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Decentralised anaerobic digestion of market waste

Case study in Thiruvananthapuram, India

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Cover picture: Market of the Sreekaryiam Grama Panchayat, Thiruvananthapuram (Picture: Florian Heeb).

Summary

In the urban areas of low- and middle-income countries, municipal solid waste (MSW) management is one of the most urgent topics. Decentralized anaerobic digestion is a promising technology to handle the large organic fraction of the MSW with the additional benefit of producing biogas as well as fertilizer.

Hence it is important to provide reliable data on the real scale application of this technology. For this purpose, a market level biogas plant in Thiruvananthapuram, south India was chosen for monitoring and evaluation. Besides technical aspects, the economical feasibility as well as operational challenges were assessed.

The monitored plant was constructed by the BIOTECH NGO, which already built a large number of decentralised biogas plants on household, institutional and market level.

Concerning economical aspects, the considerable investment costs (23’500 €) of the market level plant have to be mentioned. Further, the annual costs for operation and maintenance add up to 10-15% of the investment costs. Yet the maximal income that can be created with the production of electricity out of the biogas does only cover a third of the annual costs. Additional incomes could be generated by selling the effluent of the plant as fertilizer as well as by the implementation of projects under the clean development mechanisms (CDM) of the Kyoto protocol.

In India MSW management lies in the responsibility of the local bodies. BIOTECH meets the operational problems due to the ever-changing local political environment with including long-term operation and maintenance contracts in their projects.

The monitored market level plant was equipped with a 25 m^3 digester tank with a floating drum and was operated in a slurry-loop mode. The produced biogas was scrubbed and used to run a 5kW generator.

The treated waste consisted mainly out of fish waste. It was rich in energy and very rich in nitrogen and phosphorous (TS: 23 %; VS: 63 %TS; COD: 1.3 gO_2/gTS; N_{tot}: 8.7 %TS; P_{tot}: 1.2 %TS).

The digester was running very stable (T: 29.3 °C; pH 7.85). The organic loading rate was low (OLR: 0.568 kg kgVS m^{-3} d^{-1}), whereas the hydraulic retention time was extremely high (HRT: 262 d). The specific gas production turned out to be in a normal range (SGP: 0.399 m^3 $kgVS^{-1}$ d^{-1}). The composition of the biogas was constant (CH_4: 66.8%; CO_2: 27.4%).

The effluent of the digester was fluid and very rich in nitrogen and phosphorous, the C/N ratio was very low (TS: 9.47 g/l; COD: 8998 mgO_2/l; N_{tot}: 7520 mgN/l; P_{tot}: 547 mgP/l; C/N: 0.43). Hence the effluent is very suitable for the use as liquid fertilizer. The extremely high ammonia content of the effluent (6104 mgN/l) resulted in odour, but no inhibitory effects on the gas production were observed. Yet the currently rising nitrogen values could lead to future problems. For prevention, carbon rich waste can be added. Heavy metal analysis of the effluent did not show any extraordinary results.

Generally it can be said that the technology of decentralized anaerobic digestion is very suitable for the treatment of market waste. However it will we important to increase the economical attractiveness of market level biogas plants, i.e. by reducing the investment costs, selling of the effluent as fertilizer or the development of CDM projects.

Content

Abbreviations

A/TIC	Acids to total inorganic carbon ratio
CDM	Clean development mechanism
CDPT	City development plan for Thiruvananthapuram
CFL	Chemo fluorescent lamp
COD	Chemical oxygen demand
FRP	Fiberglas reinforced plastic
GPR	Gas production rate
HRT	Hydraulic retention time
KSUPD	Kerala sustainable urban development project
LPG	Liquefied petroleum gas
MSW	Municipal solid waste
MSWM	Municipal solid waste management
MSWR	Municipal solid waste (management and handling) rules 2000
NH_4^+	Ammonium
NH_3	Ammonia
N_{tot}	Total nitrogen
OLR	Organic loading rate
PO_4^+	Phosphate
P_{tot}	Total phosphorous
SGP	Specific gas production
TDS	Total dissolved solids
TS	Total solids
TSS	Total suspended solids
VFA	Volatile fatty acids
VS	Volatile solids
VSS	Volatile suspended solids

1 Introduction

Especially in the urban areas of low- and middle-income countries, municipal solid waste management (MSWM) is one of the most urgent topics (Zurbrügg 2002). The absence of appropriate MSWM solutions leads to grave impact on human health as well as on the environment (Zhu et al. 2008).

In India, MSWM is the duty of the local municipalities (Ministry of Environment and Forests 2000). Although it is one of the most important basic services of the local municipalities, it also is one of the most problematic ones. Mostly the applied systems are unscientific, outdated and inefficient. The coverage of the population is generally low; the poor are mostly marginalised (Asnani 2006). More than 90 percent of the municipal solid waste (MSW) generated in India is dumped in an unsatisfactory way, what creates environmental hazards to water, air and land (Kumar et al. 2009). At the same time the organic fraction of MSW is about 30-45 percent (Bhattacharyya, Kumar & Devotta 2008). According to Vögeli & Zurbrügg (2008) anaerobic digestion of the organic fraction of municipal solid waste is a very promising technology for developing countries with tropical climate. A previous literature study conducted by Sandec showed that among low and middle- countries, India has the biggest experience in decentralized anaerobic digestion of household, canteen and market waste and projects are implemented all over the country (Mueller 2007).

Therefore, the potential for biogas plants which treat household, canteen and market waste is enormous in India (Vögeli & Zurbrügg 2008). However, at the same time, the database on decentralized anaerobic digestion of MSW is rather limited at present.

1.1 Objectives

The main objective of this report is to provide reliable data on anaerobic digestion of organic solid waste on real scale. Besides technical aspects, like i.e. gas yields and effluent quality, also the economical feasibility as well as operational challenges of decentralized anaerobic digestion are assessed. In order to do so, a market level biogas plant of the BIOTECH NGO in Thiruvananthapuram, south India was chosen for the monitoring and evaluation.

A comparable report on anaerobic digestion of kitchen waste on household level with an ARTI[1] digester in Tanzania has been written by Lohri (2009).

[1] Appropriate Rural Technology Institute; http://www.arti-india.org/.

In the present study, on the one hand a detailed description of the BIOTECH NGO and the local conditions the NGO is working in is given with the aim of identifying important factors for the successful implementation of biogas projects in low and middle-income countries. Furthermore, the main problematic aspects occurring in the implementation of such projects are highlighted. On the other hand, an intensive technical monitoring was conducted at a biogas plant treating the waste of the Sreekaryiam grama panchayat market in order to provide reliable real life data of an example of decentralized anaerobic digestion of market waste on a full-scale level.

Figure 1: Geographic location of Thiruvananthapuram (A), State of Kerala, India (Google Earth).

First, an overview of the situation of SWM in Thiruvananthapuram is given. The relevant legal framework is discussed as well as the present waste generation, composition and the applied SWM practises.

In a second part, a detailed description of the organisation BIOTECH is given focussing at their applied technologies as well as on the organizational structure of the NGO. Important management and economical aspects are highlighted.

The third part shows the methodologies applied for the technical monitoring.

In the fourth part, the results of the technical monitoring of the biogas plant at the market of Sreekaryiam are presented. The characterizations of the digested waste as well as the operational parameters of the plant, the gas production and composition and the effluent quality are shown.

In the fifth and last part, the findings about the BIOTECH NGO and the results of the technical monitoring are discussed in order to make recommendations and identify the most crucial aspects for the implementation of biogas projects at market level.

1.2 Solid waste management in Thiruvananthapuram

Although the management of municipal solid waste is one of the most important basic services of the local municipalities, it also is one of the most problematic ones in whole India.

Mostly the applied systems are unscientific, outdated and inefficient. The coverage of the population is generally low; the poor are mostly marginalised (Asnani 2006).

In the following, the present situation of solid waste management in Thiruvananthapuram will be described with a special focus on market waste. Relevant regulations, generation and composition of MSW, as well as the existing MSW management practices will be discussed

1.2.1 Regulations concerning SWM

In 2000, the Ministry for Environment came up with the Municipal Solid Waste (Handling and Management) Rules 2000 (MSWR) (Ministry of Environment and Forests 2000).

These rules clearly give the responsibility for the solid waste management, particularly the infrastructure development for the collection, storage, segregation, transportation, processing and finally the disposal of municipal solid wastes to the local bodies[2].

Generally, the MSWR demand that all municipal solid waste should be managed and handled according to specified criteria.

As for the biodegradable fraction, the rules demand to process it by composting, vermicomposting, anaerobic digestion or any other appropriate biological processing for stabilization of wastes. Products of those processing have to meet specific standards. Land filling is being restricted to non-biodegradable, inert waste and other waste not suitable for biological treatment of recycling.

For biodegradable wastes from fish, meat and vegetable markets as well as from slaughterhouses, the MSWR say that they have to be managed in a way to make use of them, whereas this use is not further specified.

1.2.2 Generation and composition of MSW

The present SWM situation has recently been assessed in two reports. The first is the City Development Plan for Thiruvananthapuram[3] (CDPT) (Thiruvananthapuram Municipal

[2] In general, the urban local bodies of bigger cities with more than one million inhabitants are municipal cooperation. In smaller cities the urban local bodies are the municipalities. Panchayats are the local bodies in rural areas. In Thiruvananthapuram, the central parts of the city are governed by the city's municipal cooperation. Due to the growth of the city twelve surrounding Panchayats are adjoined to the urban area of Thiruvananthapuram.

[3] The CDP for Thiruvananthapuram has been submitted under the Jawaharlal Nehru National Urban Renewal Mission by the Thiruvananthapuram Municipal Corporation and the Local Self Government Department, Government of Kerala to the Ministry of Urban Development and the Ministry of Employment and Poverty Alleviation, Government of India.

Corporation & Local Self Government Department 2006), the second is the Final Report of the Kerala Sustainable Urban Development Project (KSUDP)[4] (Sinclair Knight Merz 2005).

The daily production of waste in the territory of the Thiruvananthapuram municipality cooperation[5] is 270 tonnes per day (KSUDP). With a population of 0.74 millions (Banthia 2004) this makes an average rate of 365 g of waste per capita and day.

The KSUDP states the share of market wastes to be 13.34 percent (Table 1). According to the CDPT the markets are with 15.43 tonnes responsible for only 5.79 percent of the daily production.

As can be seen in Table 2, organic waste has by far the biggest share on the composition of the municipal solid waste. The share of organic matter from markets and commercial areas waste is reported to be 42.09 percent.

Table 1: Sources and amount of municipal solid waste in Thiruvananthapuram in the year 2001 (Sinclair Knight Merz 2005).

Sources of Waste Generation	Waste Generation Per day [t]	Share on total waste generation [%]
Households	164.09	60.00
Shops	11.79	4.33
Hotels and restaurants	27.21	10.00
Hospitals	1.81	0.66
Tea shops	0.90	0.33
Workshops	0.90	0.33
Markets	36.28	13.34
Street sweeping	1.81	0.66
Construction works	9.07	3.33
Marriage halls & temples	18.14	6.67
Total	**272.00**	**100.00**

[4] The Final Report of the KSUDP has been prepared by Sinclair Knight Merz, Australia for the Local Self Government Department, Government of Kerala and was financed by the Asian Development Bank.
[5] This does not include the Panchayats adjoined to the city.

Table 2: Composition of the municipal solid waste in Thiruvananthapuram 2001 (Sinclair Knight Merz 2005).

Physical Composition	Households [%]	Markets/Commercial Areas [%]	Hotels & Restaurants [%]	Hospitals [%]
Paper	10.04	13.27	5.61	16.42
Glass	1.63	2.26	6.66	14.09
Textile	2.68	2.53	1.34	10.03
Plastic	5.59	13.29	3.64	9.13
Wood	1.38	0.46	1.24	0.15
Metal	1.75	3.64	0.54	1.338
Organic waste	51.50	42.09	66.86	39.45
Ash	4.06	1.61	5.5	0.96
Sand	12.84	8.87	5.49	3.00
Misc.	8.01	11.15	3.03	5.48
Total	**100.00**	**100.00**	**100.00**	**100.00**

1.2.3 Existing solid waste management practices

Figure 2: Collection of waste at an open waste collection point. The waste is dumped on the ground at special places along the roads and then collected by municipal or private workers (Picture: Florian Heeb).

The separation of waste at households is not very common although combustible parts are often burnt.

In the territory of the municipal cooperation the waste is generally collected from temporary open waste collection points along the roadside (Figure 2). Since 2006, in some areas of the municipality a door-to-door collection system exists. The waste is separated at the household and then collected by women groups and other organizations under the Capital City Clean City[6] project.

[6] The Capital City Clean City project is an initiative by the Thiruvananthapuram Municipal Cooperation with the aim to provide improved waste collection.

The collected waste is thereafter brought to two different waste transfer stations or directly transported to a mechanical compost plant in the Vilappilsala Panchayat, about 15 km away from the city. Collection and transport is mostly done by cooperation workers, but there are also three private companies involved.

At the mechanical compost treatment plant, which is in use since 2000, the waste is treated in a two stage aerobic process. The non-biodegradable refuse is afterwards dumped on nearby landfills. There are no proper sanitary landfills available. Problems like the irregular delivery from the collection system and the relatively high content of plastic bags lead to occasional shutdowns of the plant (Ambat 2003). The quality of the compost produced in Indian centralised compost treatment plants is generally considered to be rather low (Kumar et al. 2009).

It is estimated that about 70% of the waste generated on the municipality's territory find their way to the plant. The plant is designed to handle a maximum of 300 tonnes of waste per day. At present the amount of treated waste varies between 190 and 220 tonnes a day. Although the capacity is enough for the moment, the steady growing population will result in a fast increase in the amount of waste. The CDPT considers biogas plants at household, ward, institutional and market level as a good option to reduce the waste production at the source (Ministry of Environment and Forests 2000).

However, there is no waste collection system existing in the Panchayat adjoining the city, like fore example in Sreekaryiam[7]. In these places, the waste is mostly dumped besides the streets. Looking at the fact that 32% of the urban population of Thiruvananthapuram are living in the adjoined Panchayat (Banthia 2004), the amount of unmanaged waste is considerable.

The waste of the markets is mostly dumped in open places nearby; some parts are also burnt. Some of these dumping sites have developed to waste transfer points. Especially fish waste causes severe problems because it begins to smell heavily within very short periods of time (Ambat 2003).

Due to the large amount of waste that is land filled and dumped in improper manner the groundwater in Thiruvananthapuram contains excessive concentrations of lead and iron (Kumar et al. 2009).

[7] The market level biogas plant where the monitoring was performed is located in Sreekaryiam.

2 Description of the BIOTECH NGO

In the following, a detailed description of the BIOTECH NGO is given. There will be a description of their different products as well as their organisational structure. Afterwards important issues in terms of management and economical aspects are highlighted and discussed. The address and contact details of BIOTECH can be found in appendix A.

Figure 3: BIOTECH domestic plant with ferro-cement digester tank. The plant has been in use for ten years, problems have occurred only very rarely (Picture: Florian Heeb).

BIOTECH is a Kerala based NGO with the aim of providing biogas technology for the treatment of organic solid wastes in urban areas. Mr. A. Saji Das, who at present is the director of the NGO, founded it in 1994. The NGO runs three main offices in Thiruvananthapuram, Cochin and Calicut as well as five field offices all over the state and a production workshop outside the city of Thiruvananthapuram.

BIOTECH started to build first domestic level biogas plants about ten years ago and has experienced a steady growth since then (Figure 3). In 2007 BIOTECH received the Ashden Award for Food Security[8] for their achievements (The Ashden Awards 2008).

2.1 Biogas plants

Although small domestic level plants for the treatment of kitchen waste and production of gas for cooking still have by far the biggest share, BIOTECH developed several other biogas plant concepts, all of them according to the floating drum design widely used in India.

An important improvement was the introduction of fibreglass-reinforced plastic (FRP) (Figure 4). With this technology, BIOTECH is able to produce prefabricated, portable biogas plants with a volume[9] up to 6 m^3. The only necessary thing for the installation of such a plant is to dig an appropriate hole in the ground and start-up the plant with cow dung in order to inoculate the digester with the required anaerobic microorganisms. The time spent for transport and installation therefore is very low, no special manual skills are required.

[8] The Ashden Award is an award for projects with outstanding achievements in the field of sustainable energy in the UK as well as in developing countries. The awards take place once a year (www.ashdenawards.org).
[9] In the following the values of volume stand for volume of the digester tanks.

Figure 4: Fabrication of a fibreglass-reinforced biogas plant (Picture: Florian Heeb).

FRP has the advantage that the water and gas tightness is very high and the use of steel drums, which are prone to corrosion, can be omitted. A clear disadvantage is the higher cost of the full-FRP models. A 1 m^3 domestic biogas plant of the conventional design, consisting of a digester tank made of prefabricated ferro-cement elements and a FRP gasholder drum (Figure 3) costs about 10’000 RS (158 €). On the other hand, the costs of the cheapest 1 m^3 FRP plant of the new design add up to 15’000 RS (263 €)[10] (Figure 5a).

[10] More detailed costs of the domestic plants sold at present can be found in Appendix C.


Figure 5: Different types of BIOTECH biogas plants. Top middle: a) 1 m^3 domestic level plant for the treatment of kitchen waste. Top right: b) 2 m^3 domestic level plant with a link for a toilet and an inlet for kitchen waste. Top left: c) 4 m^3 institutional level plant. Lower left: d): 25 m^3 market level plant equipped with gas scrubber and generator (Pictures: Florian Heeb).

Until now, BIOTECH has built about 15'000 domestic level biogas plants for the treatment of kitchen waste (Figure 5a). The volume of the digester tank of these plants is $1m^3$. With the aid of special biogas stoves, the produced gas is used for cooking. According to a small survey undertaken in several households, the produced gas is sufficient for about 1/3 of the total cooking of an average family[11]. The digester effluent can be used as a fertilizer. The big majority of the 1 m^3 plants have been built according to the ferro-cement design. However, at present only the portable FRP models are sold. The $1m^3$ domestic level plants are sold with or without water-jacket[12].

BIOTECH also produces toilet linked biogas plants (Figure 5b). For ensuring high enough retention times, the toilet linked biogas plants have a minimum size of 2 m^2 for one family. Through an additional inlet also the kitchen waste can be added and co-digested in the plant. The produced gas is used for cooking. Totally, 170 toilet linked biogas plants have been installed, the big majority of them on the Island of Kumbalangi under the Integrated Tourist Village Project[13]. BIOTECH does not report any resentment against cooking with gas produced out of human faeces.

On institutional level BIOTECH installed about 200 biogas plants in hostels, schools, hospitals and other similar places for the treatment of canteen waste (Figure 5c). The produced biogas is directly used for cooking. Mostly, the plants have a size of about 4 to 10 m^3. The plants have a basement built of ferro-cement and a gasholder drum made of FRP-coated steel for bigger plants or a drum made of FRP for smaller plants, respectively. Some bigger institutions possess biogas plants with a size up to 50 m^3 equipped with a generator for electricity production. Those plants have basically the same design as the market level plants described beneath.

Up to date, BIOTECH has completed 28 market level plants, a further 22 plants were in planning or construction in January 2009 (Figure 5d). In Table 3 an overview over four market level plants and one big institutional plant is given. The market level plants have generally one or two floating drum digesters with a volume of 25 m^3 per digester. In most of the market level plants the feedstock consists of fish, vegetable and fruit waste, in some cases also slaughterhouse waste is processed. The plants are dimensioned to treat a maximum of

[11] The results of the survey about the domestic level plants can be found in Appendix D.
[12] In a plant with water-jacket, the drum is not floating directly in the digestate liquid but in a special water filled compartment along the digester tank. Besides giving a better aesthetical impression, this design avoids loss of biogas through the digestate surface outside the drum and therefore the emission of the greenhouse gas methane to the atmosphere.
[13] More details about biogas plants on the Kumbalangi Island can be found in Appendix D.

250 kg of waste per day. The biogas is used to produce electricity with the help of special biogas generators. Usually, the electricity is used to light the market and the surrounding streets. However, the electricity produced by the generator is not always used to the full extent. The market level plants are run in a slurry-loop system. That means that the effluent of the digester is pumped into a storage tank and from there used to flush the feedstock into the digester. Except for cleaning purposes, there is no need for adding fresh water to the process. A more detailed description of a market level plant can be found in chapter 4.1.

With the so-called Integrated Waste Treatments Systems (IWTS), BIOTECH tries to give a solution to handle even broader range of waste. An IWTS consists out of a biogas plant with a generator similar to the market level plants. Additional, the IWTS possesses a "Biocinerator", an incineration facility for dry organic matter and other combustible matters. The waste that arrives at the IWTS is sorted manually. The parts that are non-biodegradable and cannot be burnt are separated and transported to recycling facilities. At the moment, three IWTS plants have been built.

Table 3: Comparison of different market and institutional level plants.

Location	In operation since	Volume [m^3]	Feedstock	Pre-treatment	Daily load* [kg/d]	Generator power [kW]	Use of electricity	Remarks
Market of the Sreekaryiam grama panchayat, Trivandrum District	2005	25	Fish waste, occasionally small quantities of fruits and vegetables	No Pre-digester available	86	5	Lightning of 12 lamps (2x11W) in and around the market during 3.5 hours in the evening	Subject of the monitoring
Market of the Kottarakara grama panchayat, Kollam District	2007	2 x 25	Mostly fish waste, smaller quantities of vegetable and fruit waste	Pre-digester for vegetable and fruit waste in use	100	5	50 lamps (2x11W) in the market and the surrounding streets, during 3.5 hours in the evening	
Market of the Chdaamangalam grama panchayat, Kollam District	2008	25	Slaughterhouse waste	Pre-digester available but not in use	100	3	24 lamps (2x11W) in the market and the surrounding streets, during 3.5 hours in the evening	
Market of Thrikkarakara, Chdaamangalam grama panchayat, Ernakulam District	2008	25	Fish, vegetable and fruit waste	Pre-digester for vegetable waste in use	80 (fish) 60 (fruit and vegetables)	5	50 lamps (2x11W) in the market and the surrounding streets, during 3.5 hours in the evening	Massive froth formation occurred, probably due to overfeeding
Govt. Ayurveda College, Trippunithura, Ernakulam District	2007	2 x 25	Food waste from the hospital, waste from the production of ayurvedic herbal medicine	Pre-digester for herbal waste in use	200 (food waste)	5	100 Lamps (2x11W) inside the hospitals and 100 at the surroundings. Lamps inside are used as a backup for power cuts.	Excess gas is used for cooking with four biogas stoves

(*) All values except the one from Sreekaryiam are estimations from the local operators.

2.2 Personal structure

In Table 4, the allocation of the BIOTECH personnel into the different areas is listed. The allocation may give an impression on the priorities of the NGO.

Table 4: Employment structure.

Field of occupation	Number of person employed
Production	5 engineers
	50 workers
	60 associated masons*
Service	15 supervisors
	200 associated supervisors*
Operation of plants	20
Administration	30
Advertisement	20
Information	2

(*) Not directly employed by Biotech

Thirty people are working in the administrational part of the NGO. Besides the standard administrational tasks, BIOTECH runs a detailed register about every built plant. The register is not yet digitalised and therefore needs a lot of work to be kept up to date.

The fabrication of the biogas plants is taking place in a production workshop outside Thiruvananthapuram. At present, about 3000 biogas plants per year are manufactured at the workshop. The maximum capacity of the workshop is 25 biogas plants a day. Besides the 50 construction workers and fife engineers occupied at the workshop, BIOTECH has 60 associated masons that can be hired for required work at the construction sites of bigger plants.

For supervision and service of the biogas plants, only 15 persons are employed. In addition, about 200 associates who are not employed by BIOTECH itself, are responsible for the big majority of the service for the household level plants. The NGO provides them basic training about biogas technology and maintenance. The associates provide the service on their own account and therefore are able to earn an additional income with this task. With this system, it is possible to provide service even in remote places without being obliged to have own infrastructure over the whole state. Generally, BIOTECH has a big focus on service. The NGO actively contacts the owners of new biogas plants for the first months to avoid problems with the start period or inappropriate handling of the pants. In a small survey done in several households (cf. appendix E), all visited families reported good experiences with the provided service.

The market level plants are owned by the local bodies but operated by BIOTECH on a contractual basis. Usually, there is at least one BIOTECH employee that is responsible for feeding the digester, operating the generator and generally maintaining a market level plant.

The advertisement and awareness rising is taking in a relatively big part of the personnel. In the scope of their awareness rising program, the NGO has different program points like a road show (Figure 6), direct classes for schools and local demonstrations about biogas technology.

Figure 6: BIOTECH road show. The road show is equipped with a fully functional smallest scale biogas digester, as well as a TV-screen and loudspeakers for the screening of film material. The road shows travels all over the state promoting the biogas technology of BIOTECH (Picture: Florian Heeb).

Although BIOTECH does usually not launch advertisement in newspapers, the NGO has a relatively high presence in the media. For example, inaugurations of bigger plants are always made to "events" with the presence of well-known persons, e.g. ministers.

A new sector that at present only consists of two persons, but is planned to be enlarged is the information part of the NGO. The information officers are responsible to acquire knowledge about environmental issues and biogas technology and communicate it to the BIOTECH staff as well as to the public.

2.3 Management aspects of market level biogas plants

Principally, the Municipal Solid Waste (Management and Handling) Rules 2000 (MSWR) clearly demand from the local bodies to find appropriate solutions for the disposal of market waste. Yet the fact that not a single municipality in India compiled with the requirements given by the MSWR indicates that the pressure on the municipalities to implement this law is very low (Kumar et al. 2009). According to Mr. Saji Das, Director BIOTECH, the motivation for the implementation of the existing market level plants were not the MSWR or the consequences when not applying them. According to him the motivation came from the sensibility of individual local bodies towards environmental and waste problems.

In Kerala the local bodies are elected every five years and usually completely changed with every election. Because the sensibility of individual politicians is the main factor for the implementation of the market level plants, this periodical change creates big problems for the management of the plants according to Mr. Saji Das.

Without pressure from the law side, the new elected local bodies are often not willing to actively invest money in operation and maintenance of the plants implemented by their successors, what would lead to the sure breakdown of the plants.

The strategy of BIOTECH to handle these problems is to obligatorily include operation and maintenance contracts with a lifetime of five years in the implementation of new plants. The market level plants are operated by skilled BIOTECH employees. The maintenance of the plants is provided by BIOTECH on the basis of annual maintenance contracts (AMC). As BIOTECH has a vital interest to keep the plants running in order to avoid damage on its reputation, the system seems to work quiet well. Problem with the maintenance did mostly occur in older plants where AMCs were not yet included.

2.4 Economical aspects of market level biogas plants

Table 5 shows the average costs for construction, operation and maintenance of a market level biogas plant. The investment costs are substantial. The annual costs for operation and maintenance add up to maximal fifteen percent of the investment costs.

Table 5: Average costs of a market level biogas plant.

Investment costs		
Material	600’000 RS	(9’399 €)
Labour	900’000 RS	(14’098 €)
Total costs	**1’500’000 RS**	**(23’497 €)**
Operation and maintenance		
Annual operation expenses	112’500 RS	(1’762 €)
Annual maintenance contract	75’000 to 112’500 RS	(1’175 to 1’762 €)

Basically, the marked level plant provides benefits in three different ways. The main benefit is the appropriate treatment of the market waste; side products are electricity generated out of the biogas and effluent that can be used as fertilizer.

If the investment costs for the plant are compared to the maximum capacity (the plant was dimensioned for 250 kg wet weight of waste per day), a price of 6000 Rs (94 €) per kilogram of waste treatment capacity results. Because there is not enough information available on the cost of conventional waste disposal, like the transport to and treatment in the mechanical compost plant in Vilappilsala, it is not possible to calculate an actual monetary value for the service of waste disposal. However, most markets had no proper way of disposal before building the biogas plant. In these cases the waste was dumped into pits, which creates nearly no direct costs, but causes a great deal of external effects on environmental and health aspects, which cannot easily be expressed monetary.

Figure 7: Chemo fluorescent lamp installed by BIOTECH at the Govt. Ayurveda college, Trippunithura (left) and at the market of the Sreekaryiam Grama Panchayat (right). The lamps consist of two 11W bulbs (left picture: Florian Heeb; right picture: Christian Müller).

Since the electricity generated is used for public lightning, it is possible to estimate the cost for the lightning without the biogas plant. In Kerala, electricity for public lightning is not charged per unit of consumed energy but per lamp and month. The monthly charge for a lamp with two 11W chemo fluorescent lamp (CFL) bulbs, as installed in all BIOTECH projects, that are lit four hours per day, is 18 RS (0.28 €) (Kerala State Electricity Regulatory Comission 2007). With a full load of the installed 5 kW generators, a maximum of 227 of those lamps could be lit. This results in a maximum benefit of 49'090 Rs (767 €) per year out of the electricity. However, this benefit does not represent a direct financial incentive to the local bodies, because the markets mostly had no electrical lightning before. Compared to the yearly operation and maintenance costs, the benefit of the generator is not even high enough to cover half of the operation expenses.

The third potential source of income out of the biogas plants is the selling of the effluent as a fertiliser. The marketing of the products of aerobic composting as solid fertilizer is already a well-studied topic (Rouse, Rothenberger & Zurbrügg 2008). Analogue, the very nutrient rich effluent of the biogas plant could be marketed. However, it is not known which steps are required to make out of the liquid effluent a fertilizer that can be sold on the market. Therefore, further research would be necessary to estimate the benefits form this side. According to Mr. Saji Das, BIOTECH is going to take efforts in this direction.

Yet there is an additional positive effect inherent to both the production of biogas and the appropriate treatment of the waste. Biogas systems have the potential to reduce the emission of greenhouse gases in two different ways (Yapp & Rijk 2000). On the one hand, the produced biogas can be used as a substitution for fossil fuels. On the other hand, the appropriate treatment of the organic fraction of the MSW avoids emissions of the greenhouse gases methane and nitrous oxide, which occur when the waste is dumped on landfills. As methane and nitrous oxide have by far a higher global warming potential[14] than carbon dioxide, this effect is substantial. The clean development mechanism (CDM) of the Kyoto Protocol principally allows making benefits out of these reductions. The CDM permits industrialized countries with a greenhouse gas reduction commitment to invest in projects in emerging and developing economies, which lead to greenhouse gas reductions, i.e. biogas projects, and in exchange receive tradable reduction certificates. However, the biggest drawback for the implementation of small scale CDM projects are the high transaction costs due to the procedures for the certification of the projects and the following regular monitoring. Although the UNFCCC[15] developed special procedures for small-scale projects, the transaction costs would still be about 21 percent of the revenues through the certificates

[14] The global warming potential characterises the contribution of a cretin amount of a substance to the global warming relative to the contribution of the same amount of carbon dioxide. For a period of 100 years methane has a global warming potential of 25, nitrous oxide 298 (IPCC 2007).

[15] United Nations Framework Convention on Climate Change

(Bhardwaj et al. 2004). By bundling several small-scale projects, the transaction costs could be reduced, especially in cases where the monitoring can be done by simple metering. In biogas projects, the monitoring could be provided by simply installing a gas meter, which is regularly read. Like this, the transaction cost could be reduced to about 10 percent of the revenues (Bhardwaj et al. 2004). However, detailed clarifications would be necessary whether a CDM project would be feasible for future market level plants.

Finally, the problem remains that the BIOTECH market level plants require large investments and generate annual costs. Although the proper waste treatment is very valuable, it does not directly generate any monetary income and therefore no financial incentives for the municipalities.

3 Methods

In the following, the different methods applied for conducting the technical monitoring are listed. The monitoring took place over a period of about two months. Most of the feedstock and effluent analysis were performed in two periods with an interval of two weeks in between, whereas the gas production and the amount of feedstock were measured continuously. A detailed schedule of the monitoring can be found in appendix B.

3.1 Pre-treatment of effluent and feedstock samples

For collecting the effluent samples of the market level plant, the effluent pump (c.f. Figure 9) was run for one minute. In this way, fresh digester liquid was flowing out of the effluent pipe and was directly collected. The total sample volume was 1 litre. For the cuvette tests, which require specific measurement ranges, the sample was accordingly diluted with water. For the measurement of ammonia (NH_4^+) and ortho-phosphate (PO_4^{2-}) concentrations, the diluted sample was prefiltrated with Sartorius membrane filters (pore size 0.45µm, diameter 45mm).

Representative samples of the feedstock (consisting mostly of fish waste) were taken out of the waste collection bin in which the market salesmen dispose their waste. The average amount of sample taken was about 300g. The approximate composition of the sample was estimated and noted. The sample was thereafter diluted 1:1 with water and homogenised with a kitchen blender (Prestige Tulip, 600 Watt) for about three minutes. For the chemical oxygen demand (COD), total nitrogen (N_{tot}) and total phosphorus (P_{tot}) analysis the sample was afterwards diluted to the required range and homogenised one more time.

3.2 Measurement of chemical parameters

The Total Suspended Solids (TSS), Volatile Suspended Solids (VSS) and the Total Dissolved Solids (TDS) were measured according to standard methods (American Public Health Association 2005). The Total Solids (TS) were calculated as the sum of the TSS and the TDS. The fraction of Volatile Solids (VS [%]) was calculated as the share of VSS on TSS.

COD, N_{tot}, P_{tot}, NH_4^+, PO_4^+ were analysed with LANGE cuvette tests. COD was analysed with the LCK014 LANGE cuvette test, N_{tot} with LCK338, P_{tot} with LCK350, NH_4^+ with LCK303 and PO_4^{2-} with LCK049. The LANGE cuvette tests were analysed with a LANGE LASA 20 Photometer. For the digestion of the COD, N_{tot}, and P_{tot} LANGE cuvette tests a Dr. Lange LT1W thermostat was used.

The pH and temperature measurements were performed with a HACH Sension 2 pH meter and a Sension gel filled pH electrode.

The A/TIC, i.e. the acids (A) to total inorganic carbon (TIC) is a recently developed indicator for the process stability inside the digester. The A/TIC is calculated in dividing the more exactly the volatile fatty acids (VFA) trough the alkalinity (1).

$$\frac{A[mg/l]}{TIC[mg/l]} = \frac{VFA[mg/l]}{Alkaliniy\,[mgCaCO_3/l]} \qquad (1)$$

More detailed information about the A/TIC ratio can be found in appendix H. The alkalinity and volatile fatty acids (VFA) were determined with a three-point calibration after Kapp (1984). In difference to the original procedure recommended by Kapp, the step of microfiltration had to be omitted. Due to the extremely high content of small suspended particles and because a centrifuge was not available, any filtration of the undiluted effluent in reasonable quantities was not possible[16]. The measured content of VFA will therefore be somewhat higher than the real ones. Nevertheless, as shown in Lohri (2009), the A/TIC ratio represents a simple way to acquire information about the stability of an anaerobic digester even when omitting time consuming and relatively expensive step of microfiltration.

3.3 Measurement of biogas composition

Measurements of the carbon dioxide content of the untreated biogas were regularly performed over the whole monitoring period with a BRIGON CO_2-Indicator.

To get more detailed information on the biogas composition, and to be able to assess the measurements done with the BRIGON CO_2-Indicator, samples of the untreated as well as the purified biogas were taken on five days. After the end of the monitoring period these samples were taken to the ETH Zurich[17], where they were analysed for the carbon dioxide, methane and oxygen content. The analysis was done with a Trace GC Ultra gas chromatograph from Thermo Scientific.

The methane, carbon dioxide and oxygen values were measured with a packed Hayesep D 100/120 column equipped with a thermal conductivity detector. The oven, inlet and detector

[16] Due to plugging after smallest amounts of filtrate not even the filtration through any kind of textile was possible.

[17] Swiss Federal Institute of Technology Zurich, Institute of Biogeochemistry and Pollutant Dynamics, Subsurface Microbial Group.

temperature were set to 85°C, 150°C and 100°C respectively. The nitrogen carrier gas flow was 19.1 ml min^{-1}.

3.4 Measurement of daily gas production and loading rate

Figure 8: Scale for the gas content of the gasholder drum (Picture: Florian Heeb)

The daily gas production was measured with the aid of a scale showing the gas content of the drum (Figure 8). The operator of the biogas plant noted down the reading of the scale every day before and after running the generator as well as before and after occasionally burning excess gas with a flare. All volumes of gas are given under norm conditions[18], i.e. 1013 bar and 0°C.

For receiving a representative set of daily loading rates, the operator also listed daily the total weight of the market waste he fed to the digester. The wet weight of the waste was measured with a Scaletech hook-scale (precision 20g).

3.5 Measurement of heavy metal contents

Cooled effluent samples were taken back to Switzerland where they were analysed for heavy metals at Eawag.

Preliminary heavy metal measurements were performed with the inductively coupled plasma optical emission spectrometer (IPC-OES) Ciros from Spectro. The final measurements were carried out with the inductively coupled plasma mass spectrometer (IPC-MS) 7500cx from Agilent. The disintegration of the unstrained samples (0.5 ml) was carried out with a mixture of concentrated HNO_3 and H_2O_2 in a ratio of 4:1. It was first performed at room temperature and afterwards in a microwave oven. Blank values were subtracted. The received values were controlled with a certificated reference material (TM-28.3).

[18] Under the local conditions in Thiruvananthapuram the real volumes are about 1.1 times bigger than under norm conditions.

4 Results

In the following, the results of the technical monitoring of the Sreekaryiam market level plant are presented.

To get an insight into the relevant processes, first a technical description of the design and the mode of operation of the BIOTECH plant is given. Additionally, the theoretic operational parameters of such a plant under optimal conditions are calculated in order to be able to compare those values with the values obtained in the monitoring

Finally, the results of the technical monitoring are presented. A special focus is put on the comparison of the measured values with values reported in literature.

4.1 Technical description of a market level biogas plant

Basically, the BIOTECH market level plants are floating drum plants with a slurry loop system. Figure 9 shows a schematic plan of a market level plant.

The feedstock is put in the inlet tank (a), from where it is flushed into the main digester tank (b). In the digester tank, the organic waste is decomposed in the different steps of anaerobic digestion producing biogas. The digester tank is 3.0 meters deep and has a diameter of 3.4 meters. At the Sreekaryiam plant, the part of the digester tank that is actually filled with the digestate fluid[19] has a volume of 21.3 m^3. To increase the retention time for solids, there is a barrier orthogonal to the flow direction in the middle of the tank, which has a height of about 1.5 meters. The barrier holds back unsuspended solid compounds of the waste, whereas liquids can easily flow over. This leads to an increased retention time for unsuspended solids and therefore to an improved decomposition of this compounds.

On the other side of the digester tank, the digester fluid (slurry) flows into the effluent tank (c). From there, a pump (e) run with electricity of the generator (i) transports the slurry up into an overhead storage tank (d). The slurry in the overhead tank is used to flush the feedstock from the inlet tank into the digester tank. In the slurry loop design, no fresh water is used to flush the waste into the digester tank. Therefore, there is no need for fresh water except for cleaning purposes. Excess slurry is leaving the system out of the effluent tank into the drainage (j).

[19] The volume taken in by the digestate fluid is the relevant value for the calculations of the HRT, OLR, and GPR as described below.

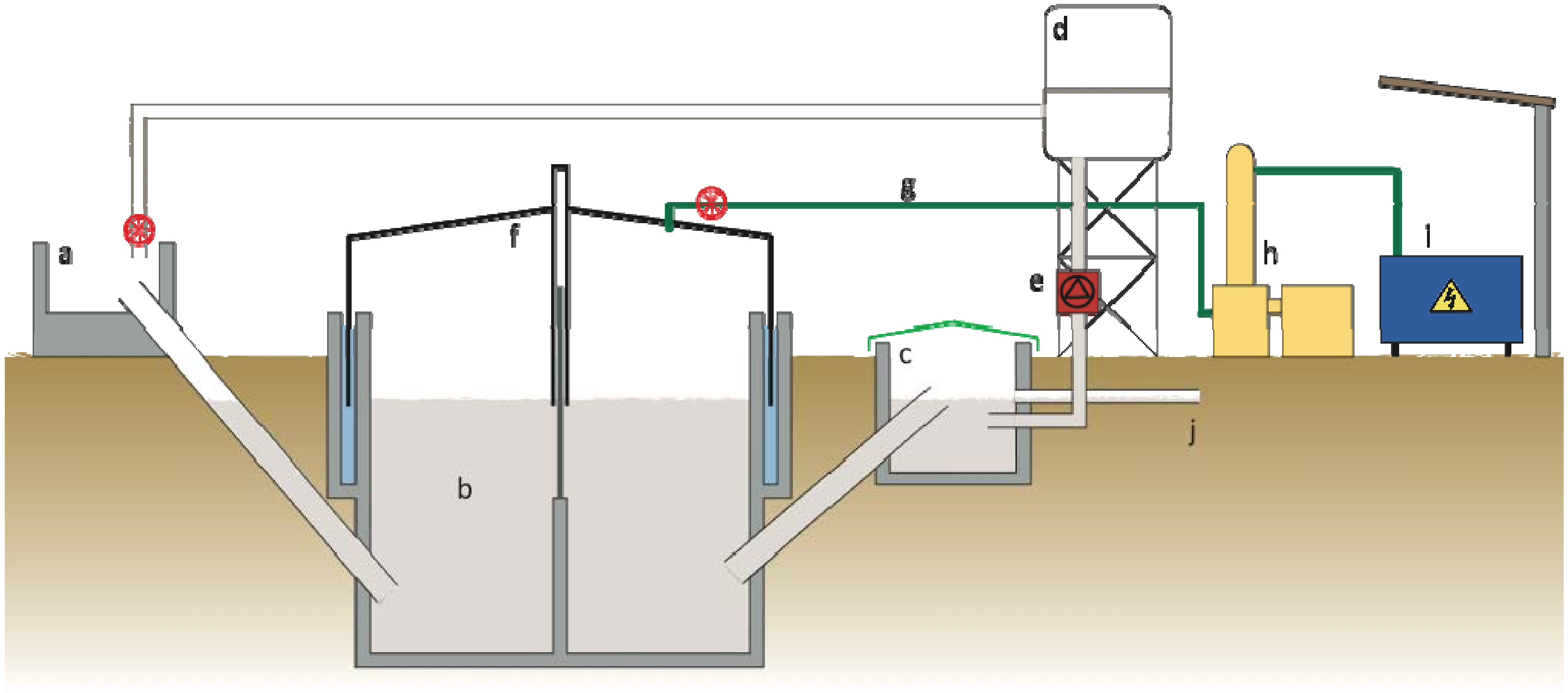

Figure 9: Schematic plan of a BIOTECH market level plant. The sketch is not drawn to scale, but the proportions have been considered as far as possible. a) Inlet tank for feedstock. b) Digester tank. c) Effluent tank. d) Effluent storage tank. e) Effluent pump. f) Gasholder drum. The drum is stabilized by a guide pole in the middle and is floating in a water jacket outside the digester. g) Biogas pipe. h) Gas Scrubber. i) Biogas generator j) Drainage connection for excess effluent.

The gas that is produced in the digester tank is trapped in the gas storage drum (f). The drum is floating in a water jacket. That means instead of floating directly in the digester fluid it is floating in a ring of water outside the digester tank. Compared with the conventional design, where the drum floats in the digester fluid, the water jacket avoids loss of biogas and odours occurring due to waste in the digester fluid outside the drum.

The gas storage drum is connected via a gas pipe (g) to a biogas scrubber (h) that has the role of reducing the content of the corrosive hydrogen sulphide (H_2S) in the biogas[20]. In the scrubber, the gas flows upwards through a packed coulomb in which water containing iron salts is circulating in counter current. The hydrogen sulphide is dissolved in the water and oxidised.

Figure 10: Excess biogas is burnt at the Sreekaryiam market level plant (Picture: Florian Heeb).

After scrubbing, the gas is used for running a five kW biogas generator (i). The utilized generators are fully operated with biogas and do not require diesel for start up. Excess gas that cannot be used for the generator is burnt with a burner, mostly without utilising the heat (Figure 10).

In addition to the design shown in Figure 9, some of the market level plants are equipped with special pre-digesters for fibrous waste like vegetables or leaves to avoid problems like scum formation due to this kind of waste (Figure 11). Basically, the pre-digester consists of a tank in which the fibrous waste is put in for about twenty days. During this time, the waste gets decomposed to a certain extent in partly aerobic and anaerobic processes. At the same time, the pre-digester tank is regularly flushed with slurry from the overhead tank, which afterwards goes to the main digester tank. Like this, the suspended and dissolved products of the decomposition in the pre-digester tank are flushed into the digester tank whereas the fibrous materials remain in the pre-digester. After the twenty days, the remaining fibrous material in the pre-digester is let to dry for about one week and then taken out manually. The fibrous material can then be used as a fertiliser in

[20] Normally the comparably hydrogen sulphide content of un-purified biogas is too high for the use in generators. The corrosive hydrogen sulphide would lead to premature breakdown of the generator (Mata-Alvarez, J. (2003). *Biomethanization of the organic fraction of municipal solid waste.* London: IWA Publishing).

agriculture similar to manure. However, these pre-digesters are not installed at the market level plant in Sreekaryiam, where the monitoring has been conducted.

Figure 11: Pre-digesters filled with vegetables (left) and with pre-digested fibrous material (right) at the Govt. Ayurveda College, Trippunithura and at the market of Thrikkarakara, respectively (Pictures: Florian Heeb).

In the following, some theoretic yields and characteristics for a market level plant as described above are calculated. These values represent optimal values.

BIOTECH designed the 25 m^3 market level plants for a maximum load of 250 kg/d waste (wet weight). Table 6 shows the theoretical characteristics calculated with the assumptions of a typical volatile solids content of 15 percent and a specific gas production[21] (SGP) of 0.5 m^3 $kgVS^{-1}$.

Table 6: Calculated theoretical yields and characteristics for maximal daily load recommended by BIOTECH.

Estimated Parameters	
Load [kgWW/d]	250
VS [g/kg]	150
SGP [m^3 $kgVS^{-1}$]	0.5
Resulting Characteristics[22]	
HRT[d]	85
OLR [kgVS m^{-3} d^{-1}]	1.76
Gas Production [m^3 d^{-1}]	18.75
GPR [m^3 m^{-3} d^{-1}]	0.88

[21] The definitions and calculations of the different operational parameters can be found in Appendix F

4.2 Monitoring of a market level biogas plant

In the following, the results of the two monitoring cycles of the Sreekaryiam market level plant are presented. First of all, the composition and the characteristics of the feedstock are discussed and compared to literature values. Afterwards, the operational parameters, the gas composition and finally the effluent quality are presented. The detailed values measured in the course of the monitoring can be found in appendix G.

4.2.1 Characterization of the feedstock

The feedstock of the Sreekaryiam plant consists almost exclusively of fish waste. Some small quantities of vegetable and fruit wastes are sporadically added. All feedstock samples that were taken did only consist of fish waste. The composition of the individual samples was estimated rather crudely by eye to get an idea of the main fractions of the waste. The clearly biggest fraction consisted of fish innards (61%). The rest consisted mostly of flesh and skin tissue (11%), heads (11%), whole small fish (8%), gills (6%) and tails (3%).

Figure 12: Typical feedstock of the Sreekaryiam market level plant (Picture: Florian Heeb).

Table 7 shows the chemical characterization of the feedstock. The COD value of 1.31 gO_2/gTS indicates that the feedstock has a relatively high energy content.

The nitrogen content of 8.7 %TS in the feedstock is very high. Several studies report nitrogen contents between 2.1 to 3.2 %TS for the organic fraction of municipal solid waste (Mata-Alvarez 2003). Also the phosphorus content of 1.2 %TS is relatively high compared to the corresponding literature values in the range of 0.2 to 0.5 %TS.

Table 7: Characterization of the feedstock. The number of analysed samples is 15 (COD), 17 (N_{tot} and P_{tot}) and 6 (TS and VS).

Parameter	Average value
TS [g/kg]	231.5
VS [%TS]	63.0
COD [gO_2/gTS]	1.31
N_{tot} [% TS]	8.7
P_{tot} [% TS]	1.2

Comparing the COD, total Nitrogen and Phosphorus values a COD:N:P ratio of 109:7:1 results. According to Mata-Alvarez (2003) the recommended COD:N:P value for MSW to be anaerobically digested is about 600:7:1.

Summarizing, it can be said that the feedstock consisting of fish waste is rich in energy and extremely rich in nitrogen and phosphorus. In literature also high contents of lipids are reported for fish waste (Mshandete et al. 2004)

4.3.2 Operational parameters

In Table 8 the operational parameters of the Sreekaryiam market level plant are listed. Compared to the maximal load of 250 kg the plant was designed for, the actual average load of 85.5 kg per day is rather low.

There is no information available on appropriate OLRs for the digestion of fish waste. Compared with recommended values for market and canteen wastes between 3-4 kgVS m^{-3} d^{-1} as given by Mata-Alvarez (2003) the OLR of 0.568 kgVS m^{-3} d^{-1} at the Sreekaryiam plant is very low. However, it may be more sensible to compare the obtained OLR with values from the digestion of slaughterhouse waste because of its relative similarity in composition to fish waste. On lab and pilot scale, digesters fed with slaughterhouse waste are reported with OLRs from 0.8 to 2.5 kgVS m^{-3} d^{-1}(Salminen & Rintala 2002; Edstrom M 2003). Yet the only value found for a full scale digester is 0.36 kgCOD m^{-3} d^{-1} and therefore even lower than the OLR of 1.22 kgVS m^{-3} d^{-1} at the Sreekaryiam plant (Banks 1994).

The combination of the low load and the absence of added fresh water leads to an extremely high hydraulic retention time (HRT) of over eight months. Compared with recommended HRTs for the digestion of canteen and market waste in the range of 12 to 14 days this value is extremely high (Mata-Alvarez 2003).

The temperature was very constant over the whole monitoring period. The average temperature of 29.3 is in the optimal range for mesophilic anaerobic processes (Mata-Alvarez 2003).

Table 8: Operational parameters of the Sreekaryiam market level biogas plant.

Parameter	Average value
Load [kg/d]	85.5
OLR [kgVS m^{-3} d^{-1}]	0.568
OLR [kgCOD m^{-3} d^{-1}]	1.22
HRT [d]	262
T [°C]	29.3
pH	7.85

The measured pH values are relatively high. The average pH of 7.85 is clearly higher than the optimal pH range of 6.5 to 7.5 given by Mata-Alvarez (2003). As high ammonia concentrations influence the pH, the measured values as well as the high alkalinity (cf. Table 10) could be an explanation for the high pH. During the whole measurement period, the pH values were very stable (Figure 13).

The A/TIC ratio was rather constant over the whole measurement period. This indicates that the process stability of the digester was high. However, to make conclusions whether the digester is underfed with the low loading rate, more comparative A/TIC data would be required (Cf. appendix H).

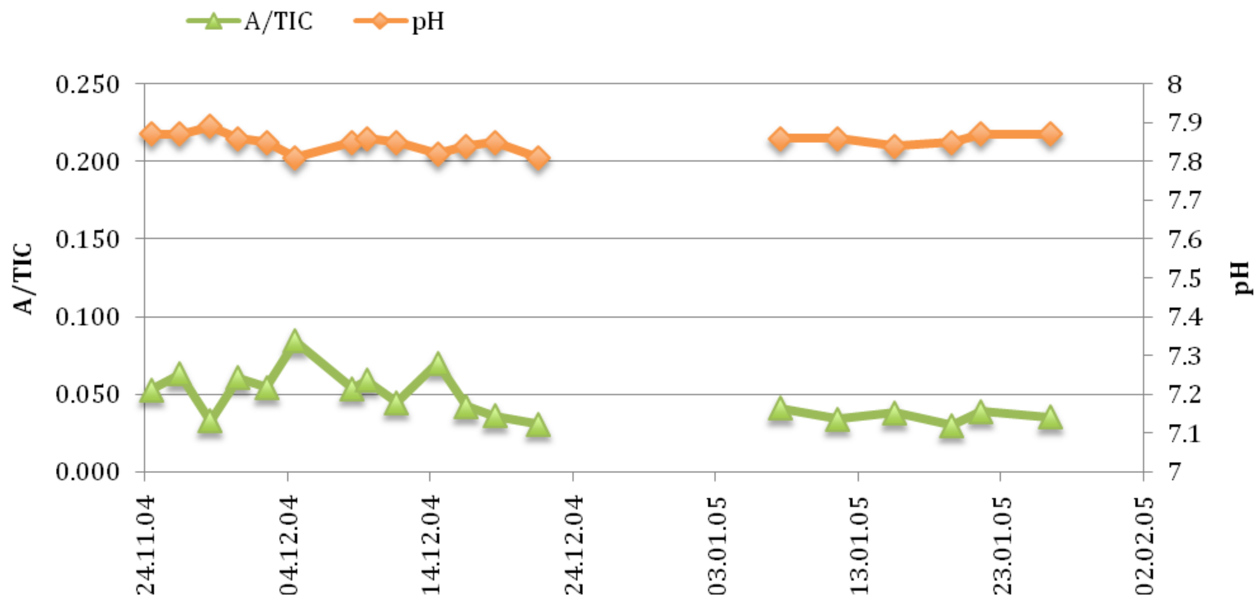

Figure 13: pH and A/TIC ratio. The pH and the A/TIC ration were rather constant over the whole measurement period.

4.3.3 Gas production and composition

In Table 9 the gas yields and the gas composition are listed. The average daily gas production of 4.97 m^3 is a little bit higher than the average demand from the generator. Therefore over the whole measurement period 2.5 percent of the gas was burnt.

Analogue to the OLR the gas production rate is relatively low. However, the specific gas production is in a normal range. In literature, SGPs for slaughterhouse waste, which has similarities to the fish waste, are given in the range of 0.3 to 0.7 m^3 $kgVS^{-1}$ d^{-1}(Deublein 2008) respectively 1.80 m^3 $kgCOD^{-1}$ d^{-1} (Salminen & Rintala 2002).

Table 9: Average gas yields and composition of the unpurified gas. The methane and carbon dioxide values were measured with gas chromatography (5 samples). All gas volumes are given under norm conditions (1013 bar and 0°C)

Gas yields	
Daily gas production [m^3 d^{-1}]	4.97
GPR [m^3 m^{-3} d^{-1}]	0.233
SGP_{VS} [m^3 $kgVS^{-1}$ d^{-1}]	0.399
SGP_{COD} [m^3 $kgCOD^{-1}$ d^{-1}]	0.192
Gas composition	
Methane content [%]	66.8
Carbon dioxide content [%]	27.4

Detailed analysis of the composition of the non-purified gas conducted with gas chromatography showed a high average methane content of 66.8 percent. As shown in Figure 14, the CO_2 content of the biogas was very constant over the whole monitoring period. The results obtained by the BRIOGON CO_2-Indicator (28.3% CO_2) suit quite well to the values measured with gas chromatography (27.4% CO_2). The rest of the gas most probably consists of small shares of water vapour, nitrogen and oxygen. Although it was not analysed, the smell of the gas indicated the presence of hydrogen sulphide.

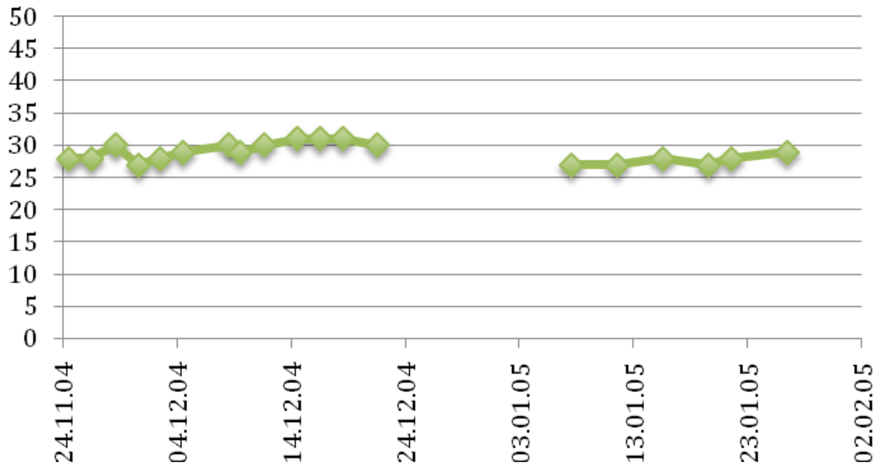

Figure 14: Carbon dioxide content of the unfiltered biogas. The gas was analysed with the BRIGON CO_2-Indicator. The carbon dioxide content was quite constant over the whole monitoring period.

With the help of gas chromatography, the effect of the scrubber on the gas composition was analysed. The results showed that there is a small but significant reduction in the carbon dioxide of 1.05 percent in average (P-value = 0.046). There is no change in the content of methane. The scrubber therefore has only very small effects on the two main components. However, because of technical reasons, it was not possible to measure the effect of the scrubber on the hydrogen sulphide content which would have been the most interesting point.

4.3.4 Effluent quality

Figure 15: Effluent tank at the Sreekaryiam market level plant (Picture: Florian Heeb).

The effluent of the Sreekaryiam market level plant is very liquid, dark and homogenous (Figure 15). The characteristics of the effluent are shown in Table 10. The bigger share of the remaining solids is dissolved. The COD and VS values show that there is still a certain amount of organic matter left in the effluent despite the HRT of over eight months.

The total nitrogen, ammonium, total phosphorous and ortho-phosphate values of the effluent are extremely high for an anaerobic digester. Whereas high ortho-phosphate values do not create problems for the anaerobic digestion, high ammonia values can be critical.

Table 10: Characteristics of the Effluent.

Parameter	Average value
TS [g/l]	9.74
TDS [%TS]	65.3
VS [%TS]	76.9
COD [mgO_2/l]	8998
N_{tot} [mgN/l]	7520
NH_4-N [mgN/l]	6104
P_{tot} [mgP/l]	547
PO_4-P [mgP/l]	491
Alkalinity [mg$CaCO_3$/l]	27775
pH	7.85

There is a large amount of studies investigating the inhibitive effect of ammonia on anaerobic digesters. The ammonia inhibition can take place at a broad range of concentrations. Different studies report ammonia inhibition between 1’400 and 17’000 mgN/l of total inorganic nitrogen[23](Chen, Cheng & Creamer 2008). Generally, it is agreed that with long enough acclimatization periods, the anaerobic microorganisms can tolerate higher ammonium concentrations than those measured (6204 mgN/l). However the methane production may be reduced. It is also reported that high pH values, as observed in the reactor, can additionally increase the inhibitory effect of ammonia on methane production. Nevertheless, the normal gas production rates measured at the Sreekaryiam plant indicate that the anaerobic microorganisms in the digester have acclimatised well to the high ammonia concentrations.

Another effect of high inorganic nitrogen concentrations in combination with a high pH is the presence of a considerable amount of ammonia in the gaseous phase. At the measured pH of 7.85 and the temperature of 29.3 °C, about 4.6% of the total inorganic nitrogen exists in the form of ammonia. Whereas ammonium is very soluble in water, ammonia is volatile. Calculating the measured ammonium values with a temperature Henry-constant of 501.7mol l^{-1} atm^{-1} a theoretical concentration of ammonia in the biogas of 42.8 ppm results. This value is far above the odour threshold. In accordance with the calculated value, the biogas of the Sreekaryiam plant has a strong, clearly distinguishable ammonia smell. This leads to odour emissions of the biogas plant during the feeding process, when slurry is used to flush in the feedstock. According to the plant operator, this odour is creating resentments from the fishermen working at the market.

There are indications that high ammonia contents can increase the possibility of intensive scum formation at least in wastewater treatment plants (Drzewicki, Filipkowska & Rodziewicz 2008). In the Sreekaryiam plant there are no indications of scum formation, whereas massive scum formation has occurred in the Market of Thrikkarakara (Chdaamangalam Grama Panchayat), where similar loads of food waste are fed to the digester.

Although the high nitrogen concentrations do not create grave inhibition of the methane production at the current level, the occurring smell surely is a danger for the general acceptance of market level biogas plants.

[23] In anaerobic reactors the total inorganic nitrogen consists mainly ammonia (NH_3) and the protonized form ammonium (NH_4^+). At normal pH ranges the biggest share of the total inorganic nitrogen is in the form of ammonium. With increasing pH value the share of ammonia increases. Generally, ammonia is the toxic form. In the monitoring the ammonium values have been measured.

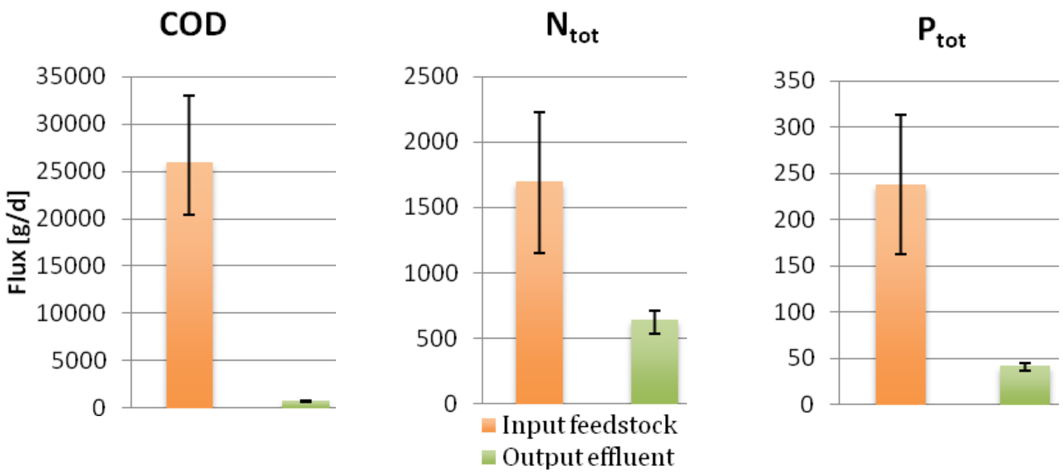

Figure 16: Values of COD, N_{tot} and P_{tot} in the feedstock and in the effluent. The error bars show the 0.25 and the 0.75 quantile. Variations in the measured concentrations as well as in the daily flow rates are considered. The average input values are clearly higher than the corresponding outputs through the effluent.

Generally, the addition of feedstock is the only flux of COD, N_{tot} and P_{tot} into the digester, whereas fluxes out of the digester are possible through the gaseous phase as well as the effluent leaving the system. Compared with the input fluxes of COD, N_{tot} and P_{tot}, the corresponding output fluxes through the effluent are by far lower (Figure 16).

There is no output flux of phosphorous through the gaseous phase and the flux of nitrogen through the gaseous phase in form of gaseous ammonia is negligible. Therefore, in equilibrium state, the input flux of N_{tot} and P_{tot} through the addition of feedstock should be equal to the output flux through the effluent. Apparently, the system was not in the equilibrium state during the monitoring period as visible in Figure 16.

Due to the very high retention time of over eight months, it will take a very long time until a new equilibrium state is reached when for example the composition of the feedstock is changed. According to BIOTECH, the slurry loop system has only been installed in 2007. Previously, the feedstock has been diluted with fresh water, what resulted in far lower concentrations of N_{tot} and P_{tot} in the digester. The measurements show that the digester is still strongly influenced by the former way of feeding and is currently changing towards the new equilibrium state.

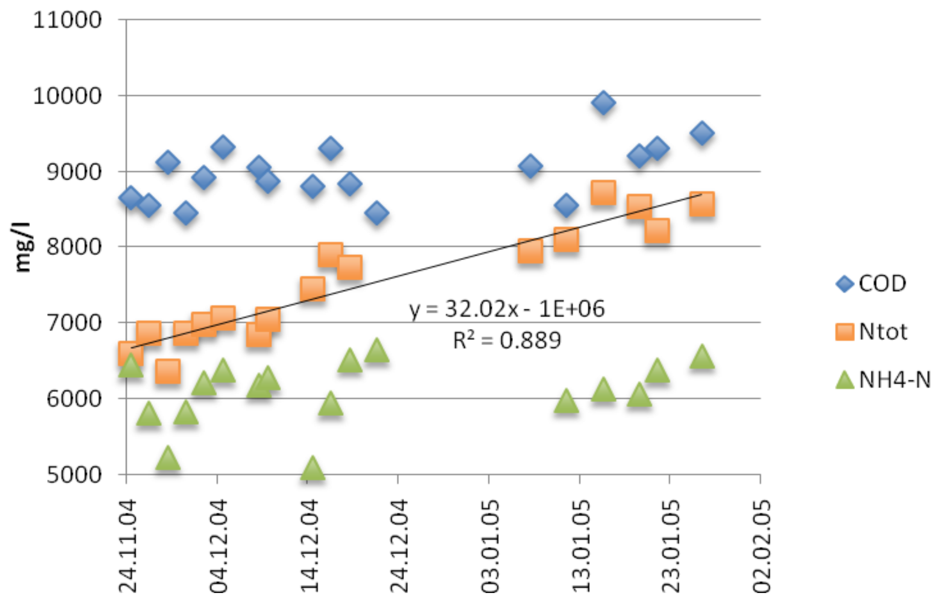

Figure 17: Changes of COD, N_{tot} and NH4-N values of the effluent over the monitoring period. A significant increase of total Nitrogen over the measurement period is visible (R^2=0.8899 for N_{tot} values).

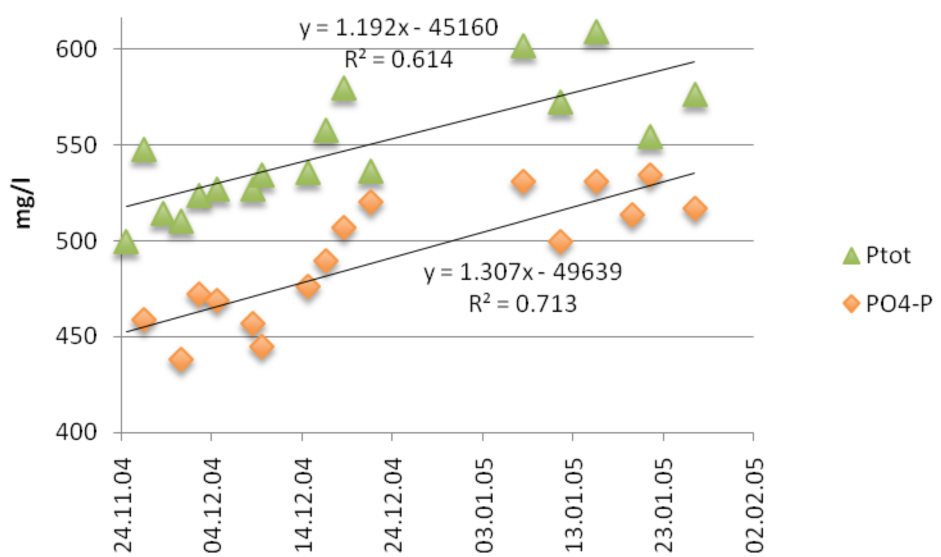

Figure 18: Changes of P_{tot} and PO_4-P values of the effluent over the monitoring period. An increase of P_{tot} and PO_4-P can be recognised but is not strongly significant (R^2=0.6143 for P_{tot} and R^2=0.71327 for PO_4-P).

The development of the N_{tot}, P_{tot} and ortho-phosphate concentrations confirm these findings. As visible in Figure 17 the N_{tot} values are constantly increasing through the monitoring period. Similarly, an increase of P_{tot}, and ortho-phosphate values is visible (Figure 18). At the same time, the COD and ammonia values do not show any tendency of increase or decrease.

As discussed above, the recent ammonia concentrations do not yet lead to a significant inhibition of the methane formation. But if no further action is taken, inhibitory levels may be reached with the present increase.

The large difference in the COD fluxes indicates that the big majority of the organic matter is decomposed to carbon dioxide and methane, which leave the system in the gaseous phase (Figure 16). This indicates a high removal efficiency for COD. However, as discussed above, the retention time is extremely high. Therefore, it is not possible to make a direct link between the present feedstock and effluent, i.e. to calculate the removal efficiency for the COD.

With the obtained average COD (8998 mgO_2/l) it is possible to make a rough estimation of the carbon to nitrogen (C/N) ratio of the effluent. With the simplifying assumption that the biomass is composed of CH_2O, the COD of the biomass is 1.07 gram O_2 per gram biomass. Therefore, a carbon content of the effluent in the order of 3374 mgC/l can be assumed. Combined with the measured nitrogen values, an average C/N ratio of 0.43 results. This means the nitrogen content is higher than the carbon content. In the standards for products of the processing of biodegradable waste as given in the MSWR, only specifications for compost can be found (C/N ratio between 20 and 40). However, liquid products of the processing of biodegradable waste, as occurring at the Sreekaryiam market level plant, are not considered in the MSWR.

Table 11: Heavy metal contents of the effluent of the Sreekaryiam plant. Values are given for the dissolved as well as the total concentrations.

Parameters	Dissolved concentration [µg/l]	Total concentration [µg/l]
Aluminium (Al)	158	43'400
Arsenic (As)	630	622
Cadmium (Cd)	2.10	80.2
Chromium (Cr)	10.54	117
Copper (Cu)	1.48	455
Lead (Pb)	2.16	55.3
Nickel (Ni)	23.9	50.82

In Table 11 the heavy metal contents of the effluent at the Sreekaryiam plant are shown. With the exception of arsenic, the majority of the heavy metal content is found in the particulate matter, the dissolved fraction is much smaller. In the MSWR, heavy metal limits are only available for compost, but not for liquid products.

Table 12: Heavy metal content in fish, shellfish and fish products from local markets in the Cochin region, Kerala (Sivaperumal, Sankar & Viswanathan Nair 2007).

Parameters	Content [µg/kgWW]
Arsenic (As)	<100 to 4'140
Cadmium (Cd)	<70 to 1'000
Chromium (Cr)	<50 to 3'650
Copper (Cu)	150 to 24'000
Lead (Pb)	<70 to 1'230
Nickel (Ni)	<32 to 1'380

As discussed in context of the total nitrogen and phosphorous measurements, the system is currently moving towards an equilibrium state, where the effluent heavy metal concentrations will be similar to the concentrations in the feedstock. In Table 12 ranges of heavy metal contents found in fish, shellfish and fish products from several local markets in the Cochin region, which is relatively near to Thiruvananthapuram, are listed (Sivaperumal, Sankar & Viswanathan Nair 2007). The values measured at the Sreekaryiam plant are rather at the lower end of the heavy metal ranges found in this study. Therefore, the obtained heavy metal values can easily be explained with the input through the added fish waste, no extraordinary heavy metal contents are visible.

5 Discussion

The present situation in Thiruvananthapuram shows that solid waste management is still a big problem. Especially in the panchayats adjoined to the city, where a waste collection system is mostly missing, there is a big potential for decentralized solutions. Decentralized solutions are also explicitly demanded by the laws for municipal level markets.

As the number of implemented biogas plants show, BIOTECH is very successful in offering decentralized waste treatment systems at household, institutional and market level. At least at market level, this success cannot be explained with financial incentives as the investment costs for those biogas plants are considerable. On the other hand, the financial benefits resulting from the generated electricity cover only about a third of the annual expenses for operation and maintenance. Therefore, the BIOTECH market level plants are currently not directly cost-efficient. Proper waste disposal, which is the main benefit, has not yet a monetary value for the municipalities, although it is an extremely important and valuable service to the community. At the same time, the pressure on municipalities to implement the existing SWM regulations is very low. Hence the main factor for the implementation of biogas plants on municipal level is the awareness of individual politicians for the importance and benefits of appropriate MSWM solutions.

The reasons for the success on municipal level have to be identified in the service quality offered by BIOTECH as well as in the way the NGO deals with the political environment on the municipal level. On the one hand, BIOTECH takes relatively big efforts in creating awareness about the waste problem and biogas technology among the politicians and among the local population. On the other hand, the NGO has found a way to deal with the frequent changes of the local governments (every five years) by including long-term operation and maintenance contracts in their projects. As the NGO has a vital interest in avoiding breakdowns of plants due to the resulting damage on their reputation, the service quality of the operation and maintenance is high. With the applied contracts, it is possible to keep running a long-term project like the biogas plant, which is designed to work for decades in a political environment that changes every five years.

However, it is important to find ways to increase the economical incentives for the local bodies to invest in market level biogas projects.

One possible way to generate additional income is to sell the effluent of the plant as liquid fertilizer. In literature as well as in regulations, the focus mostly lies on solid products of the biological treatment of the organic fraction of the MSW, mainly on compost. There is nearly no information about liquid products of decentralized biological waste treatment. Yet the analysis of the effluent showed that it is rich in nutrients and has a very low C/N ratio. This combination makes the effluent very suitable for the use as a liquid fertilizer. Generally, liquid fertilizers have the advantage that they can be mixed with the irrigation water and therefore do not require laborious insertion of the fertilizer into the soil, as it is the case with solid fertilizer (Koller 2002). Liquid fertilizers provide a fast availability of the nutrients, whereas solid fertilizers like compost provide a better long-term supply of nutrients. It would be important to acquire more information about the market potential of liquid fertilizers, specifically in south India and generally in regions where similar systems could be applied.

The CDM of the Kyoto Protocol represent a second way for additional income generation. With the CDM, the reduction of greenhouse gas emissions through the substitution of fossil energy as well as through the appropriate treatment of the biodegradable waste can generate revenues. Yet, further investigations would be necessary to clarify whether CDM projects would be technically possible and economically feasible for decentralized anaerobic digestion.

Due to the absence of comparable economical data on alternative technologies, it cannot be said how the economical potential of the BIOTECH market level biogas plants is positioned compared with other possible SW treatment technologies like e.g. centralised composting or incineration.

Focusing on the results of the technical monitoring of the Sreekaryiam market level plant, the special nature of the treated waste has to be highlighted. The observed waste composition does not correspond to the typical composition of the organic fraction of MSW. In Sreekaryiam as well as in other market level plants, the treated waste consists mainly out of fish wastes. Most probably, the treatment of fish and also slaughterhouse waste has priority to the municipalities due to the fact that these wastes are very fast creating problems with odour emissions and hygiene if dumped into pits. Environmental and health problems due to the dumping of the other fractions of the market waste, like vegetable and fruit waste, are less obvious.

The analysed fish waste is rich in energy and extremely rich in nitrogen and phosphorus. Therefore, this kind of waste is a very challenging task for anaerobic digestion. The observed C/N ratio of the waste is about a factor six lower than recommended in literature for optimal anaerobic digestion of the organic fraction of MSW. Accordingly, the monitoring showed high nitrogen contents of the effluent. There are odour emissions from the biogas plant due to the high ammonia content of the effluent, which create resentments among the salesman of the market.

Yet it has to be highlighted that the gas production is in a normal range despite the rather difficult nature of the treated waste. The measured pH and A/TIC values indicate that the anaerobic digestion process is very high.

Because the slurry loop system of the Sreekaryiam plant was introduced about one year ago and the waste had been diluted with water before, the digester has not yet reached an equilibrium state. At present, the nitrogen and phosphorous levels are rising. If no measures are taken, the nitrogen content will most probably increase to inhibitory levels what could lead to the failure of the digester.

In Kayhanian (1999) two different ways to handle high nitrogen contents are recommended. The first way is to dilute the digester content by adding fresh water. Because the idea of the slurry loop system applied at the Sreekaryiam is to be independent of fresh water supply, this way may not be appropriate. The second way, which seems more appropriate, is to adjust the C/N ratio of the feedstock. In addition to the presently used fish waste, carbon rich waste could be fed to the Sreekaryiam plant to reach this aim. Principally, carbon rich waste would be available in the form of vegetable and fruit waste on the market itself. Because of the fibrous nature of big parts of fruit and vegetable waste, the installation of pre-digesters would be advisable.

As mentioned above, the investment costs for a BIOTECH market level plant are relatively high. Therefore, the question arises whether the daily waste load could be increased and thus the treatment costs per kilogram waste could be decreased. In other words, the question is whether the market level plants could be operated with a higher OLR. Taking into account the maximal load of feedstock recommended by BIOTECH, the obtained OLR is still low compared to literature values for market and canteen waste. Therefore, market level plants dealing only with fruit, vegetable and food waste could most probably be dimensioned smaller and hence less expensive. Yet, the situation looks different if a big share of the feedstock consists of fish waste. Existing data is rare on anaerobic digestion of fish wastes. However, considering the high content of energy, nitrogen and lipids and the resulting problems for the process of anaerobic digestion, the low ORLs as observed at the

Sreekaryiam plant may be necessary. This opinion is supported by data from anaerobic digestion of slaughterhouse waste, which has similar characteristics. However, to make sound recommendations about appropriate loading rates, more data on full-scale anaerobic digestion of fish waste or waste with comparable characteristics would be required.

In summary it can be said, that, although there are some technical challenges due to the high share of fish residues in the market waste, the technology of decentralized anaerobic digestion, as applied at the market level plants of BIOTECH, definitively is very suitable for the treatment of market waste. However, the most important task will be to improve the economical attractiveness of such projects. There are several possible ways to do so, fore example by reducing the investment costs, selling the effluent as fertilizer or the development of CDM projects. If the economical attractiveness can be increased, the potential for this technology is very big.

6 Acknowledgements

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Appendix

A Details of BIOTECH

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B Monitoring schedule

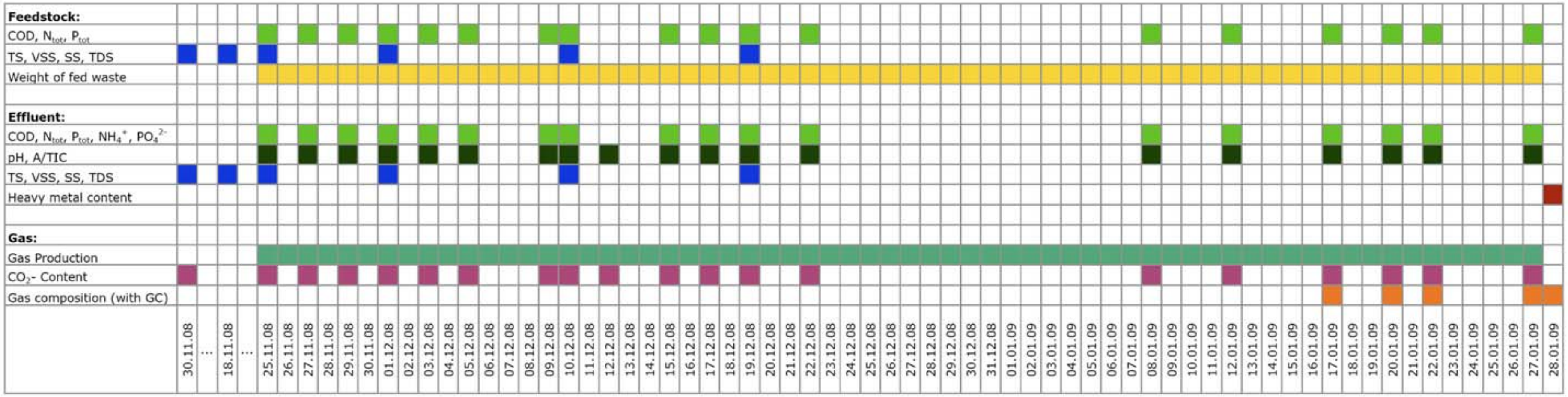

Figure 19: Schedule of the monitoring.

C Prices for domestic level BIOTECH plants

In Table 13 the prices for the domestic level plants of BIOTECH from 2008 can be found. After the control of the finished plant by an official, the customers can receive subsidies between 2700 and 3500 Rs from the Ministry of New and Renewable energy of the Central Government. Some panchayats also give certain subsidies for domestic biogas plants.

Table 13: Prices for domestic level BIOTECH plants from October 2008.

Model	Price
Ordinary domestic plant 1 m^3	15’000 RS
Water jacket domestic 1 m^3	22'000 RS
Water jacket domestic plant with link for toilet 2 m^3	39'000 RS

D Kumbalangi Integrated Tourism Village

The island of Kumbalangi lies in the large brackish water ecosystem of the Backwaters near the city of Cochin. As the Backwaters are one of the most important tourist attractions in the state of Kerala, the Kumbalangi village has become the first integrated tourism village. In this project, which is carried out by the local panchayat in collaboration with the tourism department, the village should become a main tourism attraction.

Figure 20: Hanging toilets at the Backwaters.

Figure 21: Toilet linked BIOTECH biogas plant on the island of Kumbalangi.

At the same time, the steadily increasing environmental pollution of the water endangers the attractiveness of the Backwaters. Especially the practices of the “hanging” latrines as well as the uncontrolled dumping of waste have a severe impact (Figure 20). In an attempt to improve this situation, BIOTECH built 150 2 m^3 toilet linked biogas plants and 615 1 m^3 biogas plants for the treatment of kitchen waste on the island (Figure 21). The cost for a 2 m^3 plant with a ferro-cement digester tank as installed in Kumbalangi is 22’000 RS (333 €), the cost for the 1 m^3 model was 10’000 RS (152 €). The local panchayat and the tourist department paid the biggest share of these costs. The owner of the plants had to pay amounts in a more or less symbolic range.

E Household level survey

During the monitoring time of the market level biogas plant, a small-scale survey was conducted in eight families and one small ayurvedic hospital using household level biogas plants of the BIOTECH NGO. The survey is not intended to be representative but did deliver some interesting results. In the following the findings of the survey are listed:

Four of the visited plants were built less than one year ago. One plant was built 10 years ago, another one 7 years ago, another three 3 years ago.

Seven of the questioned families used LPG; one family did use firewood in addition to the biogas. The average time of cooking with the biogas was 113 (±41)[24] minutes per day,. The average monthly savings from the substitution of LPG respectively firewood through biogas is 199 RS [3 €] (±67 RS [1 €]).

All seven families using LPG stated that the burning of biogas is producing less heat or that cooking with biogas requires more time. The family using firewood reported a big increase in comfort for cooking.

In all the families, the woman of the house was responsible for feeding and maintaining the digester. The daily effort for doing so was stated to be 5 to 10 minutes in eight cases and 15 minutes in one case.

Three families used fresh water to dilute the waste in a 1:1 ratio, four stated only to use the wastewater from fish and rice cleaning for the dilution of the waste. The average amount of solid kitchen waste daily fed to the digester was 3.6 kg (±1.5 kg). In the cases that added wastewater, the average volume was 5.9 litres (±1.8 litre).

Two families reported to collect waste from other households for additional biogas yield.

In four cases the former way of disposal of the kitchen waste consisted of dumping in the backyard. At three families waste collection was available. Composting had been practiced in two cases, but had faced several problems.

The effluent was used as fertiliser in 8 cases; the experiences were good in all cases. One family specially stressed the importance of diluting the effluent for the use as fertilizer.

In eight cases the main motivation for buying a biogas plant was to find a proper way of disposal for the kitchen waste. In five cases the saving of cooking fuel was mentioned as secondary motivation. In one case the spreading of the biogas technology was stated to be the main motivation.

Concerning how the customers did get to know of the offers of the BIOTECH NGO four families did state they have viewed demonstrations of the biogas technology from BIOTECH, i.e. the road show. Two families learned about BIOTECH because of their presence in media. In another two cases the families were actively approached by BIOTECH. Finally one family has been actively searching for appropriate waste treatment technology.

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[24] Standard deviation

Four families using a plant without water jacket reported slight odours when removing the waste from the fluid ring outside the drum. In two cases condensed water in the tubing was mentioned but in both cases it was not considered as a problem. At one plant the breeding of mosquitoes was considered as a problem. Four families stated to use small quantities of kerosene to inhibit the breeding of mosquitoes on the fluid ring outside the drum. In one case a family reported lower biogas production during the rainy season. One family reported the breeding of worms. In another case a coconut falling from a tree once smashed the drum.

In all cases the satisfaction with the service of BIOTECH was good.

In all cases the expectation was fulfilled, all customers would recommend the plants. In all but one cases neighbours and friends were interested in the technology.

Only one visited family was estimated to belong to a lower income class, the rest were estimated to belong to the middle class or upper middle class.

F Operational Parameters

The most important operational parameters for the description of anaerobic processes are listed and explained underneath (Mata-Alvarez 2003; as cited in Lohri 2009).

Hydraulic Retention Time (HRT)

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

$$HRT = \frac{V}{Q}$$

HRT = hydraulic retention time [days]

V = reactor volume [m^3]

Q = flow rate [m^3/day]

Organic Loading Rate (OLR)

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.

$$OLR = \frac{Q \times S}{V}$$

OLR = organic loading rate [kg substrate/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.

$$GRP = \frac{Q_{biogas}}{V}$$

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 (VS) or chemical oxygen demand (COD) 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.

$$SGP = \frac{Q_{biogas}}{Q \times S}$$

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:

$$\eta_{\%} = \frac{Q \times S - Q \times S_e}{Q \times S} \times 100$$

$\eta_{\%}$ = TS, VS or COD removed, as percentage [%]

Q = inlet and outlet flow rate [m^3/day]

S = TS, VS or COD concentration in the inlet flow rate [kg/m^3]

S_e = TS, VS or COD concentration in the effluent flow rate [kg/m^3]

G Results of the monitoring

Table 14: Summary of the results of the effluent, feedstock and gas analysis.

	Effluent														Feedstock							Gas
Time	pH	T	VFA [mg/l]	Alk [mg/l]	A/TIC	TSS [mg/l]	VSS [mg/l]	TDS [mg/l]	TS [mg/l]	CSB [mg/l]	Ntot [mgN/l]	NH4-N [mg/l]	Ptot [mgP/l]	P04-P [mg/l]	TSS [mg/l]	VSS [mg/l]	TDS [mg/l]	TS [mg/l]	CSB [mg/kg]	Ntot [mgN/kg]	Ptot [mgP/kg]	CO_2 after filter [%]
3.11.08						3760	2850	4810	8456						61750	58250	172000	281508				
18.11.08						3286	2530	6542	9828						84750	47856	131064	215814				
25.11.08	7.87	29.3	1422	26731	0.053	3272	2492	5902	9174	8654	6594	6444	500		90372	65660	126580	216952	407568			28
27.11.08	7.87	28.6	1590	25219	0.063					8562	6867	5814	548	459					163433	11170	1604	28
29.11.08	7.89	28.8	930	28340	0.033					9132	6363	5233	515						324368	13926	2508	30
1.12.08	7.86	29.2	1634	26955	0.061	3228	2492	6644	9872	8451	6867	5830	510	438	93132	60450	146802	239934	155584	11836	1085	27
3.12.08	7.85	29.3	1498	27449	0.055					8932	6983	6218	524	473						21208	2127	28
5.12.08	7.81	29.2	2189	25898	0.085					9331	7077	6380	527	469					326705	18836	3018	29
9.12.08	7.85	28.9	1468	27185	0.054					9054	6852	6183	527	457						21186	3498	30
10.12.08	7.86	29	1638	27623	0.059	3470	2740	6960	10430	8877	7046	6283	534	445	123164	59488	89570	212734	276584	12694	3322	29
12.12.08	7.85	29.3	1222	27179	0.045																	30
15.12.08	7.82	29.7	1929	27429	0.070					8806	7455	5104	536	476					392304	19602	3586	31
17.12.08	7.84	29.8	1184	28061	0.042					9313	7907	5944	558	490						25551	2284	31
19.12.08	7.85	29.6	1014	27898	0.036	3384	2586	7324	10708	8845	7739	6525	580	507	85361	47372	136438	221799	369600	19382	4070	31
22.12.08	7.81	29.3	922	29650	0.031					8455		6654	537	521					231000	15180	2141	30
8.1.09	7.86	29.4	1194	28974	0.041					9071	7949		602	531					289784	17006	2860	27
12.1.09	7.86	29.4	973	28299	0.034					8560	8106	5992	572	500					302544	32560	3718	27
16.1.09	7.84	30.01	1129	29500	0.038					9902	8726	6137	609	531					331936	26180	3366	28
20.1.09	7.85	30	865	28712	0.030					9200	8537	6073		514					448800	27720	3749	27
22.1.09	7.87	29.2	1094	27936	0.039					9312	8222	6380	554	534					272624	16183	1465	28
27.1.09	7.87	29.6	1014	28687	0.035					9512	8568	6573	576	517					255992	26928	2746	29

H The concept of the A/TIC ratio

In the following, a short overview about the methodology to assess the A/TIC ratio can be found.

TITRATION METHODOLOGY ACCORDING TO KAPP FOR MONITORING OF ANAEROBIC DIGESTION: VFA, alkalinity and A/TIC-ratio

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1. Introduction

An increase in volatile fatty acids (VFA) concentration (or the proportional decrease in carbonate alkalinity concentration) is the first practical measurable indication that an anaerobic treatment system is in a state of stress. If the system is not rectified at this early stage, failure is likely. Current methods for VFA measurement include distillation, colorimetry, gas chromatography and various titration techniques. In terms of simplicity, speed and cost-effectiveness it is generally accepted that titration methods are superior for the purpose of on-site routine monitoring and control, particularly in developing countries (Lahav & Morgan, 2004).

2. Anaerobic digestion process

Anaerobic digestion essentially occurs in two steps. In the first, organic matter is converted by hydrolytic and acidogenic bacteria to intermediates such as VFA (mainly acetic acid), CO_2 and H_2. In the second step, these intermediates are converted to methane by methanogenic bacteria. A major danger for overall anaerobic conversions is presented when the microorganism population is not balanced. Disturbances like abrupt temperature change, accumulation of toxic substances, excess of organic biodegradable feed etc. can result in a digester overload. These disturbances mainly affect methanogenic bacteria, whereas acidogenic bacteria are much more tolerant, also in terms of the acceptable pH-range. They continue to produce acids, which in turn inhibit the methane formers, which have a much slower growth rate. This imbalance, if not corrected in time, can finally result in a digester failure (Mata-Alvarez, 2003). It is worth noting that the pH-value of the digester indicates instability of the anaerobic process with quite a delay, since the pH only changes when the substrate-specific buffer capacity has been consumed (Eder & Schulz, 2006). Adequate control of alkalinity and VFA concentration are therefore more suitable to monitor the stability of the anaerobic digestion process.

3. Titration procedure for measurements of VFA and alkalinity according to Kapp

The method according to Kapp (1984), based on a principle suggested by McGhee (1968), was originally developed for the control of mesophilic sludge digesters. The basic idea is that the acid required to titrate a sample from pH 5.0 to pH 4.0 can be considered proportional to the content of VFA present in the sample. This applies because between pH 5 and 4 there is usually no weak acid/base subsystem present that strongly effects acid consumption apart from the acetate acid/base subsystem. Moreover, the pK_a (dissociation constant) values of acetic acid, propionic acid, butyric acid and valeric acid are all close to 4.75. Thus they show very similar buffering characteristics and can be lumped together as one parameter.

The only additional buffer considered in the VFA-procedure of Kapp is the carbonate subsystem of HCO_3^-/CO_2 which has a pK_a of approximately 6.3. Other buffer systems are assumed to be negligible (Buchauer, 1998).

The recorded results of the Kapp titration procedure are evaluated by an iteration scheme which is based on a combined empirical theoretical approach.

<u>Analysis description of 4-point-titration according to Kapp (Buchauer, 1998)</u>

- Before analysis, the sample needs to be filtered through a 0.45µm membrane filter.
- Filtered sample (20-50ml) is put into a titration vessel, the size of which is determined by the basic requirement to guarantee that the tip of the pH electrode is always below the liquid surface.
- Initial pH is recorded
- The sample is titrated slowly with 0.1N sulphuric acid until pH 5.0 is reached. The added volume A1 [ml] of the titrant is recorded.
- More acid is slowly added until pH 4.3 is reached. The volume A2 [ml] of the added titrant is again recorded.
- The latter step is repeated until pH 4.0 is reached, and the volume A3 [ml] of added titrant recorded once more.
- A constant mixing of sample and added titrant is required right from the start to minimise exchange with the atmosphere during titration.

<u>Calculation scheme according to Kapp</u>

$$Alk = A * N * 1000 / SV \quad (1)$$

Alk = Alkalinity [mmol/l], also referred to as TIC (Total Inorganic Carbon)

A = Consumption of sulphuric acid (H_2SO_4, 0.1N) to titrate sample from initial pH to pH 4.3 [ml]. A = A1 + A2 [ml]

N = Normality [mmol/l]

SV = Initial sample volume [ml]

$$VFA = 131'340 * N * B / SV - 3.08 * Alk - 10.9 \quad (2)$$

VFA = Volatile fatty acids [mg/l acetic acid equivalents], in A/TIC also referred to as A (see 4.A/TIC)

N = Normality [mmol/l]

B = Consumption of sulphuric acid (H_2SO_4, 0.1N) to titrate sample from pH 5.0 to pH 4.0 [ml], due to HCO_3/CO_2 buffer. B = A2 + A3 [ml]

SV = Initial sample volume [ml]

Alk = Alkalinity [mmol/l]

4. A/TIC-ratio

The A/TIC-method (German: FOS/TAC) was developed at the Federal Research Institute for Agriculture (FAL) in Braunschweig, Germany. Used as an indicator of the process stability inside the digester, it expresses the ratio between Volatile Fatty Acids and buffer capacity (alkalinity), or in other words the amount of Acids (A) compared to Total Inorganic Carbon (TIC).

$$\frac{A\ [mg/l]}{TIC\ [mg/l]} = \frac{VFA\ [mg/l]}{Alkalinity\ [mg/l]} \quad (3)$$

Alkalinity [mmol/l] needs to be converted to TIC [mg/l $CaCO_3$] by multiplying it with half the molecular weight of $CaCO_3$ (100.084/2=50.042), as each molecule of $CaCO_3$ can take up $2H^+$ ($CaCO_3 + H_2O \rightarrow Ca^{2+} + HCO_3^- + OH^-$).

It is worth noting that the original FOS/TAC-method according to FAL was based on a 3-point-titration method using approximate empirical figures (Nordmann, 1977).

Calculation example for VFA, alkalinity and A/TIC according to Kapp:

Initial sample volume [ml]	Normality of titrant H2SO4 [mmol/l]	Initial pH	A1= H2SO4 [ml] to titrate sample from Initial pH to pH5	A2 = H2SO4 [ml] to titrate sample from pH 5 to pH4.3	**A = A1+A2** H2SO4 [ml] to titrate sample from Initial pH to pH4.3	A3 = H2SO4 [ml] to titrate sample from pH4.3 to pH4.0	**B = A2 + A3** H2SO4 [ml] to titrate sample from pH5 to to 4.0
20	**0.1**	6.72	3.64	0.25	**3.89**	0.08	**0.33**

Alkalinity [mmol/l]

= 3.89ml * 0.1mmol/l * 1000 / 20ml = 19.45 mmol/l (1)

VFA [mg/l] (considered to be acetic acid)

= 131'340 * 0.1mmol/l * 0.33ml / 20ml – 3.08 * 19.45mmol/l – 10.9 = 145.9 mg/l (2)

A/TIC

$$\frac{\text{VFA [mg/l]} = \textbf{A [mg/l]} = 145.9\text{ mg/l}}{\text{Alkalinity [mmol/l]} \rightarrow \textbf{TIC [mg/l]} = 19.45\text{mmol/l} * (100.084/2) = 973.3\text{ mg/l}} = \underline{0.15} \quad (3)$$

The results of the A/TIC-ratio are normally below 1.0. Each digester has its own A/TIC-ratio optimum which needs to be determined by conducting measurements on a regular basis. Significant changes of the A/TIC-ratio indicate disturbances of the process stability at an early stage in order to introduce counter-measurements (decrease or increase of feedstock quantity, addition of buffer capacity) at the appropriate time.

5. Researches on anaerobic digestion using the titration method of Kapp

Within different research projects of Eawag/Sandec (Swiss Federal Institute for Aquatic Sciences and Technology / Department of Water and Sanitation in Developing Countries), the titration method according to Kapp was applied on substrate samples of biogas digesters in India (Heeb, 2009), Lesotho (Müller, 2009) and Tanzania (Lohri, 2009). The samples were filtered using a kitchen sieve and textile mash to analyze VFA, alkalinity and A/TIC-ratio. Lohri includes furthermore a description and results of another simple yet less accurate and therefore less recommendable 3-point-titration method (according to Nordmann, 1977) and some experiments concerning the influence of different pre-treatment methods (sieve, centrifuge, membrane filter) of the digester samples on the VFA and alkalinity results by Kapp.

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