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# Evaluation of a biogas plant in Adeiso, Ghana

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Cover: Biogas plant consisting of digesters, gas storage balloons and fruit waste collection, at HPW Fresh & Dry Ltd. in Adeiso, Ghana. Photo: Johanna Grim, 2012.

# Abstract

The purpose of this study was to evaluate the function, stability and performance of the biogas plant at HPW Fresh & Dry Ltd. in Adeiso, Ghana. The study showed that the process was functioning, with an adequate average organic loading rate and methane content of the biogas. However, the digesters had low alkalinity and were sensitive to disturbances, and the uneven feeding caused considerable pH and biogas flow variations.

The influent consisted of 47 % fruit waste and 53 % water. At eight times during the project period, poultry manure was added. The feeding occurred mainly between 8 am and 5 pm, ranging from 0 to 20 $m^3$ per digester and day. The average daily feeding to one digester was 9.1 $m^3$ which gives an organic loading rate varying between 0 and 5.5 kg ODM per $m^3$ and day. The average value was 2.6 kg ODM per $m^3$ and day.

The methane content of the biogas varied between 39 % to 61 %, with an average of 51 % in Digester 1 and 50 % in Digester 2. The methane content decreased during the day due to the feeding. The $H_2S$ content was as high as 1900 ppm in the beginning of the period, probably due to accidental addition of sulphur containing preservatives to the digesters. The concentration decreased steadily as a result of process recovery.

From the two digesters combined the total biogas flow was estimated to values between 24 and 59 $m^3/h$. The flow increased generally during the day, which is explained by the feeding pattern.

The pH of the influent varied between 3.6 and 5.2 with an average value of 4.0. The pH increased when poultry manure was added. The pH of the digestate was 6.6-7.1 with an average of 6.9 in both digesters. The temperature ranged from 31 to 34°C with an average of 33°C and was higher in the end of the period. Generally, the pH decreased during the day, due to the feeding pattern. On days with more feeding, the pH decreased more. The pH was higher and more stable in the end of the project period, which is due to higher alkalinity and/or higher temperature.

The alkalinity was low, the bicarbonate alkalinity was measured weekly to values between 2 000 and 3 300 mg $HCO_3/l$, while the total alkalinity ranged from 3 300 to 4 300 mg $HCO_3/l$. However, the alkalinity increased during the period, probably due to the addition of poultry manure.

The nutrient content in the substrates was low, giving a high C/N ratio. This implies a nitrogen shortage in the digesters. Also, the ash content in the poultry manure was high, making it desirable to replace it with another source of nitrogen.

From the findings of the study recommendations on further development of the plant were made. These included a more even feeding, an improved mix of substrates and monitoring of operation parameters.

# Sammanfattning

Syftet med denna studie var att utvärdera funktion, stabilitet och prestanda hos en biogasanläggning vid HPW Fresh & Dry Ltd. i Adeiso, Ghana. Studien visade att processen fungerade med en adekvat genomsnittlig organisk belastning och metanhalt. Emellertid hade rötkammarinnehållet låg alkalinitet och processen var därmed känslig för störningar. Den ojämna matningen orsakade stora variationer i pH och biogasflöde.

Det inkommande materialet bestod av 47 % fruktavfall och 53 % vatten. Vid åtta tillfällen tillsattes också hönsgödsel. Matningen skedde huvudsakligen mellan kl. 8 och 17, allt från 0 till 20 $m^3$ per rötkammare och dygn vilket innebär en organisk belastning mellan 0 och 5,5 kg VS per $m^3$ och dygn. Den genomsnittliga dagliga matningen per rötkammare var 9,1 $m^3$ vilket motsvarar 2,6 kg VS per $m^3$ och dygn.

Metanhalten i biogasen varierade mellan 39 % och 61 %, med ett genomsnitt på 51 % och 50 % i rötkammare 1 respektive rötkammare 2. Metanhalten minskade under dagen på grund av matningen. Halten av svavelväte var så hög som 1900 ppm i början av perioden, förmodligen på grund av oavsiktlig tillsats av svavelhaltiga konserveringsmedel. Koncentrationen minskade stadigt som en följd av processåterhämtning.

Det totala biogasflödet uppskattades till mellan 24 och 59 $m^3/h$. Flödet ökade generellt under dagen, vilket beror på matningsvariationer. pH hos inkommande material varierade mellan 3,6 och 5,2 med medelvärdet 4,0. pH ökade när hönsgödsel tillsattes. pH för rötkammarinnehållet var 6,6-7,1 med ett genomsnitt på 6,9 i båda rötkamrarna. Generellt minskade pH under dagen, på grund av matningsvariationerna. På dagar med mer matning minskade pH-värdet mer. pH var högre och mer stabilt i slutet av projektet, vilket beror på högre alkalinitet och/eller högre temperatur.

Temperaturen varierade från 31 till 34°C med ett genomsnitt på 33°C. Temperaturen var högre i slutet av perioden.

Alkaliniteten var låg. Bikarbonatalkalinitet mättes veckovis till värden mellan 2 000 och 3 300 mg $HCO_3$/l, medan den totala alkaliniteten varierade från 3 300 till 4 300 mg $HCO_3$/liter. Alkaliniteten ökade dock under perioden, förmodligen på grund av tillsatsen av hönsgödsel.

Halten av näringsämnen i substratet var låg, vilket ger en hög C/N-kvot och en kvävebrist i rötkamrarna. Dessutom var askhalten i hönsgödseln hög, vilket gör det önskvärt att ersätta det med en annan kvävekälla.

Från studiens resultat har rekommendationer om vidare utveckling av anläggningen utformats. Dessa inkluderade en jämnare matning, en förbättrad mix av substrat samt övervakning av driftparametrar.

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# Preface

This report is the outcome of the course *Project Work in Energy Systems Engineering, 15 credits,* which is a part of the Master Programme in Energy Systems Engineering at SLU and Uppsala University. The study is part of the Minor Field Studies Scholarship Programme, financed by Sida, the Swedish International Development Cooperation Agency.

The study was conducted by Johanna Grim and Maria Johansson at HPW Fresh & Dry Ltd. in Adeiso, Ghana, during the period 16/1-9/3 2012.

We would like to thank **Dr. Cecilia Sundberg**, Dept. of Energy and Technology, SLU and **Dr. Elias Aklaku**, Dept. of Agricultural Engineering, KNUST, for guidance throughout the project.

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Uppsala, 20/8 2012

Maria Johansson & Johanna Grim

# 1 Background

Waste management is an important part in reducing harmful anthropogenic impact on the environment. Globally, approximately 900 Mtons of waste was generated in 2002 (IPCC, 2007). The food industry produces large amounts of waste, and one way of treating this is through anaerobic digestion. Anaerobic digestion of organic waste has several advantages. The product, biogas, is a renewable energy resource that could replace fossil fuel for electricity and heat generation. Purified biogas can also be used as a vehicle fuel. Finally, the process can be part of wastewater treatment and the effluent can be used as a soil fertilizer. A life cycle assessment from North Carolina State University showed that anaerobic digestion is the most environmentally beneficial way to handle food waste, compared to compost and landfill with and without gas collection (Levis & Barlaz, 2011).

## 1.1 Biogas in Ghana

In Ghana, an interest for biogas emerged in the late 1960s, but it was first in the middle of the 1980s that the Ghanaian government started to pay attention to the biogas technology (Arthur et al., 2011). Ghana Energy Commission has set up a “Strategic National Energy Plan” for the period 2006 – 2020, to ensure that the energy demand is covered in a sustainable way. One of the targets is to reach 1 % biogas in hotels, restaurants and institutional kitchens by 2012 and 2 % by 2020 (Allotay et al., 2006). Also, the Renewable Energy Directorate of Ghana promotes an increased use of different biomass technologies such as biogas (Ministry of Energy, 2010).

The total number of biogas plants in Ghana is unknown, but according to an estimation about 200 biogas plants have been constructed this far. The actual number of plants could be higher because of unknown projects started by individuals and small companies (Bensah et al., 2010). Most of the plants are relatively small and are located at schools and hospitals in urban areas. The main purpose is to improve the state of sanitation (Arthur et al., 2011). However, a significant fraction of the biogas plants in Ghana does not function well as a result of lack of adequate substrates, gas leakages and lack of maintenance and operational knowledge (Kemausuor et al., 2011).

Agriculture is an important sector in Ghana, employing half of the population and accounting for almost one third of GDP. The most important crop is cocoa, but also coffee, fruits and vegetables are exported (Utrikespolitiska institutet, 2012). Some waste from the production is used for animal feeding, but a large fraction is used for landfill. Anaerobic digestion is therefore a technology with large potential in Ghana.

## 1.2 HPW Fresh & Dry Ltd.

HPW Fresh & Dry Ltd. is owned by the Managing Director Maik Blaser and by HPW AG, a Swiss company exporting fruit from Africa, Costa Rica and Thailand. The factory is situated in Adeiso, Ghana, approximately 60 km northwest of Accra. HPW Fresh & Dry Ltd. (HPW) exports dried fruits such as mango, pineapple, coconut and banana to the European market. It is the largest factory for dried fruits in West Africa and has a capacity of 250 tonnes dried fruits per year (HPW fresh & dry, 2012b).

The company intends to supply the factory’s total need for electricity and heat through renewable energy. The biogas plant, which uses fruit waste from HPW and from other fruit factories nearby, supplies gas to a generator and a boiler for heat and electricity generation. There are also solar panels at the roof of the factory. The factory started operating in May 2011 and the biogas plant has been in operation since July 2011 (Blaser, 2012).

## 1.3 Biogas production

Biogas mainly consists of methane, 55-80 %, and carbon dioxide, 20-45 % (Christensson et al., 2009). Also small fractions of water vapor, nitrogen, nitrous oxide are present (Gerardi, 2003). Biogas is produced in different steps by different types of microorganisms, see Figure 1.1.

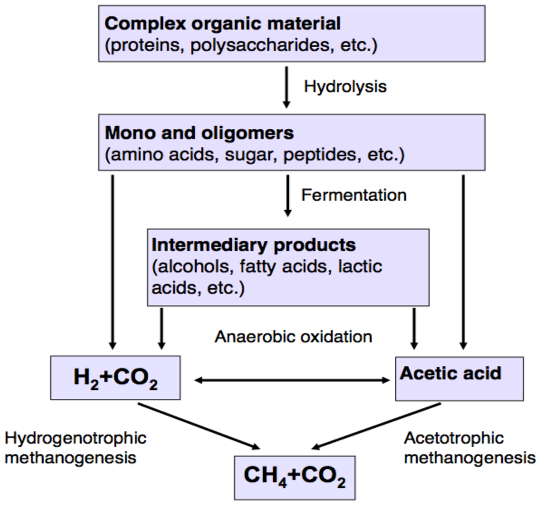

Figure 1.1. Schematic picture of the different microbiological steps of the biogas process (Jarvis & Schnurer, 2009).

The main steps are hydrolysis, fermentation, anaerobic oxidation and methanogenesis. In the hydrolysis, enzymes are exuded to decompose large organic molecules like proteins and polysaccharides to smaller molecules like amino acids and simple sugars. These are converted into alcohols, fatty acids and other intermediate products by many different types of microorganisms in the fermentation (Jarvis & Schnürer, 2009). In the anaerobic oxidations, hydrogen gas and acetic acid is produced by acetogens (McMahon et al., 2001). These microorganisms cooperate with the methanogens that consume hydrogen gas, since the hydrogen gas concentration needs to be kept on a low level in order for the anaerobic oxidations to function. From the acetic acid and hydrogen gas methane is produced by two different types of methanogens, in the hydrogenotrophic methanogenesis and in the acetotrophic methanogenesis (Jarvis & Schnürer, 2009).

Anaerobic digestion is a complex process which is affected by the type of substrate, the physical conditions in the digester and the way the plant is operated. Below, some key parameters for biogas production are described.

### Substrates

Different substrates contain carbohydrates, fats and protein in different fractions and the composition of the substrate affects the biogas production. The substrate is the food for the microorganisms and needs to provide an energy source as well as elements for building new cells. A diverse substrate that contains carbohydrates, fats, proteins and important nutrients is beneficial and makes it possible for many different microorganisms to thrive in the digester (Carlsson & Uldal, 2009). Unbalanced substrates can give different problems.

### ***Proteins and fats***

When protein is decomposed, ammonium and ammonia are produced, the equilibrium depending on the pH. Ammonia inhibits the microorganisms and reduces the methane production. Therefore, if the substrate has too high protein content, problems with ammonia inhibition can occur. If the fat content of the substrate is high, it might cause problems with foaming (Carlsson & Uldal, 2009).

### ***Carbohydrates***

There are different types of carbohydrates, mono-, di- and polysaccharides. If the substrate contains high levels of mono- and disaccharides, the first steps in the process, the hydrolysis and the fermentation, are quicker than the last step, the methanogenesis. In the first steps volatile fatty acids (VFA) are produced and consequently, accumulation of fatty acids may be a problem. This can affect the pH and give instability problems which are explained by the relation between VFA, $H_2$ and different microorganisms (Jarvis & Schnürer, 2009).

The VFA are consumed in the anaerobic oxidation by microorganisms called acetogens. The acetogens are sensitive to $H_2$, one of their own rest products. $H_2$ is consumed by the methanogens in the methanogenesis. Since the methanogens are inhibited by VFA, high concentrations of VFA will lead to an increase in the $H_2$ concentration which will inhibit the acetogens and increase the VFA further. In the worst case this can bring the process to a complete halt. VFA toxicity is worsened by low pH (McMahon et al., 2001).

## pH

The pH affects the digester performance since the methane producing microorganisms are sensitive to low pH. The biogas process works satisfactory at pH 6.8-7.2 but the process efficiency is best when pH is 7.0-7.2 (Gerardi, 2003).

## Continuity

The anaerobic digestion can be a continuous or batch process. Continuous digestion means that organic material is pumped continuously into the digester. This is possible for liquid substrates, i.e. substrates with low dry matter content. In a semi-continuous process substrate is fed between one and eight times a day. This is suitable for substrates with dry matter content ranging between 5 and 15 % (Jarvis & Schnürer, 2009).

## Hydraulic retention time

The hydraulic retention time is the time it takes to replace the organic material in the digester. If the hydraulic retention time is too short, the full digestion potential of the organic matter will not be utilized since some of the matter will go through the process undigested. Also, important microorganisms might be washed out from the process. If the hydraulic retention time is too long, the methane production potential of the digester per time unit is not fully utilized (Gerardi, 2003).

## Temperature

The biogas process can be conducted at different temperature intervals. Different microorganisms can survive and be active at different temperatures. Most often, the process is mesophilic, 25 - 40°C, or thermophilic, 50 - 60°C. Generally, a thermophilic process is faster than a mesophilic, since the activity of the microorganisms increases with higher temperature.

The optimum temperature in a mesophilic process is 35°C. If the temperature falls below 32°C the activity of the methanogens is reduced. However, the microorganisms producing volatile fatty acids can work well at lower temperatures, which might lead to accumulation of fatty acids. Consequently, too low temperatures can give instability problems. The microorganisms are also sensitive to fluctuations in temperature (Gerardi, 2003).

### Alkalinity

The alkalinity is a measure of the buffer capacity, i.e. the amount of basic substances, mainly bicarbonate ions, in the digester. The basic substances bind to hydrogen ions which prevents pH drop when acids are added. In order to achieve a proper control of the pH in the process, the alkalinity needs to be high enough (Gerardi, 2003).

The bicarbonate alkalinity (BA) is a measure of how much bicarbonate ions is present in the digester and the total alkalinity (TA) is a measure of the total amount of basic substances. For stable mesophilic processes, BA values ranging from 3000 to 15 000 mg bicarbonates per liter and TA values ranging from 5000 to 20 000 mg bicarbonates per liter have been measured (Jarvis & Schnurer, 2009).

### C/N-ratio

Considering the nutrients of the substrate the carbon nitrogen ratio (C/N-ratio) is of importance. C/N-ratios in the range of 10-30 is adequate in biogas processes. Too high C/N-ratio means the microorganisms will suffer from nitrogen deficiency and also that high concentrations of fatty acids will form (Jarvis & Schnürer, 2009). Too low C/N-ratio can give problems with ammonia inhibition, see *Proteins and fats* above.

### Organic loading rate

The organic loading rate (OLR) is the amount of new organic material that is added to the process in relation to time. To calculate the OLR, the dry matter (DM) and the organic dry matter (ODM) of the substrate must be known. OLR is given as kg added ODM per $m^3$ digester volume and day.

A mesophilic biogas process should have an organic loading rate of 2-3 kg ODM/$m^3$ day (Jarvis & Schnürer, 2009).

### Degree of digestion

The degree of digestion is a measure of how much of the organic material that is decomposed and the maximum possible degree of digestion varies with different substrates. For fruit and vegetable waste, the maximum degree of digestion is approximately 91 % (Edström & Nordberg, 2004).

# 2 Purpose

The purpose of this study was to evaluate the quality and quantity of produced biogas in relation to the amount and type of substrate digested in the plant. The purpose was also to assess the stability of the process. Another purpose was to gather information of interest for a possible future Life Cycle Assessment of the process.

The study aimed to answer the following questions:

- How did the gas quality vary over the period?
- How did the amount of produced gas vary over the period?
- How did the pH and temperature in substrate and digester vary over the period?
- Which was the average Organic Loading Rate (OLR) of the plant?
- How did the OLR vary over the period?
- How much energy could be produced?
- What was the nutritional value of the substrate and the effluent?

Based on these questions, the function, stability and performance of the plant were assessed, and recommendations for improving operation were made. Also, a detailed description of the plant was provided.

# 3 Description of the biogas plant

The biogas plant at HPW's factory in Adeiso, Ghana, has been in operation since May 2011. A schematic picture of the plant (Figure 3.1) describes the process from waste to biogas. Initially, a two stage process was used, but since this did not work well the process was changed into a one stage process with two parallel digesters.

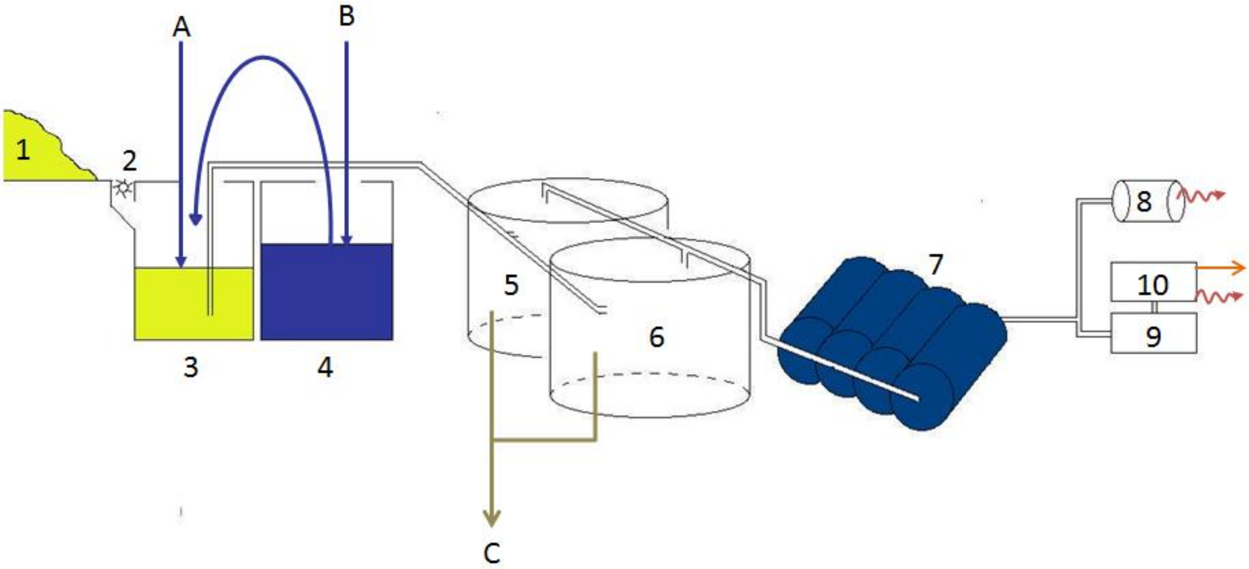

Figure 3.1. Schematic picture of the biogas plant. The fruit waste (1) is shredded (2) and enters the mixing tank (3). Water from the water tank (4) and waste water from the factory (A) is added to the mixing tank. The water in the water tank consists of rain water and additional water brought with a tank trailer. Sometimes it is also recirculated water from the digesters (B). The influent is pumped into the digesters (5 & 6), where the biogas production takes place. The gas flows into the gas storage balloons (7), and further to the boiler (8) which produces heat or via the gas cleaning system (9) to the gas engine (10) which produces heat and electricity. The effluent (C) is removed from the digesters with the tank trailer.

## 3.1 Influent

The digesters are fed with fruit waste from HPW's fruit drying factory in Adeiso. Waste from Blue Skies ltd. and PEELCO ltd., two neighboring fruit processing companies, also contribute to the biogas production. PEELCO is situated 14 km from the site and Blue Skies 24 km from the site (HPW Fresh & Dry Ltd., 2012a). The waste from HPW is brought to the biogas plant by a hand-operated trailer while the rest arrives by truck.

The fruit waste from PEELCO and Blue Skies consists mainly of peels and stocks from pineapples. The fruit waste from HPW consists mainly of mango peels, pineapple peels and pineapple stocks. Small amounts of banana peels are also added. The mango seeds and the pineapple crowns are deposited at the dumping site nearby. During November-January and April-May no mango waste is fed to the process due to the seasonal cultivation of mangoes (HPW Fresh & Dry Ltd., 2012b).

Some human waste from the factory's washrooms is added to the digesters. There is an interest in using other substrates in the biogas production and materials that are into consideration are poultry manure and palm kernel cake.

### Pre-treatment

Before the fruit waste enters the mixing tank (Figure 3.) it is shredded by an electrical drum shredder (Figure 3.3) which cuts the waste into 2-4 cm pieces. The human waste enters the mixing tank through a sewage pipe together with waste water from the washrooms. The area of the mixing tank was measured to be 6.76 $m^2$ and the depth is about 4 m. The mixing is done by an 11 kW electrical mixing pump (HPW Fresh & Dry Ltd., 2012c).

Figure 3.2. Mixing tank

Figure 3.3. Drum shredder

### Water

The solid waste is mixed with water. Waste water from the washrooms enters the mixing tank together with the human waste. This water originates mostly from toilet flushing and hand washing during day and from the laundry machines during night. Sometimes, when no preservatives are used, waste water from the factory's processing rooms also enters the mixing tank.

Additional water from the adjacent water tank is pumped into the mixing tank during shredding. The area of the water tank was measured to be 7.40 $m^2$ and the depth is about 4 m. During the dry season the water tank is filled several times a week with water from a small river nearby. The water is fetched by a tractor with a tank trailer of 6000 l (Bright, 2012). Sometimes, the effluent from the digesters is recirculated to the water tank. When it rains, rainwater is collected in the water tank.

## 3.2 Feeding of digesters

The substrate/water mix, the influent, is pumped with an electrical mixing pump of 11 kW into the two digesters (HPW Fresh & Dry Ltd., 2012c). The feeding occurs mainly between 8 am and 5 pm, usually 1-8 times per day, which means the digesters are operated in a semi-continuous mode (Jarvis & Schnürer, 2009).

## 3.3 Biogas production

The digesters are made of concrete and have a volume of 450 $m^3$ each. The height is approximately 4 m and the diameter is 12 m (Blaser, 2012). The digesters are submerged about halfway into the ground.

At the side of each digester there is a shaft where the digester content can overflow if the gas pressure in the digesters increases too much. The digester content is stirred with an automatically axial stirring device of 11 kW. The stirring is supposed to occur every hour during five minutes. The stirring of Digester 1 is operated automatically while the stirring of Digester 2 is operated manually due to a failure.

The temperature in the digesters is about 31˚C, which means that the process takes place in the mesophilic temperature interval. There is the possibility to heat Digester 1, but thus far it has not been utilized.

From the digesters the gas flows to four PVC gas storage balloons whose volumes were measured to 90 $m^3$ each.

## 3.4 Biogas use

The gas is used in the generator and in the boiler, see Figure 3.4 and 3.5. Initially the gas could also flow to the kitchen to be used as a cooking fuel, but the pipe has broken. The generator is manufactured by Camda Generator Work Co. Ltd., and has a rated power of 120 $kW_{electric}$. The boiler at 200 $kW_{heat}$ is manufactured by Baltur S. p. A. (HPW Fresh & Dry Ltd., 2012c) but has been reconstructed to better fit the purpose (Blaser, 2012).

The fruit dryers at HPW need hot water. When the heating from the solar panels is not enough the biogas is used to operate the boiler or the engine.

Figure 3.4. Biogas engine

Figure 3.5. Biogas boiler

A gas cleaning system from Camda Generator Work Co., Ltd. treats the gas before it enters the engine. It reduces the hydrogen sulfide content of the gas by using cylinders filled with activated charcoal. Previously, the cylinders contained iron oxide. There is also a water separation cylinder which reduces the gas water vapor content (HPW Fresh & Dry Ltd., 2012c).

During the project period a small air pump was installed at the top of each digester with the purpose of further reducing the hydrogen sulfide content of the gas.

## 3.5 Effluent

The effluent is removed from the digesters with a pipe inserted into the overflow shaft, see Figure 3.6. The pipe is connected to the tank trailer and the effluent is sucked out. There is also a 42 mm pipe at the ground level where samples of the effluent easily can be taken out (Blaser, 2012a).

Figure 3.6. The effluent is taken out through the overflow shaft.

The initial intention was to use the effluent from the digesters as a fertilizer. This has not been possible so far because of the farmer’s skepticism and instead the effluent is deposited at the dumping site nearby. Sometimes, when there is shortage of water, the effluent is recirculated to the water tank.

# 4 Methodology

## 4.1 Composition of influent

The average fractions of fruit waste and water in the influent was calculated from the daily average amount of fruit waste and water used.

### Amount of fruit waste

The amount of fruit waste generated from HPW was calculated from the daily recordings of processing weight, cut weight and weight of rejects from the factory. The mango seed fraction of the processing weight was estimated through weighing the mango seeds from one day's production and relating the weight to the processing weight that day. The mango seed fraction was assumed to be constant. The waste weight was calculated according to Equation 1.

$$\begin{aligned}&Waste\ weight = \\ &processing\ weight - cut\ weight\ - (processing\ weight * mango\ seed\ fraction) + rejects \quad (1)\end{aligned}$$

There was no possibility to weigh the waste from PEELCO and Blue Skies. The total amount of waste generated at PEELCO during a week divided by the number of trucks gave an estimation of the waste amount in each truck from PEELCO. The waste amount per truck was assumed to be constant. The amount of fruit waste from Blue Skies was estimated by comparing the truck from Blue Skies to the truck from PEELCO.

### Amount of poultry manure

When poultry manure was fetched from the nearby poultry farm, the bags, which had a known weight, were counted by the staff.

### Amount of water

The amount of water used was calculated from daily measurements of the levels in the water tank and the mixing tank and estimations of the water volume from the washrooms. The areas of the mixing tank and the water tank were measured to enable the calculations.

The level in the water tank was measured before opening in the morning and after closing in the evening. The difference, together with the number of fillings from the tank trailer, gave the amount of water used during the day. Measurements on days with rainfall were discarded since the additional inflow from the drainage system could not be measured.

The level in the mixing tank was measured after closing in the evening and before opening the following morning. The rising of the level gave the water volume from the washrooms during the night. Some nights shredding took place, which raised the level in the mixing tank further. These measurements were discarded since the volume of the shredded material was unknown.

The water flow from the washrooms to the mixing tank during the day was impossible to measure. Estimations on how many times each worker used the toilet and washed his/her hands daily gave the water volume from the washrooms during day. The volume used for one hand wash was estimated from measurements of 24 worker's hand washing.

## 4.2 Feeding of digesters

The volume fed into the digesters was calculated using the area of the mixing tank combined with measurements of the level in the mixing tank before and after each feeding. Records were taken each time feeding occurred.

A ruler was inserted on the wall of the mixing tank, with marks every 10 cm, see Figure 4.1. The accuracy can therefore be assumed to be ±5 cm.

**Figure 4.1. A ruler is inserted in the mixing tank**

## 4.3 Biogas quality and flow

A connection was constructed at Digester 1 in order to enable analysis of the gas from either Digester 1 or Digester 2, see Figure 4.2. Between the 2nd and 9th of February the gas from Digester 2 was impossible to analyse due to a flow meter that occupied the pipe opening.

**Figure 4.2. Biogas analysis of the gas from Digester 1 with a Sewerin Multitec 540 gas analyser.**

The gas analyser Sewerin Multitec 540 from Hermann Sewerin GmbH was used to measure the fractions of methane, carbon dioxide and hydrogen sulfide in the gas. The gas composition was analysed for both digesters twice daily, at 9 am and 4 pm. To investigate the gas quality change during the day, analysis was also performed each hour during one day.

The flow was estimated through measurements of the time necessary to fill one balloon, see Figure 4.3-4.6. First, the valves were adjusted in order for the boiler to empty one balloon. The valves were then adjusted to let the gas from the digesters fill this balloon and the time it took was measured.

Figure 4.3. Empty balloon

Figure 4.4. Filling of the balloon

Figure 4.5. Filling of the balloon

Figure 4.6. Full balloon

To obtain the flow in standard cubic meters per hour, corrections for the gas temperature had to be made. When the balloon was full the temperature of the shady side was measured with an infrared thermometer, PCE-891 from PCE Deutschland GmbH, see Figure 4.7. The pressure in the balloons was assumed to be atmospheric pressure.

Figure 4.7. The temperature of the balloon is measured with an infrared thermometer.

The volume of one balloon was calculated from measurements of the width and length of an emptied balloon. The balloons were assumed to be identical, ideal cylinders.

## 4.4 Influent pH and temperature

The pH and temperature of the influent was measured daily at 10 am. A sample was fetched with a bucket attached to a pipe. The pH was measured with a ZQ168 Portable pH meter from Zhengzhou Hornsen Instrument Co. ltd., see Figure 4.8, and the temperature was measured with a Thermocouple thermometer HD 9016 from Delta Ohm, Italy, see Figure 4.9.

Figure 4.8. The pH of the influent was measured with a portable pH meter.

Figure 4.9. The temperature of the influent was measured.

## 4.5 Digestate pH and temperature

Samples of the digestate were taken twice daily, at 9 am and 4 pm, from a pipe at the ground level of the digester, see Figure 4.10.

Figure 4.10. Sample of digestate

The temperature and pH were measured immediately in the same way as for the influent see Figure 4.11 and 4.12.

Figure 4.11. pH of digestate was measured.

Figure 4.12. Temperature of digestate was measured.

To investigate the change of digestate temperature and pH during the day, analysis was also performed every hour during one day.

## 4.6 Alkalinity

The alkalinity of the digestate was measured through titration five times with one week's interval. 150 ml of digestate was titrated with 0.05 M hydrochloric acid at the lab at HPW, see Figure 4.13. The bicarbonate alkalinity (BA) was obtained by titration to pH 5.75 and the total alkalinity (TA) by titration to pH 4.0 (Jarvis & Schnürer, 2009). The pH was measured with a PCE-168 pH meter from PCE Deutschland GmbH using two decimals for the first three titrations, but due to a breakdown of the equipment the pH meter with accuracy of one decimal was used for the last two titrations.

BA and TA were calculated according to

$$BA = a * M * 61 * f * k \qquad (2)$$

$$TA = a * M * 61 * f * k \qquad (3)$$

where

- a is the amount of HCl used to reach the desired pH
- M is the molarity of the hydrochloric acid
- 61 is the molecular weight of bicarbonate
- f is the dilution factor of the digestate
- k is a correction factor of 1.25, that takes into account that only 80 % of the salts participate in the reaction (Jarvis & Schnürer, 2009).

The calculated values were converted to mg bicarbonate per liter digestate.

Figure 4.13. Setup of lab equipment for analysis of alkalinity.

## 4.7 Dry Matter, Organic Dry Matter and Nutrient content

Analysis to determine the fractions of dry matter, organic dry matter, nitrogen, phosphor and potassium in the substrates, the influent and the digestate was performed by CSIR[1] Soil Research Institute in Accra. Samples of the different substrates were brought for analysis twice, the 8th and 15th of February, while the influent and the digestate were analysed three times, the 8th, 15th and 23rd of February.

Samples were collected in plastic containers in the morning and stored in a cooling bag on the way to the laboratory. Samples of mango and pineapple were collected at random from the shredding area. Poultry manure and palm kernel cake were delivered from the nearby farms. The influent was collected with a bucket after mixing. The digestate samples were collected from the overflow pipe, with the tank trailer that is used for emptying the digesters.

In the laboratory, the samples were kept refrigerated when they were not worked on (Ababio, 2012).

From the results of the influent and the digestate a statistical analysis of the average value and the standard deviation was performed, according to Jonsson & Norell (2007).

## 4.8 Organic Loading Rate

The organic loading rate (OLR) was calculated according to

$$OLR = (V_{fed} * DM_{influent} * ODM_{influent} * \rho) \,/V_{digester} \tag{4}$$

where

- $V_{fed}$ is the daily volume fed to one digester
- $DM_{influent}$ is the dry matter fraction of the influent
- $ODM_{influent}$ is the organic fraction of the dry matter
- $\rho$ is the density of the influent
- $V_{digester}$ is the volume of one digester.

Measurements of the influent density were made three times during one day. 10 l of the influent was weighed.

## 4.9 Degree of Digestion

The degree of digestion (DoD) was calculated according to

$$DoD = (DM_{influent} * ODM_{influent} - DM_{effluent} * ODM_{effluent})/(DM_{influent} * ODM_{influent}).(5)$$

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[1] Center for Scientific and Industrial Research

# 5 Results

## 5.1 Composition of influent

The fruit waste in one truck from PEELCO weighed about 7 tons (PEELCO ltd., 2012) and the weight of the fruit waste from Blue Skies was estimated to 5 tons per truck. The average daily amount of fruit waste was 9.0 tons.

Poultry manure was fed 8 times according to Table 1.

**Table 1. Time and amount of poultry manure fed to the digesters.**

| Date | Amount of poultry manure, tons |
|---|---|
| 28 Jan | 0.36 |
| 1 Feb | 1.0 |
| 18 Feb | 1.2 |
| 20 Feb | 2.4 |
| 23 Feb | 3.8 |
| 1 March | 2.2 |
| 4 March | 2.1 |
| 8 March | 2.1 |

On a daily basis, 65 factory workers and 37 other employees were present at HPW. The water amount used for hand washing was measured to be 0.84 l per wash. The factory workers washed their hands about five times and the other employees about two times daily. The toilet, which had a six liters bin was used one time per person and day (Bright, 2012; Erabah Essando, 2012). This gives a total water flow from the washrooms of 0.95 $m^3$ per day.

The average daily amount of water originating from the water tank was 6.4 $m^3$ while the average water amount from washrooms during night was 2.3 $m^3$. In total, the average water volume added to the substrate was 9.7 $m^3$ per day.

When only fruit waste was used as a substrate the water measurements showed that the influent consisted of 47 % fruit waste and 53 % water. On the days when poultry manure was fed the water use was impossible to measure due to rainfalls. Consequently, no composition of the influent was obtained these days, but observations told that significantly more water was needed when poultry manure was fed.

## 5.2 Feeding of digesters

Mainly, the feeding of the digesters occurred between 8 am and 5 pm. Figure 5.1 shows the feeding per day to Digester 1 and Digester 2 separately. The daily feeding to Digester 1 varied between 2.7 and 20 $m^3$ and in Digester 2, the feeding varied between 0 and 19 $m^3$ per day. The average feeding per day and digester was 9.1 $m^3$.

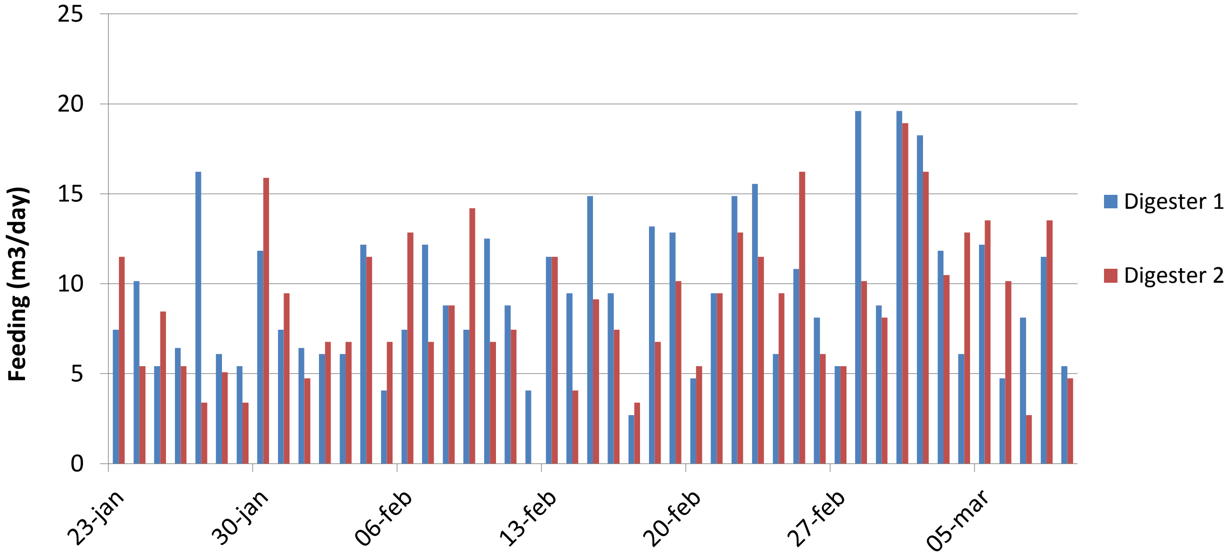

Figure 5.1. Daily feeding of Digester 1 (blue bars) and Digester 2 (red bars).

## 5.3 Biogas quality and flow

### Methane

During the period the methane content of the biogas varied according to Figure 5.2 and 5.3 for Digester 1 and Digester 2 respectively. The graphs show measurements at 9 am and 4 pm every weekday.

The highest methane content was measured to 61% and the lowest value recorded was 39 %. The average methane content was 51 % and 50 % from Digester 1 and 2 respectively.

The methane content was higher in the morning than in the afternoon every day during the period, without exception. Figure 5.4 and 5.5 show the feeding and the methane content in Digester 1 and 2 respectively between 9am and 6 pm on the 13th of February. The methane content decreased during the day in both digesters.

### Carbon dioxide

The carbon dioxide content of the gas from Digester 1 and 2 is shown in Figure 5.2 and 5.3. The highest value of the carbon dioxide content was 46 % while the lowest value was 27 %. On average the carbon dioxide content of the gas was 37 % and 36 % from Digester 1 and Digester 2 respectively.

The feeding and the variation of carbon dioxide content on the 13th of February is shown in Figure 5.4 and 5.5. The carbon dioxide content increased during the day in both digesters.

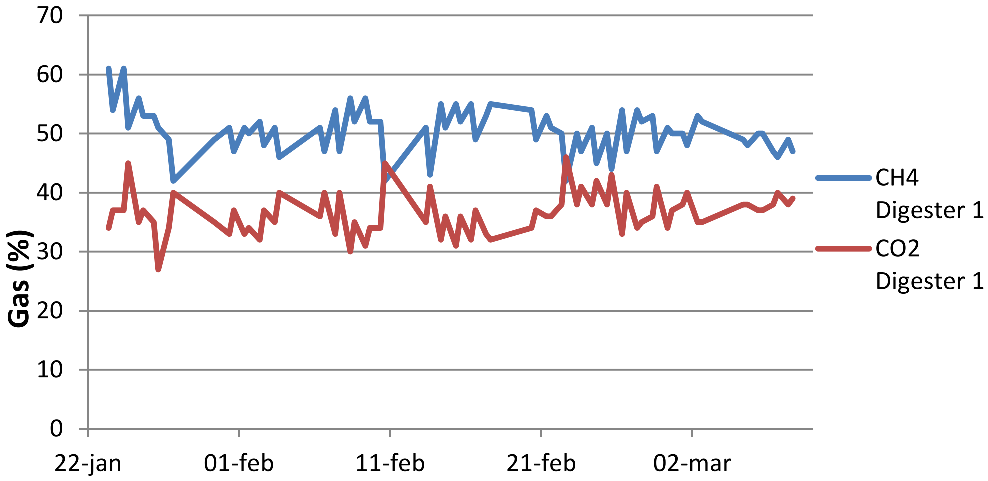

**Figure 5.1. Methane, $CH_4$, and carbon dioxide, $CO_2$, content in the biogas from Digester 1.**

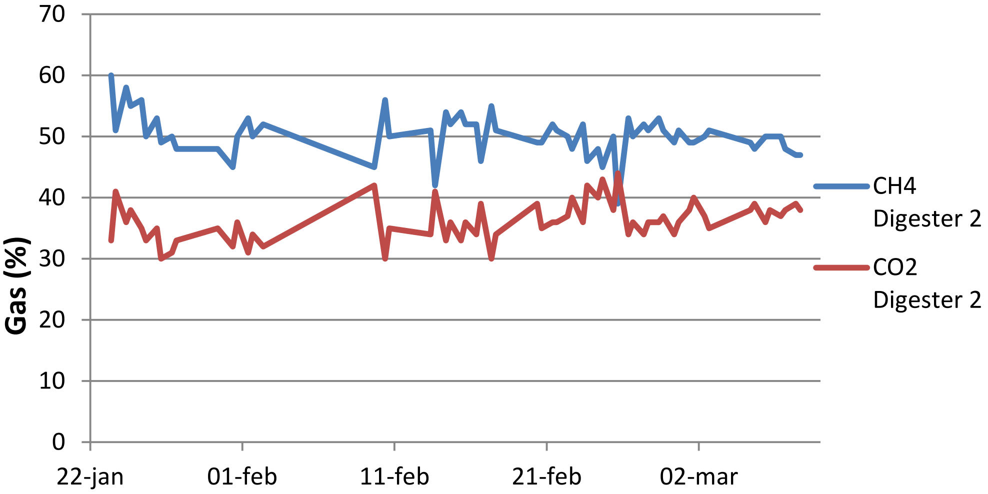

**Figure 5.2. Methane, $CH_4$, and carbon dioxide, $CO_2$, content in the biogas from Digester 2.**

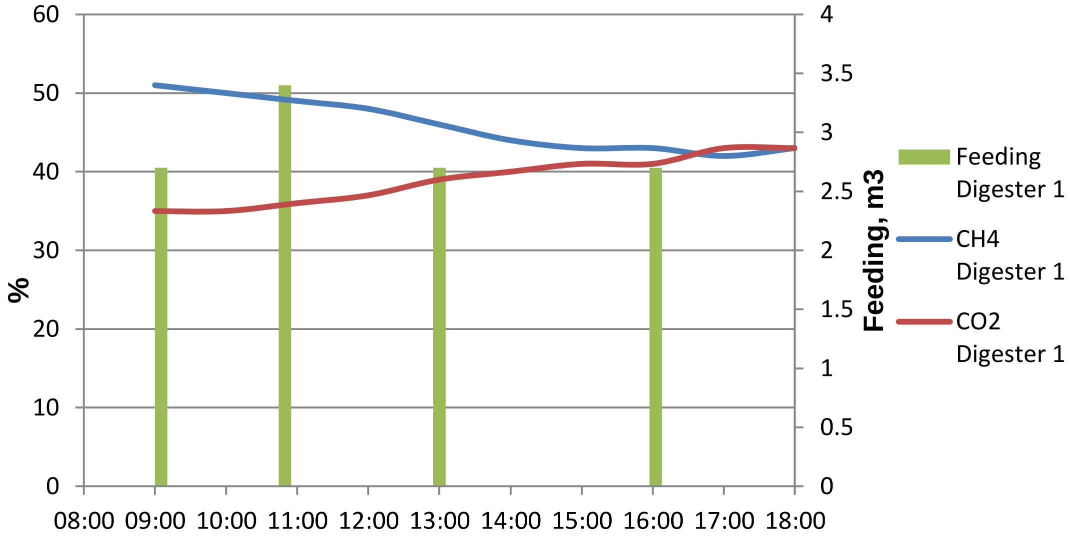

**Figure 5.4. Methane, CH4, and carbon dioxide, CO2, content in the biogas from Digester 1 together with the feeding on the 13th of February**

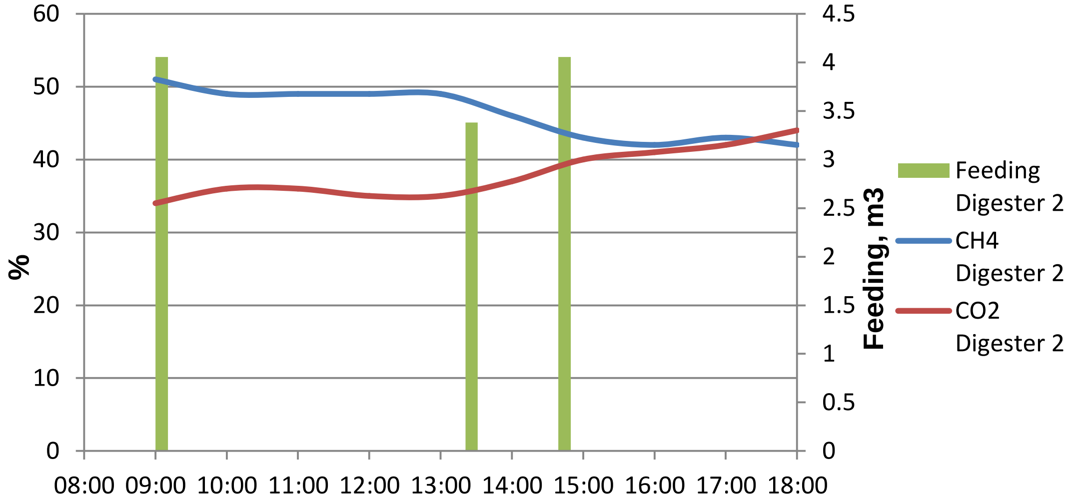

Figure 5.5. Methane, CH4, and carbon dioxide, CO2, content in the biogas from Digester 2 together with the feeding on the 13th of February

## Hydrogen Sulfide

The hydrogen sulfide content varied according to Figure 5.6 and 5.7. The $H_2S$ content was highest in the beginning of the period with a recorded value of maximum 1900 ppm in the gas from Digester 1 and 1500 ppm in the gas from Digester 2. The hydrogen sulfide in Digester 1 decreased steadily until the 9th of February when a considerable decrease was observed, before it started to vary significantly. The analysis of the gas from Digester 2 shows a similar pattern.

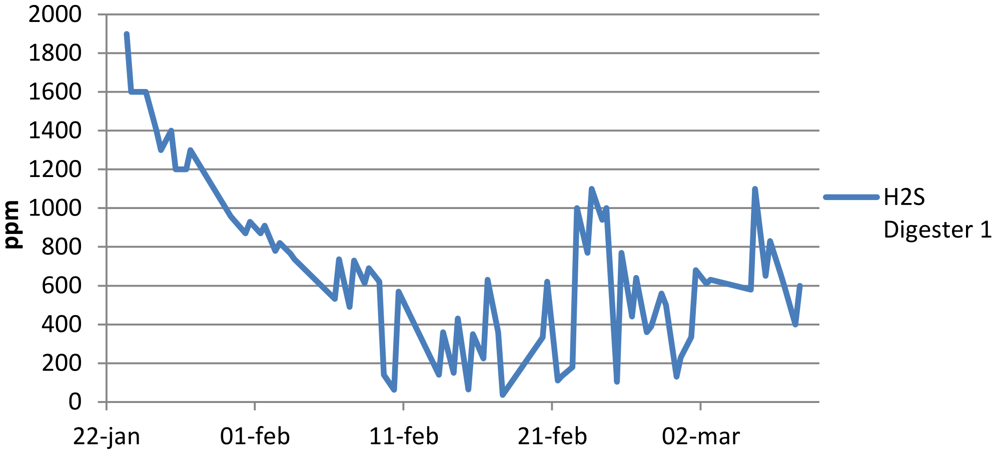

Figure 5.6. Hydrogen Sulfide, $H_2S$, content in the biogas from Digester 1.

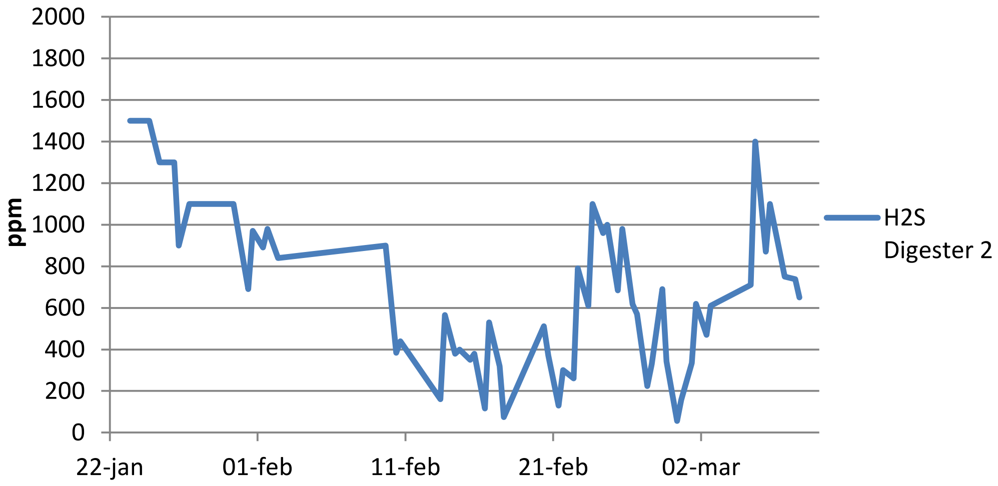

Figure 5.7. Hydrogen Sulfide, $H_2S$, content in the biogas from Digester 2.

## Biogas flow

The estimations of the biogas flow from Digester 1 and Digester 2 together on the 9th and 22nd of February are presented in Figure 5.8. They show that the flow was higher in the afternoon than in the morning.

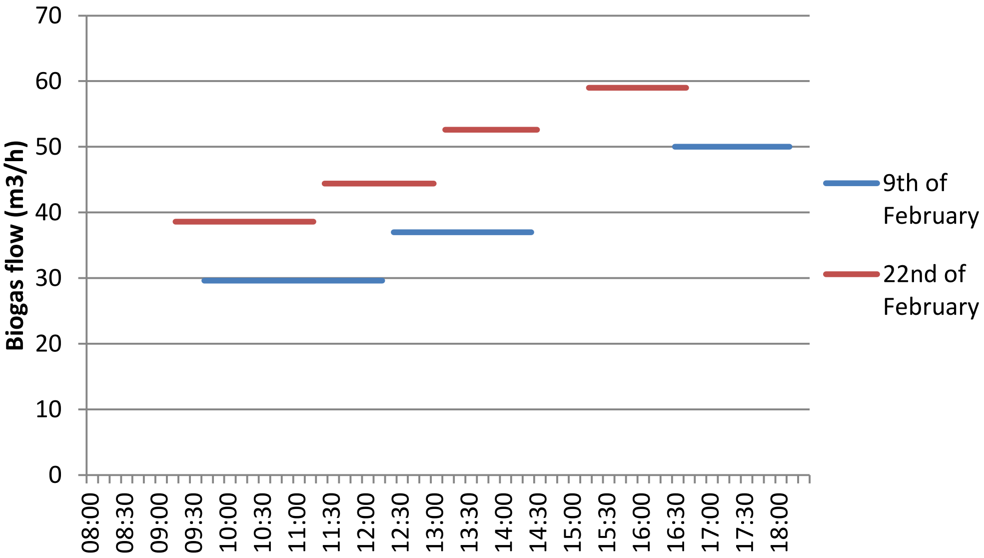

Figure 5.8. Estimations of the total biogas flow on the 9th and 22nd of February.

Four other estimations were made in the morning on other days, giving biogas flows of 41, 45, 24, and 48 $m^3$ per hour.

## Methane production

By using the estimated biogas flow and the average values for methane content and organic loading rate, the specific methane production could be calculated. The biogas flow was measured to values between 24 and 59 $Nm^3/h$. This gives a range of 0.13 – 0.32 $Nm^3$ $CH_4$/kg ODM.

## 5.4 Influent pH and temperature

The pH of the influent is shown in Figure 5.9. It varied between 3.6 and 5.2 while the average value was 4.0. On the 22nd and 24th of February and on the 2nd of March increases in the pH were observed.

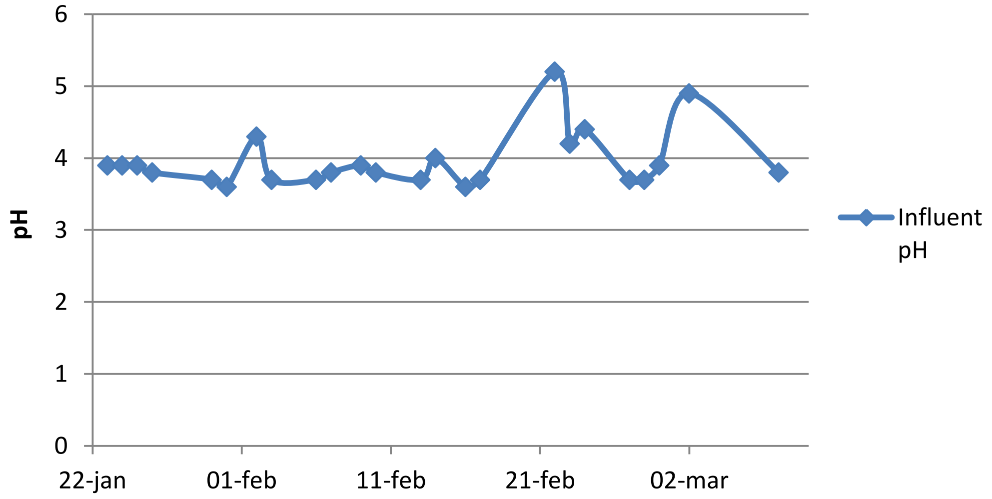

Figure 5.9. pH of the influent in the mixing tank.

The temperature of the substrate varied between 29 and 35°C with an average value of 32°C.

## 5.5 Digestate pH and temperature

Figure 5.10 shows the pH in Digester 1 and Digester 2. In Digester 1 the pH value varied between 6.6 and 7.1 while it varied between 6.6 and 7.0 in Digester 2. The average pH was 6.9 in both digesters.

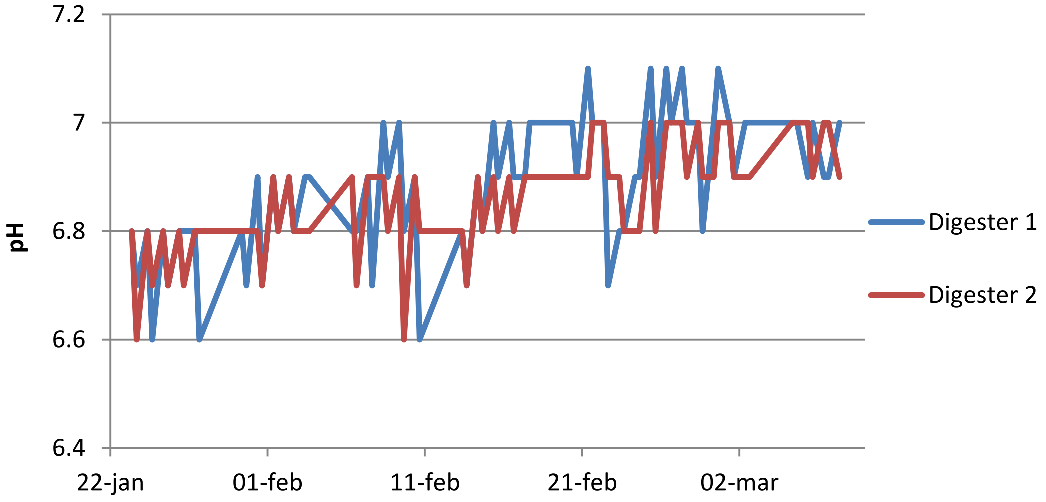

Figure 5.10. pH of the digestate in Digester 1 (blue line) and Digester 2 (red line).

The pH and the feeding between 8 am and 6 pm on the 13th of February in Digester 1 and 2 respectively are shown in Figure 5.11 and 5.12. The pH decreased from 6.9 to 6.7 in both digesters, but in Digester 1 the decrease started earlier than in Digester 2.

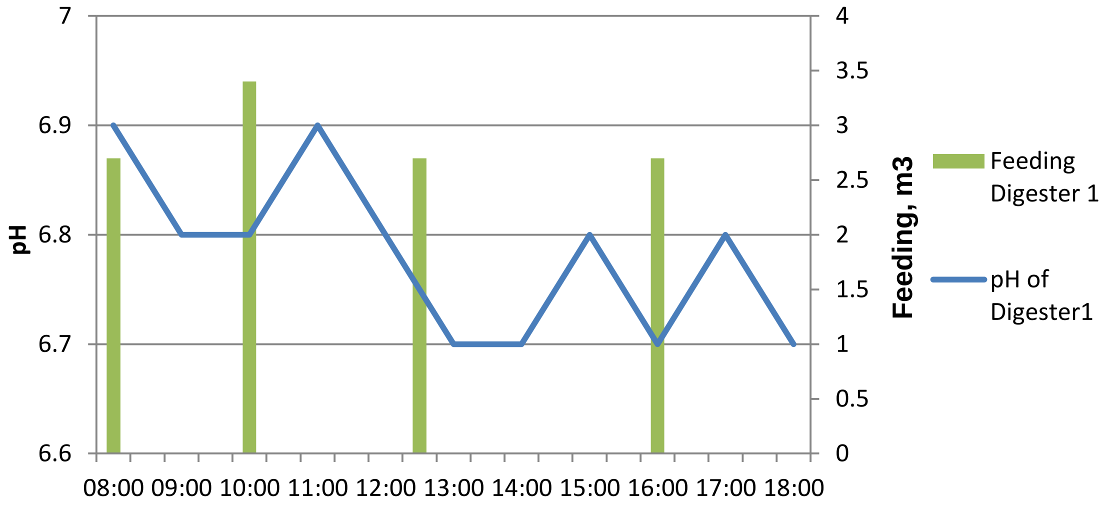

Figure 5.11. Feeding and pH during one day in Digester 1.

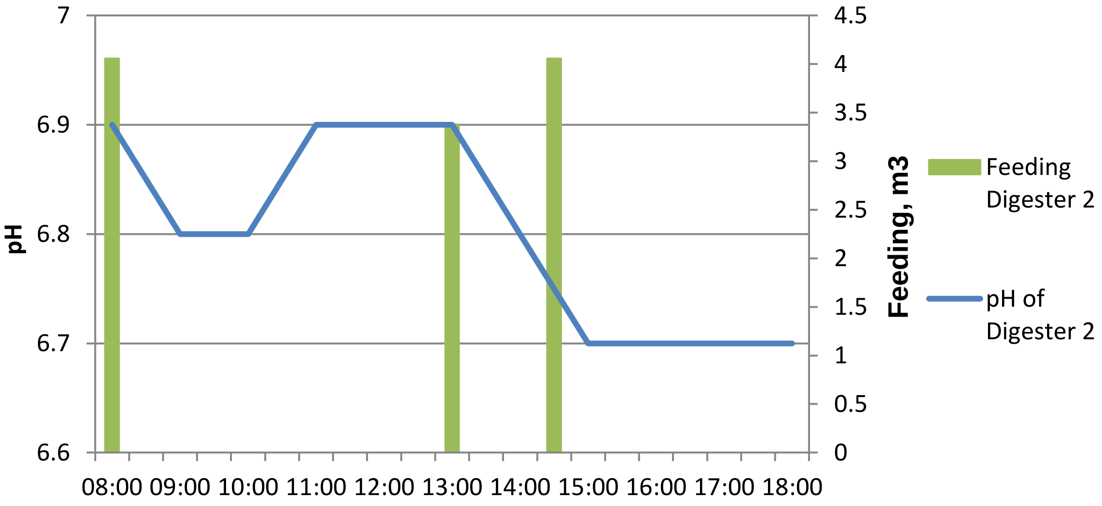

Figure 5.12. Feeding and pH during one day in Digester 2.

The temperature of the digestate is presented in Figure 5.13. The lowest value observed was 31°C while the highest value was 34°C. The average temperature was 33°C in both digesters. The temperature was similar in both digesters and increased during the period.

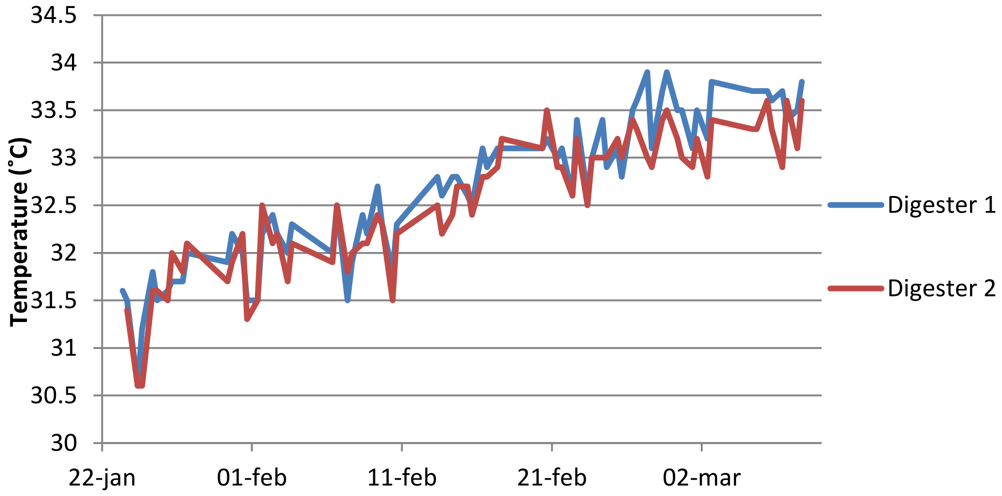

Figure 5.13. Temperature of the digestate in Digester 1 (blue line) and Digester 2(red line).

## 5.6 Alkalinity

Figure 5.14 shows the bicarbonate alkalinity (BA) and the total alkalinity (TA) of the digestate in Digester 1 and Digester 2. BA varied between 2 000 and 3 300 mg $HCO_3$/liter while TA varied between 3 300 and 4 300 mg $HCO_3$/liter.

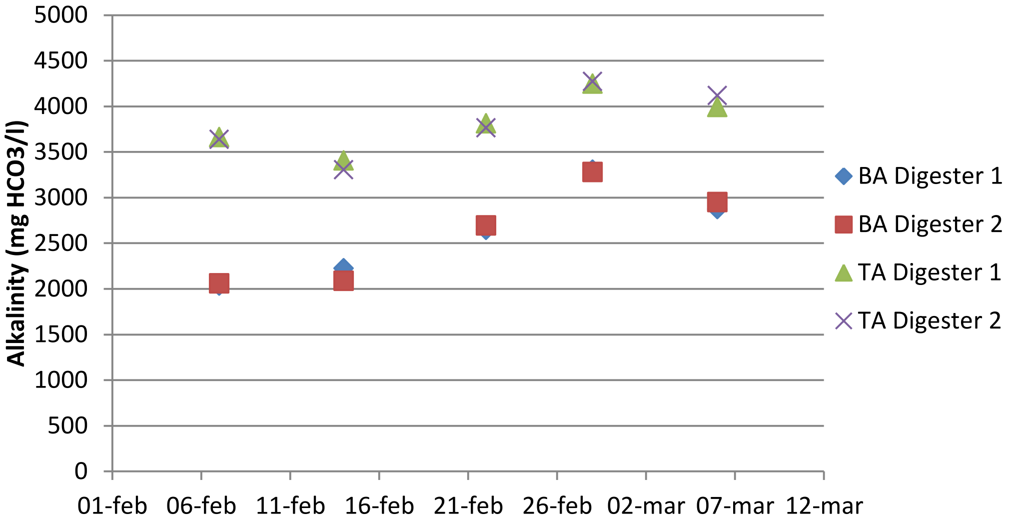

Figure 5.14. The bicarbonate alkalinity (blue and red dots) and the total alkalinity (green and purple dots).

## 5.7 Dry Matter and Organic Dry Matter

The results for dry matter content and organic dry matter content of the substrates, influent and effluents are presented in Table 2.

**Table 2. Dry matter and Organic Dry Matter of different substrates, influent and effluent.**

| | Dry Matter, % | Organic Dry Matter, % of DM |
|---|---|---|
| **Pineapple** | 12.7 | 93.3 |
| **Mango** | 22.0 | 95.5 |
| **Poultry Manure** | 90.5 | 53.4 |
| **Palm Kernel Cake** | 52.5 | 96.4 |
| **Influent** | 13.0 ± 0.43 | 97.2 ± 0.60 |
| **Effluent, Digester 1** | 1.19 ± 0.12 | 71.0 ± 1.00 |
| **Effluent, Digester 2** | 1.26 ± 0.15 | 71.4 ± 0.87 |

## 5.8 Nutrient content

Table 3 shows nutrient content of the substrates, the influent and the effluent.

**Table 3. Nutrient content of different substrates, influent and effluent.**

| | N, % of DM | P, % of DM | K ,% of DM |
|---|---|---|---|
| **Pineapple** | 0.12 | 0.02 | 0.30 |
| **Mango** | 0.12 | 0.01 | 0.16 |
| **Poultry Manure** | 0.29 | 0.04 | 0.22 |
| **Palm Kernel Cake** | 0.14 | 0.04 | 0.21 |
| **Influent** | 0.13 ± 0.012 | 0.017 ± 0.0047 | 0.20 ± 0.081 |
| **Effluent, Digester 1** | 0.10 ± 0.022 | 0.12 ± 0.040 | 0.43 ± 0.034 |
| **Effluent, Digester 2** | 0.12 ± 0.012 | 0.14 ± 0.052 | 0.41 ± 0.073 |

## 5.9 Organic Loading Rate

The organic loading rate varied between 0.8 and 5.5 kg ODM per $m^3$ and day in Digester 1 and between 0 and 5.3 kg ODM per $m^3$ and day in Digester 2. In Digester 1 and Digester 2 respectively the average organic loading rate was 2.7 and 2.5 kg ODM per $m^3$ and day.

## 5.10 Degree of Digestion

The degree of digestion was 93 % in both digesters.

# 6 Discussion

## 6.1 Composition of influent

Many measurements of the water use were discarded due to rainfall and shredding that occurred in the evening. Also, observations have been made that the tank trailer was not always totally full. This decreases the accuracy of the substrate/water composition of the influent.

The amount of fruit waste from PEELCO and Blue Skies is a rough estimation which decreases the accuracy. Since Blue Skies sent their waste to different customers there was no other way to evaluate the amount sent to HPW.

## 6.2 Nutrient content

The N, P and K contents were low in the analysed pineapple and mango waste compared to literature. The nitrogen content of the analysed pineapple was 0.12 % of DM while values in literature range from 0.72 to 0.95 % (Visvanath et al., 1991; Bardiya et al., 1996; Mainoo et al., 2009; Lane, 1984). The analysed mango waste had lower nitrogen content than examples in literature, 0.12 % compared to 0.5 - 0.91 % (Visvanath et al., 1991; Nagle et al., 2011). Also the phosphorus and potassium content in the analysed fruit samples were lower than what is found in literature (Mainoo et. al., 2009; Visvanath et. al., 1991; Lane, 1984).

The nitrogen and phosphorus content in the palm kernel cake and in the poultry manure were low compared to literature (Ramachandran et al., 2007; Fjäderfäcentrum, 2007).

The low nutrient content in the effluent is explained by the low nutrient contents in the different substrates.

The carbon content given by Visvanath et al. (1991) is 39.8 % of DM for mango peels and 38.9 % of DM for pineapple waste. This gives a C/N ratio of 332 for mango and 324 for pineapple which is very high compared to the ideal C/N range of 10-30 (Jarvis & Schnürer, 2009). This indicates the microorganisms in this process were suffering from nitrogen shortage.

## 6.3 Dry matter and organic dry matter

The dry matter content should be below 15 % in order to pump the influent (Christensson et. al., 2009). Amongst the different substrates only the pineapple waste had dry matter content below 15 %. The dry matter of the poultry manure was as high as 91 %. A significant amount of additional water was necessary to achieve a pumpable influent. The analysis of the influent showed a dry matter content of 13 % which means the amount of water used is sufficient.

The ash content in the poultry manure was high, which might cause future problems with sedimentation (Nordberg, 2012; Aklaku, 2012). Therefore it would be desirable to replace the poultry manure with another nitrogen source.

## 6.4 Feeding

All the technical staff learned how to do the recordings but it is possible that someone forgot to fill in the form which would affect the accuracy negatively. The accuracy of the feeding records is also affected by the fact that the measurements were done on a ± 5 cm basis which correspond to ± 0.34 $m^3$.

The irregular feeding was due to different reasons. The feeding pump broke several times during the project period which made feeding impossible. One time a tractor failure made it impossible to remove effluent from the digesters and therefore, nothing could be fed. The variation of the feeding was also due to the way the work was planned. Sometimes, a lot of waste was fed in a short time which made the waste run out.

A more regular feeding would be desirable, since it would give a more stable pH, gas production and methane content of the biogas (Nordberg, 2012).

## 6.5 Organic Loading Rate

The irregular feeding caused an irregular organic loading rate (OLR). The OLR ranged considerably outside the recommended limits, 2-3 kg ODM/$m^3$ day. A too low OLR can make the process gradually cease while a too high OLR means that undecomposed material will accumulate in the digester. For example, fatty acids can accumulate which will cause a pH drop. Too much variation in the OLR gives an unstable biogas process (Jarvis & Schnürer, 2009).

The average OLR was within the recommended limits for a biogas plant in the mesophilic temperature interval.

## 6.6 Degree of digestion

The calculation of the degree of digestion was based on analysis of the liquid effluent that was taken out from the digesters. There was also a solid part of the effluent coming out from the overflow shaft that was not taken into account in the calculations. This means the degree of digestion is over estimated and can not be fully trusted.

## 6.7 Biogas quality and flow

The accuracy of the average methane-, carbon dioxide and hydrogen sulfide content was lower in Digester 2 due to the gap in the data collection.

### Methane & Carbon Dioxide

The methane content is given as 50 % for biogas from carbohydrates (Carlsson & Uldal, 2009; Berglund & Börjesson, 2003) and 51-53 % for biogas from fruit and vegetable waste (Viswanath et al., 1991). These values correspond to the average values in this study, which were 50-51 %.

The theoretical methane content in biogas from a protein substrate is 60 % (Jarvis & Schnürer, 2009). When poultry manure was added in significant amounts, from the 18th of February and forward, an increase in the methane content would have been expected. No such increase in the methane content was observed which can be due to that the amount of poultry manure added was too small to make a difference. Another explanation is that microorganisms that are able to digest proteins have been washed out from the process since only carbohydrate-rich substrates have been fed for a long time (Jarvis & Schnürer, 2009).

The analysis showed that the methane content always decreased during the day. This was due to that feeding occurred mainly between 8 am and 5 pm. When substrates rich in sugar are added to the digester, the first microbiological steps, the hydrolysis and fermentation, are carried out quickly, and carbon dioxide is produced. The methanogenesis is a slower process than the hydrolysis and fermentation, which means that carbon dioxide will accumulate (Nordberg, 2012).

On the 13th of February when the gas analysis was performed continuously during the day the methane content decreased earlier in Digester 1 than in Digester 2. This was due to that the feeding occurred earlier in Digester 1 than in Digester 2 and shows that the system responds quickly to the feeding.

Methane and carbon dioxide should make up approximately 96-97 % of the biogas (Nordberg, 2012). In this study, the sum was on average 87 %. This implies either that there was air in the system or that air leaked into the analysis instrument when measuring. The first explanation is most plausible, since the sum was as high as 98 % at some occasions, even though the measurements always were carried out in the same way. Air may have entered the digesters when influent was pumped, since the mixing of the influent could whisk air into the mixing tank (Aklaku, 2012).

## Hydrogen Sulfide

The hydrogen sulfide content should not be above 200 ppm in order to avoid corrosion problems in the engine (Nordberg, 2012). Initially, the content was considerably higher, but decreased. Observations indicate that the gas cleaning system reduced the hydrogen sulfide content to acceptable levels in the end of the project period.

The initially high hydrogen sulfide content was probably due to accidental addition of the preservative sodium metabisulfite to the digesters. The hydrogen sulfide content decreased as a result of process recovery.

The rapid decrease in the hydrogen sulfide content between the 9th and 10th of February was due to small air pumps that were installed on the top of each digester. These made bacteria use the air to convert the hydrogen sulfide to elementary sulphur and water (Christensson et al., 2009). That the decrease did not last was probably due to the beginning of feeding poultry manure that has higher protein content than fruit waste and consequently higher sulphur content.

## Biogas flow

It is worth mentioning that the estimation of the gas flow was rough. The uncertainty which is estimated in the uncertainty analysis below is considerable since it was hard to decide exactly when the balloons were full.

The temperature of the gas was hard to determine since the surface temperature varied over the balloons. An uncertainty analysis with respect to the time span and the temperature was made.
That the pressure in the balloons was atmospheric is a reasonable assumption since the gauge pressure should have been small as long as the balloons were expanding. A better accuracy of the flow would have been obtained with a gas flow meter, but the available flow meters were undersized.

The conclusion that the flow increased during the day was enhanced by the observation that the inflation of the balloons seemed higher and the flow through the open pipe during the gas analysis felt stronger in the afternoon. The increased flow was due to the feeding pattern. Feeding of an easily decomposed substrate can give a rapid response in microbiological activity (Nordberg, 2012), which explains a higher biogas production in the afternoon.

The estimations also showed that the gas flow varied between days, which can be explained by the difference in feeding between days.

### *Analysis of uncertainty*

After performing the estimation several times, the exact time to fill a balloon could be assumed to be within an uncertainty span of maximum ± 10 minutes. The average gas temperature could be assumed to be within a range of ± 10°C.

The result of the uncertainty analysis is shown in Table 4 and 5.

**Table 4. Uncertainty analysis of the biogas flow rate with respect to the time it takes to fill one balloon.**

| Date | Starting time | Time to fill balloon (min) | Flow rate ($m^3/h$) | + 10 min Flow rate ($m^3/h$) | - 10 min Flow rate ($m^3/h$) |
|---|---|---|---|---|---|
| 9/2 | 09:40 | 155 | 30 | 28 | 32 |
| 9/2 | 12:15 | 127 | 37 | 34 | 40 |
| 9/2 | 16:30 | 99 | 50 | 45 | 56 |
| 10/2 | 10:15 | 111.5 | 41 | 38 | 45 |
| 16/2 | 10:30 | 102 | 45 | 41 | 50 |
| 22/2 | 09:15 | 119 | 39 | 36 | 42 |
| 22/2 | 11:15 | 103 | 44 | 41 | 49 |
| 22/2 | 13:00 | 87 | 53 | 47 | 60 |
| 22/2 | 15:15 | 85 | 59 | 53 | 67 |
| 28/2 | 09:15 | 188 | 24 | 23 | 26 |
| 8/3 | 09:30 | 95 | 49 | 44 | 55 |

**Table 5. Uncertainty analysis of the biogas flow rate with respect to the gas temperature.**

| Date | Starting time | Temperature when full (°C) | Flow rate ($m^3/h$) | + 10°C Flow rate ($m^3/h$) | - 10°C Flow rate ($m^3/h$) |
|---|---|---|---|---|---|
| 9/2 | 09:40 | 48 | 30 | 29 | 31 |
| 9/2 | 12:15 | 41 | 37 | 36 | 39 |
| 9/2 | 16:30 | 25 | 50 | 48 | 52 |
| 10/2 | 10:15 | 48 | 41 | 40 | 43 |
| 16/2 | 10:30 | 47 | 45 | 44 | 47 |
| 22/2 | 09:15 | 48 | 39 | 37 | 40 |
| 22/2 | 11:15 | 49 | 44 | 43 | 46 |
| 22/2 | 13:00 | 49 | 53 | 51 | 54 |
| 22/2 | 15:15 | 21 | 59 | 57 | 61 |
| 28/2 | 09:15 | 48 | 24 | 24 | 25 |
| 8/3 | 09:30 | 45 | 49 | 47 | 50 |

The analysis shows that uncertainties in gas temperature have less importance than the judgement of the exact time it takes to fill the balloons. Even though the time estimations have quite a large impact on the results, especially for the higher flows, the uncertainty analysis shows that the measurements still provide relevant information on the biogas production. The biogas production has varied between 24 ± 2 $m^3$/h and 59 ± 8 $m^3$/h.

### Methane production

The calculated methane production was 0.13 – 0.32 $Nm^3$ $CH_4$/kg ODM. The wide range is due to the variation of the estimated gas flow. Values for pineapple and mango given in literature are higher, ranging from 0.36 to 0.52 $Nm^3$ $CH_4$/kg ODM (Gunaseelan, 2004), but since these are based on batch processes, the results in this study seem reasonable.

## 6.8 pH, alkalinity and temperature

The pH and temperature were measured in samples from the periphery of the digesters. If the stirring was not good enough when the samples were taken the result could have been affected.

### pH

The low pH of the influent was due to the high acidity of mango and pineapple. The increase that was noticed some days matched the feeding of poultry manure.

The pH in the digestate was sometimes too low. Even though the average pH was 6.9, a slightly higher pH would be desirable in order to obtain a more stable process (Nordberg, 2012). A slight increase during the project period was observed and one reason was that poultry manure was added to the digesters as an additional substrate, see Table 1 and Figure 5.10. Poultry manure has a higher pH than fruit waste, according to literature around 7.4 (Gelegenis et. al., 2006). The poultry manure also increased the alkalinity, see chapter 5.6. Another reason could have been that the temperature in the digesters was higher in the end of the period. This gives an increased microbiological activity, especially among the methane-producing organisms, resulting in a better ability in consuming fatty acids (Nordberg, 2012).

The variation of the pH in the digestate was significant. During days with large amounts of feeding the pH dropped. This trend can be seen in Figure 6.1 which shows the daily feeding, x-axis, and the pH change during the day, y-axis, in Digester 1. Generally, a larger amount of feeding results in a bigger pH drop. On some occasions, marked red, this trend can not be seen. These occasions have been controlled and the explanation is that a large part of the feeding occurred after the pH measurement at 4 pm. The relationship between pH and feeding is due to the acidity of the fruit waste. Another reason is that fatty acids are produced fast, due to the rapidity of the first steps in the biogas process, when a lot of sugar-rich matter is added.

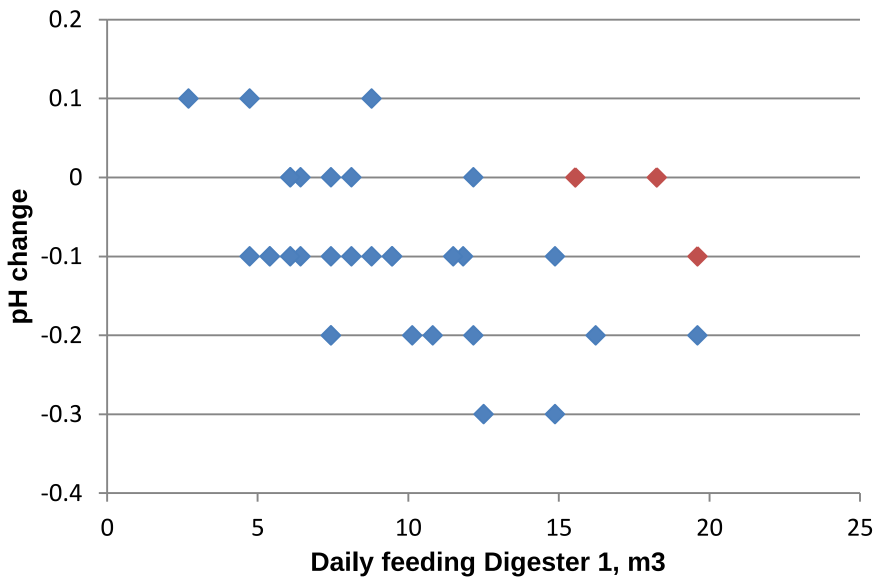

Figure 6.1. pH change as a function of daily feeding. Red dots are used on days when feeding occurred after the pH measurement.

On the 13th of February when the pH was measured continuously during the day the pH decreased earlier in Digester 1 than in Digester 2. This was due to that the feeding occurred earlier in Digester 1 than in Digester 2.

## Alkalinity

The alkalinity result is less accurate for the last two titrations since a pH meter with accuracy of only one decimal was used.

The low alkalinity explained the instability of the pH. BA was within the recommended limits for a mesophilic plant, 3000-15 000 mg HCO3/liter, at one occasion. The other measurements showed values below the lower limit. TA was always below the lower limit, 5000 mg $HCO_3$/liter (Jarvis & Schnürer, 2009). A higher alkalinity would withstand the acidic influent better.

The increase in alkalinity during the period depends on the poultry manure that was added. Poultry manure has relatively high nitrogen content. The nitrogen can contribute to an increased alkalinity since the ammonia react with dissolved carbon dioxide and form ammonium bicarbonate (Jarvis & Schnürer, 2009; Gelegenis et. al., 2007). The increased alkalinity can also depend on calcium carbonates in the poultry manure (Aklaku, 2012).

## Temperature

The increased temperature of the digestate during the period depended on the increased temperature outside. There is no trend in how the digestate temperature varied over the day, which means that the daily variations in outside temperature did not affect the digestate immediately. Since the volume of the digesters was large, inertia of the system was reasonable.

A higher temperature gives a larger biogas production. The optimal temperature interval for the mesophilic methanogens is 35 - 37°C. If the temperature is lower they grow slower than the microorganisms in the fermentation step. This means that acids can accumulate and damage the

process (Jarvis & Schnürer, 2009). The temperature in the digesters was always below 35 °C. Thus, a temperature increase could give both a larger biogas production and a more stable pH.
The temperature should be fixed and not vary more than ±0.5°C. If the alkalinity in the digester is good, variations in temperature of ±2-3°C can be accepted (Jarvis & Schnürer, 2009). During the period, temperatures between 31 and 34 °C were measured. Since the alkalinity of the process is low the temperature changes could harm the process.

No connection between the influent temperature, feeding and digestate temperature could be seen in this study.

## 6.9 Future Life Cycle Assessment

One of the purposes with the study was to gather information for a future life cycle assessment, LCA. In Chapter 4 information on amount of building material, power of different devices, effluent handling and transport distances can be found. A more precise measurement of the biogas flow or the energy production is necessary for an LCA. Another major factor that needs to be estimated is the environmental impact from the dumped effluent. Also different leakage points should be investigated, for example the mixing tank, the pipe for effluent removal and possible damages. Duration of running different electrical equipment needs to be analysed.

# 7 Conclusions

The biogas plant at HPW Fresh & Dry Ltd. was sensitive to disturbances. This was due to the type of substrate used, which resulted in a low alkalinity. The uneven feeding and the low alkalinity combined gave significant variations in methane content and pH during the day. The irregular feeding also resulted in an irregular production rate.

However, the process was functioning rather well, with a sufficient dry matter content of the influent, a proper average organic loading rate and a good average methane content of the biogas. Also, the process showed signs of robustness, since the pH and methane content were able to recover after large feeding portions and significant pH drops.

The feeding of poultry manure during the end of the period increased the alkalinity which resulted in a higher and more stable pH. However, the pH and the alkalinity were still too low.

The temperature of the digesters was adequate, but a slightly higher temperature would be optimal.

# 8 Recommendations

The authors of this report would like to recommend HPW Fresh & Dry Ltd. to:

- Even out the feeding. The amount of feeding should as far as possible be the same every day. The feeding should also occur during the night and in smaller portions, see chapter 6.4 and 6.5. The authors suggest a feeding plan which implies 1.3 $m^3$ of feeding every third hour to each digester. This would add up to a larger daily amount of influent than is available today. However, the authors believe it is necessary with a high target to obtain an adequate feeding, since problems with pumps etc. will disturb the feeding plan.

- Continue with the current feeding of poultry manure since it increases the alkalinity and is a source of nitrogen, see chapter 6.8. However, the risk of sedimentation when feeding poultry manure needs to be taken into consideration.

- Continue searching for other substrates rich in nitrogen to replace the poultry manure in order to avoid sedimentation.

- Measure the methane and hydrogen sulfide content of the biogas daily in order to survey the quality of the biogas, see chapter 4.3.

- Measure the pH daily and the alkalinity weekly to obtain a continuous knowledge of the state of the process, see chapter 4.5 and 4.6.

- Decrease the feeding rate if the pH decreases considerably. The relation between feeding and pH is described in chapter 6.8.

- Decrease the feeding rate if the alkalinity decreases further, see chapter 6.8. Alternatively, increase the fraction of poultry manure or other substrates containing nitrogen.

- Investigate the possibility of implementation of a heating system for the digesters, since a higher temperature could improve the process, see chapter 6.8.

- Investigate opportunities of use of the effluent as fertilizer since that would improve the environmental benefits of the plant.

# 9 References

## 9.1 Published materials

### Books

Gerardi, M. H. (2003) *The Microbiology of Anaerobic Digester*. ISBN 0-471-20693-8. New Jersey: John Wiley & Sons, Inc.

Jonsson, D. & Norell, L. (2007) *Ett stycke statistik*. 3 ed. ISBN 978-91-44-02989-4. Lund: Studentlitteratur AB.

### Reports

Allotay, F.K.A., Akuffo, F.O., Ofosu-Ahenkorah, A.K., Gbeddy, F., Tagoe, I. & Wennerberg, C. (2006) *Strategic National Energy Plan 2006-2020*. Energy Commission Ghana.

Berglund, M. & Börjesson, P. (2003) *Energianalys av biogassystem*. Lund: Lunds tekniska högskola, Institutionen för teknik och samhälle, Avdelningen för miljö- och energisystem. ISSN 1102-3651.

Carlsson, M. & Uldal, M. (2009) *Substrathandbok för biogasproduktion.* Malmö: SGC, Avfall Sverige. Report SGC 200. ISSN 1103-4092.

Christensson, K., Björnsson, L., Dahlgren, S., Eriksson, P., Lantz, M., Lindström, J., Mickelåker, M. & Andersson, H. (2009) *Gårdsbiogashandbok.* Malmö: Swedish Gas Centre. Report SGC 206.

Edström, M. & Nordberg, Å. (2004) *Producera biogas på gården – gödsel, avfall och energigrödor blir värme och el*. JTI Report 107.

Fjäderfäcentrum (2007) *Produktion av biogas från fjäderfägödsel*. Skara.

IPCC (2007) *Waste Management, In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A., (eds)]. Cambridge, United Kingdom & New York, USA: Cambridge University Press.

Jarvis, Å. & Schnürer, A. (2009) *Microbiological Handbook for Biogas Plants.* Rev 2010. Malmö: Swedish Waste Management & Swedish Gas Centre. SGC Report 207.

### Articles

Arthur, R., Baidoo, M. F. & Antwi, E. (2011) *Biogas as a potential renewable energy source: A Ghanaian case study*. Renewable Energy 36, 5, 1510-1516. ISSN 0960-1481.

Bardiya,N., Somayaji, D. & Khanna, S. (1996) *Biomethanation of banana peel and pineapple waste.* Bioresource Technology 58, 1, 73-76. ISSN 0960-8524.

Bensah, E. C., Antwi, E. & Cudjoe Ahiekpor, J. (2010) *Improving Sanitation in Ghana-Role of Sanitary Biogas Plants.* Journal of Engineering and Applied Sciences 5, 2, 125-133

Gelegenis, J., Georgakakis, D., Angelidaki, I. & Mavris, V. (2007) *Optimization of biogas production by co-digesting whey with diluted poultry manure.* Renewable Energy 32, 13, 2147-2160. ISSN 0960-1481.

Gunaseelan, V. N. (2004) *Biochemical methane potential of fruits and vegetable solid waste feedstocks*. Biomass and Bioenergy 26, 389-399.

Kemausuor, F., Obeng, G. Y., Brew-Hammond, A. & Duker, A. (2011) *A review of trends, policies and plans for increasing energy access in Ghana*. Renewable and Sustainable Energy Reviews 15, 5143– 5154

Lane, A.G. (1984) *Laboratory Scale Anaerobic Digestion of Fruit and Vegetable Solid Waste,* Biomass 5, 245-259.

Levis, J. V. & Barlaz, M. A. (2011) *What is the most environmentally beneficial way to treat commercial food waste?* Environmental Science & Technology 45, 17, 7438-7444

Mainoo, N.O.K., Barrington, S., Whalen, J.K. & Sampedro, L. (2009) *Pilot-scale vermicomposting of pineapple wastes with earthworms native to Accra, Ghana.* Bioresource Technology 100, 5872–5875.

McMahon, K. D., Stroot, P.G., Mackie, R.I. & Raskin, L. (2001) *Anaerobic codigestion of municipal solid waste and biosolids under various mixing conditions—II: microbial population dynamics*. Water Research 35, 7, 1817-1827. ISSN 0043-1354.

Nagle, M., Habasimbi, K., Mahayothee, B., Haewsungcharern, M., Janjai, S. & Müller, J. (2011) *Fruit processing residues as an alternative fuel for drying in Northern Thailand*. Fuel 90, 818-823.

Ramachandran, S., Singh, S.K., Larroche, C., Soccol, C.R. & Pandey, A. (2007) *Oil cakes and their biotechnological applications – A review.* Bioresource Technology 98, 10, 2000-2009. ISSN 0960-8524.

Viswanath, P., Sumithra D. S. & Nand, K. (1991) *Anaerobic digestion of fruit and vegetable processing wastes for biogas production.* Bioresource technology 40, 1, 43 – 48.

## 9.2 Unpublished materials

### Web pages

Utrikespolitiska Institutet (2012-01-27), *Ghana – Utrikeshandel*, Available: http://www.landguiden.se/Lander/Afrika/Ghana/Utrikeshandel [2012-02-09]

Ministry of Energy (2010) *Renewable Energy Directorate – Policy*. Available: http://www.energymin.gov.gh/ [2012-02-09]

### Unpublished documents

Blaser, M. (2012a) *Trainings Manual on Energy Generation*. HPW Fresh & Dry Ltd., Technical Department. Adeiso, Ghana.

HPW Fresh & Dry Ltd. (2012a) *Records of vehicle distance meter*. March, 2012. Adeiso, Ghana.

HPW Fresh & Dry Ltd. (2012b) *Information sheet.* Received from M. Blaser, January 2012. Adeiso, Ghana.

HPW Fresh & Dry Ltd. (2012c) *HPW f&d plant.xlsx*. Excel document received from M. Blaser, January 2012. Adeiso, Ghana.

## Personal communication

Ababio, F.O., Head of Department, Soil Research Institute, Centre for Scientific and Industrial Research. Personal communication, February 2012. Accra, Ghana.

Aklaku, E., Researcher, Kwame Nkrumah University of Science and Technology. Personal communication, January-April 2012. Adeiso, Ghana.

Blaser, M., Managing Director, HPW Fresh & Dry Ltd. Personal communication, January-March 2012. Adeiso, Ghana.

Bright, K., Technical Manager, HPW Fresh & Dry Ltd. Personal communication, January-March 2012. Adeiso, Ghana.

Erabah Essando, A., Production Manager, HPW Fresh & Dry Ltd. Personal communication, January-March 2012. Adeiso, Ghana.

Nordberg, Å., Researcher, Dept. of Energy and Technology, SLU. Personal communication February-April 2012, Uppsala, Sweden.

PEELCO ltd., Production Manager, PEELCO ltd. Personal communication, January 2012. Accra, Ghana.