustrated paper can be consulted in case of questions about the feeding procedure and when minor problems occur (see Appendix B3).
- Encouraging the customers to call ARTI-TZ immediately in case of any difficulties so that a complete restart of the CBS can be avoided.

4.2.3 Results of second inspection tour

The second inspection tour on 27 November disclosed that 10 CBS were functioning whereas 2 were still not in use.

One of the CBS still not functioning is located in a remote rural area outside Dar es Salaam and its digester size is 2000l. According to the operator, he prefers to sell the kitchen waste to nearby pig farmers and therefore does not have sufficient feedstock to operate the plant. The second CBS not in use was heavily overfed already during the first inspection tour. According to the advice of ARTI-TZ, the feeding was interrupted in order for the pH to rise up to at least 6, before starting regular feeding again. However, the digester still showed high acidity on the second inspection tour (pH<5) and its gas was not combustible. Limestone (previously diluted with water) could be added to increase the pH.

All other CBS were functioning and proved that the services done by ARTI-TZ following the first inspection were successful. Points of concern on all plants remained the frequent blocking of the gas hose by condense water and in two cases the long distance (up to 15m) between digester and burner.

While in 3 household digesters, a handful insect larvae was discovered, one household CBS and one digester at Azania Secondary School displayed a large population of insect larvae (Figure 39).

Figure 39: Insect larvae found in digester of AZANIA Sec. Scool

A closer look at the Zoology Department (DSM University) revealed that

- 80-90% of the larvae (and pupae) found in the digester were species of the *Psychodidae* family (engl. sewage flies or moth flies), which do not bite and are no serious disease transmitter.
- 10-20% of the larvae (and pupae) were *Culex*, which are the most widespread mosquito species in Dar es Salaam. They act as human nuisance and as vector of filarial parasites.
- *Anopheles* mosquitoes (transmitter of Malaria parasites) were not found due to the high organic pollution of the digester liquid. According to Marquardt et al. (2000), *Anopheles* larvae occur in a wide range of habitats but most species prefer clean, unpolluted water.

5 Discussion

5.1 Assessment

To guarantee a transparent evaluation regarding the suitability of ARTI Compact biogas systems as a treatment option for organic solid waste on household level in Dar es Salaam, the assessment has been divided into the following five criteria groups.

5.1.1 Technical aspects

If operated properly, the ARTI Compact biogas system is robust in terms of structural and biological stability.
All material necessary for the installation of a CBS is locally available. Various recommendations regarding the use of material and enhanced feeding procedure can be found in 5.2.1. Longevity is not considered to impose a problem, as there is a 30-year guarantee on the water tanks given by the manufacturer.
Blocking of the inlet pipe seems to occur frequently as a result of insufficient cutting or diluting of the feedstock. In addition, it was observed that the moistness of the system attracts African Giant Land Snails (*Achatina fulica*) which can also lead to clogging of the inlet (Figure 40).

Figure 40: African Giant Snail

The gas loss through the rim between digester and gasholder (approximately 22%) leaves room for improvement as the emission of biogas reduces the efficiency of the system and spreads undesired greenhouse gases.
Although the research CBS at ARDHI did not cause any problems and was regarded as simple to operate, the inspection tours clearly proved that a proper follow-up service is not optional but absolutely essential. This is predominantly important during the first 3 months after the purchase of a CBS, as long as the daily routine of the operator has not been consolidated. Climatic conditions in DSM are favourable for the CBS, as average air temperature is optimal for anaerobic process (30-35°C) and the negative influence on process stability and gas production caused by rainfall is minimal.

Biological performance

Average gas production of the research plant when feeding FW and MW are positive and rather high compared to literature findings (Table 27).

Table 27: Comparison of gas production from research results with findings from literature

Source	*Feedstock*	*TS [%]*	*VS [%]*	*CH4 content [%]*	*Gas [Nl/kg VS]*
Lohri, 2009	**Food waste**	**24**	**91**	**57**	**572**
Eder&Schulz, 2003	Kitchen waste	9-37	80-98	45-61	200-500
Deublein, 2008	Leftovers (Canteen)	9-37	75-98	-	400-1000
Lohri, 2009	**Market waste**	**10**	**88**	**66**	**628**
Eder&Schulz, 2003	Market waste	28-45	50-80	62	450
Deublein, 2008	Market waste	8-20	75-90	-	400-600

The average pH value of all visited CBS (in operation) was 6.5, which is at the low end of the recommended pH range (6.5-7.5) for one-stage systems (Welliger et al., 1991, Mata-Alvarez, 2003, Eder & Schulz, 2006).

5.1.2 Economical aspects

According to Costech (2006), the major barrier for dissemination of the biogas technology in Tanzania is the high investment cost. This statement is also applicable for the ARTI CBS. The monthly income of the majority of population in the city of Dar es Salaam varies between 20,000 TZS (20 US$) and 200,000 TZS (200 US$) and the Tanzania Department of Statistics estimates the city's monthly per capita income at around 40 US$ (Sanga, 2003). Considering these facts, the 850'000 TZS investment cost for a household plant limits the range of potential customers to members of the high-income class only.
It is further questionable, if the gap between material cost of a CBS (360'000 TZS) and price of the system (850'000TZS) needs to be as high as it is or if another strategy would be more helpful in accomplishing the goal of wide disseminating of the technology.

The biomethanization of 2kg kitchen waste (consisting of 1kg food waste and 1kg market waste → 17%TS, 90%VS) in the ARTI research CBS resulted in an average of 200l biogas (61% CH_4), which in turn resulted in a burning duration of 45 min. This is approximately 1/3 of the average cooking time of 2.5h per day and family (household with 5 members).
An average household using 84kg of charcoal per month (Sanga, 2003) can therefore save one third of charcoal (28kg), which is an equivalent of 23'000 TZS (current monthly expenditures per household and month: 70'000 TZS). The amortisation period hence adds up to approximately 3 years.

Charcoal industry is one of the largest informal sectors in Tanzania, providing employment especially to the very poor part of society. As these people may probably not benefit directely from the ARTI technology because of its high investment costs, they might even see a decrease in possibilities for income generating activities. The poverty reduction potential is thus assessed to be very low.

As there are currently no competing products on the Tanzanian market for anaerobic digestion of organic solid waste on household level, the potential market viability is regarded to be good. The most critical market factor is quality and reliability of installed digesters, as mouth to mouth propaganda can also work counterproductive in case of bad performances. Consequently, an accurate quality control service is imminent.

5.1.3 Environmental aspects

Viewed from an environmental perspective, the anaerobic digestion of organic solid waste in an ARTI Compact biogas system bears several positive consequences:

- 83% - 92% reduction of organic load and hence less pollution through open dumps
- 30% diminution of charcoal use and therefore less deforestation
- Reduction of methane emission, if produced biogas is properly burned
- An odourless high-quality fertilizer
- A high potential for awareness-rising as it perfectly shows that waste can be looked at and used as a valuable resource ('from waste to value').

5.1.4 Socio-cultural and political aspects

The acceptance of biogas in Tanzania is high and it even carries the perception of being modern (Schmitz, 2007). Yet there is low awareness about waste separation, which can result in non-biodegradable material landing inside the digester (bones, wood, plastic…) or biodegradable matter not being fed into the digester. The day-to-day operation of a CBS requires a high level of discipline and routine to maintain a high gas production. It is therefore important to lay emphasis on proper instructions and facilitate the daily handling as much as possible.
There is no explicit political support, but also no specific obstacles have been observed in regard to biogas dissemination.

5.1.5 Safety issues

Although a theoretical risk of explosion with biogas exists, such catastrophe is not likely to occur. Danger arises mainly in closed chambers, where a mixture of air and biogas (6-12%) evolves. However, no explosion related to biogas utilisation has been reported in Tanzania (Schmitz, 2003), which is probably a result of the commonly open and therefore well ventilated rooms where digesters and burners are located. Both methane (lighter than air) and carbon dioxide (heavier than air) are toxic gases but are not considered to impose a serious threat to human health because of the airy architecture of Tanzanian buildings.

The hazard of attracting serious disease transmitters by the open area of digester liquid (rim) is relatively low, but can not be completely neglected. While *Anopheles* mosquitoes are unlikely to appear in digesters because of the high organic pollution, *Culex* mosquitoes will not despise this kind of breeding ground. Due to the physical construction of mosquito larvae (Appendix C4), they need to live underneath the liquid surface to suck oxygen through their breathing tube. Any turbulence disturbs this vitally important activity. As flooding or flushing of breeding place prevent the breeding of mosquito larvae (Cheesbrough, 1987), stirring the rim surface sporadically with a stick can therefore diminish the larval mosquito population.

If biogas is continuously produced but not constantly used, the capacity of the gasholder will be exceeded. There is hardly any danger for the dome to topple over, as the gasholder will be slightely lifted by the pressure of the gas. The abundant biogas can thus bubble out through the rim which is comparable to a safety pressure valve.

Although hydrogen sulphide is a toxic gas (Table 10), desulphurisation on the biogas resulting from an ARTI CBS at household level is not necessary. Since CH_4 and CO_2 are both odourless (but nevertheless dangerous), the appearance of H_2S can even be helpful in detecting gas leakages. Simple experiments have been done by adding a low-tech sulphur trap to the research plant. Yet the efficiency of the trap could not be fully measured due to the low H_2S detection range of the Dräger X-am 7000 sensor.

It is worth mentioning that a well functioning CBS does not release any bad odour and is therefore user-friendly in this regard.

5.1.6 Overview of suitability assessment

Table 28 presents an overview of the previously discussed criteria and their evaluation in terms of suitability. The criteria listed do not claim completeness or equality of importance, but demonstrate a possibility to assess a question incorporating different aspects.

Table 28: Overview of suitability assessment

Criteria of suitability	*Very low* --	*Low* -	*.OK.* o	*Good* +	*Very good* ++
• **Technical aspects**				**X**	
Local availability of material					X
Suitability of parts used			X		
Biological performance					X
Simplicity of operation				X	
Optionality for maintenance (follow-up service)		X			
Climatical suitability					X
• **Economical aspects**		**X**			
Widespread affordability (investment cost)	X				
Savings through energy substitution			X		
Potential market viability				X	
Poverty reduction potential	X				
• **Environmental aspects**					**X**
Reduction of organic waste					X
Reduction of deforestation (charcoal use)					X
Benefits from organic fertilizer					X
Awareness rising potential (nutrient circle)					X
Reduction of greenhouse gas emissions				X	
• **Socio-cultural and political aspects**			**X**		
Acceptance and reputation of biogas					X
Awareness of waste separation		X			
Change of daily routine			X		
Political support			X		
• **Safety issues (nuisances)**				**X**	
From explosion				X	
From disease spreading (mosquitoes)			X		
From toxic effect of CH4 & CO2				X	
From H2S				X	
Odour					X
• **OVERALL SUITABILITY**				**X**	

5.2 Recommendations

5.2.1 General

The ARTI Compact biogas system (CBS) seems more feasible for households in urban areas, as organic solid waste generated in rural region are preferably used as animal feed. Discussions with customers previous to their purchase of a CBS should emphasize on

- The realistic amount of organic waste possibly generated in their household (and the possibility to organize additional waste in their neighbourhood).
- The approximate operational effort per day and the responsibility of the person operating the ARTI Compact biogas system.
- The presumable output of biogas and its energy equivalent (hours of cooking).

(- The possibility of getting money refunded through well maintenance of the CBS → rebate system, see 5.2.3).

As a result of the inspection tours, the CBS seems suitable for households aiming to save money in the long term (by replacing conventional cooking fuels). These households should be targeted and could be reached by a more attracting (reduced) price per unit. Most household of the high-income class however did not seem to pay much attention to the functioning of the system as the financial factor is not essential to them.
On an institutional level, the CBS seem to be more successful, as the schools can purposely appoint an employee responsible for the daily feeding of the plant. This employee is thus interested in good maintenance and performance of the system, as his salary directly depends on it. In addition, CBS can help eco-lodges with the aim of offering an environmental friendly alternative to mass tourism to live up to their philosophy.

5.2.2 Technical

Installation

The most essential technical recommendation for improvement concerns the size of digester and gasholder. A better fit between these two elements would considerably reduce the loss of biogas to the atmosphere. While this loss is about 22% of total digester area using SIMTANKs (see 2.3.2), AFRITANKs (1000l tank: Ø1.07m, 750l tank: Ø0.98m) would reduce this waste area to approximately 14%. According to ARTI-TZ, negotiations with AFRITANK are on its way. Instead of clueing parts like nipple, elbow and gas tap with Araldite, it is advisable to use solid tape. While one broken part can thereby easily be unscrewed and replaced, broken objects which are clued together eventually require the replacement of the whole gasholder.
To minimize the risk of a blocked inlet-pipe, ARTI-TZ started to install a swift-elbow instead of a T-connector at the lower end of the inlet-pipe. However, it is more recommendable to attach a 2”-ball valve to the T-connector (as it has been done on the research plant), through which the blocking material can easily be removed.
Even properly operated CBS permanently create condense water which lead to clogging of the gas hose on a weekly basis. Although such minor problems can easily be corrected by removing the water, it can also lead to a complete standstill of the system if no actions are undertaken. In Appendix C6, three suggestions for condense water drains can be found.

Daily operation

It is highly recommended to adopt the enhanced feeding procedure as described in 3.1.2 (Feeding plan, phase 2) which includes

- previous dilution of cut-up feedstock to prevent blocking
- feedback of effluent (20l) to mix bacteria with fresh influent and prevent distinctive pH gradients inside the digester

The inlet pipe should permanently be covered to avoid entering of giant snails. A 5l-bucket can facilitate the operators' understanding of the required daily feeding load. Additionally, a 20l bucket with a clearly visible 10l-mark can be recommended to measure the amount of water to dilute the feedstock with. Complaints of customers about the weak flame of the burner can be prevented by advising them to lay half a cement brick on the gasholder. A phone number of an 'ARTI biogas doctor' on the digester can help in case of any questions.

Follow-up service

A clear after-sales service strategy should be developed. After the installation, three services should be conducted which are included in the price of a Compact biogas system.

1st service (2 weeks after installation before the first feeding): Demonstration and explanation of the feeding procedure (potential feedstocks, pre-treatment, dilution, feedback of effluent, condense water removal, indication of possible problems, utilisation of effluent, distribution of manual, encouragement to call 'biogas doctor' in case of questions)

2nd service: (3-4 weeks after 1st service): Check-up of CBS (see check-list, Appendix B4), short interview with operator about experiences and problems

3rd service: (6 months after installation): Check-up of CBS, short interview with operator about experiences and problems

All services should be documented and the date and status marked on a sticker on the digester. The 2nd and 3rd follow-up services should possibly be arranged to take place during feeding time. This allows observation and gives room for the ARTI technician to comment the procedure. After the 3rd service, a sporadic inquiry by phone can give valuable information about the status of functioning and the satisfaction of the customer. Another service package over a certain period can be offered against payment.

Each time an ARTI technician visits an operating CBS, 5-10l of effluent should be collected and brought back to a large demonstrational, regularly fed 'mother plant' at the ARTI office. The aggregate of bacterial samples from all existing plants which are cultivated there act as a reservoir of diverse inoculum and can be used when setting-up a new CBS to guarantee a potent, odourless start-up mix.

5.2.3 Economical

Previous to the sale of an ARTI Compact biogas system (CBS), the realistic amount of kitchen waste generated in the household should be estimated and the customer given the option to choose between two alternatives:

- A regular CBS (1000l) which is only fed with the daily waste generated in the household. The output can substitute up to 1/3 of the expenses for cooking fuel.
- A larger CBS (1500-2000l), which requires the organisation of additional waste from restaurants, markets and/or chips sellers nearby. On one hand the investment cost is higher, on the other hand also the biogas output and therefore the substitution of cooking fuel rises. It should be clearly communicated that this alternative requires more logistical effort to collect the waste and more operational effort to feed the plant.

Since the price of 850’000 TZS for a household-CBS constitutes the main barrier for a wide dissemination of the ARTI technology in Tanzania, the price strategy should be reconsidered. A rewarding rebate system could eventually motivate the users to take better care of their CBS. On the 2nd and 3rd follow-up service, the customers could be awarded with 50’000 TZS each, if their CBS is properly maintained and functioning well. One year after the purchase of the system, another 50’000 TZS could be given back to the owner if the plant is working without problems. If the CBS needs to be fixed on one of these three occasions, the price of 50’000 TZS can be considered as repairing fee. Hence the actual cost of a well maintained CBS can be reduced from 850’000 to 700’000 TZS.
The aim of this rebate system is a high percentage of smoothly operating CBS which directly helps the ARTI technology by evoking positive mouth-to-mouth propaganda.

5.2.4 Environmental

A better fit of digester and gasholder will also benefit the environment as it reduces the emission of greenhouse gases to the atmosphere. In cases of water shortage, the feedstock can as well be diluted with effluent (yet inhibiting components like heavy metals will thereby not be diluted).
One advantages, which can as well be communicated is the saving of wood and thus the reduction of deforestation (0.9kg charcoal per day and household = 5.6kg wood/day/household).

5.2.5 Socio-cultural and political

Since waste separation is not common in many developing countries, emphasis should be laid on patient explanation. Moreover, concrete examples should be given to illustrate the different kind of wastes suitable as feedstock. It is recommended to give the operational instructions not only to the owner of the biogas plant, but particularly to the person responsible for the daily feeding.

It should be considered that every new technology which requires a change in daily habits needs to convince its customers in the beginning, regardless to society and culture.

5.2.6 Safety

Attention should be paid to the location of the digester and the gas burner. The plant should stand in direct sunlight and as close to the gas burner as possible, whereas the burner itself should be placed in a well ventilated room. The customers should be informed about the dangers of gas leakages (intoxication, explosion) and advised to check vulnerable spots regularly by smelling. To avoid breeding of mosquitoes, it is further advisable to stir the rim surface with a stick on a weekly basis.

5.2.7 Simple monitoring of ARTI-plants

A check list as suggested in Appendix B4 should guide the ARTI technicians during their monitoring. In terms of chemical-physical parameters, pH (optimum 6.5–7.5) and digester temperature (optimum 25-35°C) should be recorded. An interview with the operator should give indications regarding the comprehension of the system, the satisfaction of the customer and eventual problems that have occurred.

Table 29: Recommended equipment for monitoring of ARTI CBS

Equipment	*Purpose*
Check-list and pen	Guidance, keeping record of services
pH-Litmus stripes or pH meter (+ calibration standards)	pH measurement
Lighter or matches	Checking combustibility of biogas
Soap	Checking air tightness (with soapwater)
Tools (screwdriver, knife, glue, seal tape, hose clips…)	Repairing
Condense water traps	Installation
Empty water bottles (5-10l)	Collection of digester liquid
Digital Camera	Picture of problems
Customers manual and contact number	To be contacted in case of questions
Sticker: “checked by ARTI on (date) by (name)”	Proof of service, attaching to digester

For more detailed information about the process stability and efficiency of the CBS, the A/TIC-ratio (Appendix A2) and composition of biogas could be further analyzed. However, these measurements require either deeper understanding of the chemical background of anaerobic digestion (A/TIC) or expensive instruments (Dräger).

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Table of Figures

List of Tables

Appendix

CONTENT OF APPENDIX

A Laboratory

B ARTI

C Various

D Presentation