SUSTAINABILITY OF MUNICIPAL WASTEWATER TREATMENT PLANTS OPERATIONS IN ETHEKWINI MUNICIPALITY

By

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DECLARATION

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Dedication

Thank you, God for having afforded me this opportunity and the strength to pull through this amidst all the challenges and personal setbacks I suffered. Amongst these was the loss of my two siblings during this period, thus I dedicate this to them.

I also dedicate this thesis to my own family especially my superheroes, my children who had to do without me for the major part of the time. My family had to sacrifice a lot including not taking vacations and never complaining. That includes not having properly cooked meals which I guess is the part they enjoyed! Thank you so much for your understanding.

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Prof. Matambo our paths first crossed around 2013/14, then we were serving on a committee comprising of colleagues from other spheres of government, academia, NGOs and of course project developers. Prof. Matambo and his then colleague also from UNISA Dr Martin Meyer, were representing the academia. We then lost contact after I took up a new job offer in a new province and put my studies on hold due to the workload. After completing my B-Tech studies at UNISA, I was inspired by Prof. Dianne and I then considered studying towards my Master’s degree. I then approached several potential supervisors however, I was not interested in the research topics that they were proposing. I had not heard of IDEAS then, but I then searched further and came across Prof. Matambo’s name. I then asked if he could supervise me and I then indicated what I was then interested in. He tentatively agreed but he wanted to fill me in first about IDEAS and what they were seeking to achieve. And of course, our meeting was virtual since we were at the height of COVID-19. After providing him with my background including my work experience as well as our involvement in the SABIA activities, he then remembered who I was. Let us say whilst I thought I knew him, I have realised that whilst he is friendly he is super strict and does not compromise when it comes to the quality of work he expects. The last 2 – 3 years including preparing for the group weekly meetings and the one on one (whilst working full time) were no mean feat! Thanks for pushing me and unlocking the potential in me.

Where do I start with Dr Ayo? The guy is brilliant and so underrated I think. I had started working on my initial proposal, which was proving impossible given the angle I was taking, I then had my inception meeting with Dr Ayo. After explaining what I had in mind and what I working on and the challenges I was encountering, he said indeed there was no way I could achieve my objective then given my approach. Due to my years in the industry, my proposal adopted an industrial angle instead of an academic research. I must say there were times when I felt that he is too harsh for making me change or reconsider my proposal but looking back, not only am I glad that I did but also that he was not holding back and was saying things as they are. Just to assure him, I would also tell him that I prefer that brutally honest

opinion and that I was too thick-skinned and was not taking things personally. I think that helped me to make sure that before our meetings I know my story and have done my research at least. Importantly, thanks Dr Ayo for helping me to brush off my Excel skills and especially plotting the graphs, thanks!

To my colleagues in eThekwini, in particular, my Water and Sanitation colleagues, thank you for your valuable inputs and guidance: Mr Lusapho Tshangela, the Senior Manager (Treatment Works, Head Office) our initial meeting regarding my proposal and your advice regarding which wastewater treatment plants (WWTPs) I should consider for my research. Since 2020 when I started on this journey and throughout all the different phases, you have been consistent in your support. You then introduced me to the Works Area Managers, Ms Zanele Mkwanazi and Ms Reneshree Pillay, responsible for Phoenix WWTP and Kwa-Mashu/Verulam WWTPs, respectively. You then asked that they assist and since then not once did I have to come to you again complaining about lack of support from them! The same was to happen with Ms Nomvula Ndlovu, the Technician, to whom I was introduced on day 1, in November 2020. Ms Ndlovu was my number-one to-go to person throughout this journey. She assisted by liaising with the area managers, the Plant superintendents, the Scientific Laboratory team, the Industrial effluent monitoring team, the Process Controllers and the operators, and the Operations data, the list is endless. Not even once has she tired out, complained, nor not responded to my request. Not even when I contacted her during her leave, she will acknowledge them and undertake to respond when she gets back to work and this she will do without fail. The Superidents of the 3 Works – Mr Mandla Mbatha (Kwa-Mashu), Mr Sipho Mabaso (Phoenix) and Mr Selvan Reddy (Verulam), and the Process Controllers and Operators at the 3 Plants who gave me their time and support including our conversations during their night shifts, much appreciated.

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Abstract

Municipal wastewater pollution in developing countries is a great concern due to partially treated or untreated wastewater. Inflow and Infiltration (I/I) is a challenge in municipalities that receive stormwater as it impacts the capacity and efficiency of the sewage plants. As such this study sought to evaluate the impacts of the I/I on the 3 wastewater treatment plants (WWTPs) namely: Kwa-Mashu, Phoenix and Verulam in eThekwini that were assessed. The operating data for twelve-months in 2019 calendar year of each plant were evaluated which factored in the storm water contribution. The total monthly and average daily flows and influent loads were more variable especially during the wet weather seasons. Kwa-Mashu with operating capacity of 65 000 m^3/d after recording up to 51,1 mm average daily rainfall resulting in inflows up to 96 305 m^3/d. Phoenix had an operating capacity of 29 000 m^3/d however, received inflows up to 35 284 m^3/d whilst it recorded the maximum of 8 mm rainfall in December 2019. Verulam mainly treats 8 000 m^3 wastewater but could receive up to 10 675 m^3/d whilst it recorded rainfall up to 16 mm. Using the IBM SPSS statistical package, moderate to strong correlations between rainfall intensity (I) and flowrate (Q) in the 3 WWTPs assessed were observed. Kwa-Mashu showed a strong/ large correlation (0.756). Verulam showed a weak/small correlation (-0.42) between rainfall and inflow, while Phoenix also had a week/small correlation (0.164).

The wastewater influent (Q_w) characteristics as well as effluent quality indicators are also impacted by the additional pollution in the storm water contribution. This can result in a short-term risk of non-compliance in the discharged effluent. Thus the treatment efficiency based on Chemical Oxygen Demand (COD), Ammonia (NH_3) Total Suspended Solid (TSS) and PV4 removal were evaluated in the 3 (WWTPs) that were assessed. These involved analysing both the influent and the effluent data. Kwa-Mashu showed high concentrations of COD whilst Phoenix had the least and Verulam was in between. Kwa-Mashu influent COD ranged from 720 – 940 mg/l, Verulam received up to 848 mg/l COD whilst Phoenix influent COD concentrations ranged from 456 – 615 mg/l . The influent NH_3 in Kwa-Mashu ranged from 17 – 33 mg/l in, about 26 – 44 mg/l and 30,8 – 41 mg/l in Verulam and Phoenix, respectively. The treatment efficiency in Kwa-Mashu was equally high for all the key parameters evaluated recording as high as 96% for COD removal followed by Verulam then Phoenix. Phoenix was receiving wastewater with relatively low concentrations however,the effluent was equally high, showing generally poor treatment by the WWTP, as low as 34% for COD.

Municipal wastewater are designed to treat wastewater, however, sludge treatment and disposal are a challenge. Sludge produced may be re-used to produce bio-energy and other bio-commodities however, it contains pollutant loads such as pathogens and heavy metals. Sludge can be stabilised with anaerobic digestion which is becoming an integral part of a modern WWTPs. Hence there is a surge in anaerobic digestion with a potential of recovery and reuse of biogas globally. Thus anaerobic digestion optimises the financial and environmental footprint of the WWTP. This study sought to review the anaerobic digestion fundamentals, the applicable process parameters, the types of digesters, the biogas utilisation, challenges and opportunities, and the biogas developments with focus in South Africa.

Biochemical methane potential (BMP) experiments using the AMPTS II were performed in order to assess the potential to produce biogas. Triplicates samples of thickened sewage sludge and digested sewage sludge from the 3 WWTPs assessed were used as subtrates and inoculum, respectively. Each 50 mL bottle reactor sample operating at mesophilic temperature of 37 ^{o}C was incubated for 31 days where the gas produced was measured in the thermostatic water bath through the water displacement. Connected to the computer, a digital pulse for every 2 mL of gas that flows was recorded and the values were read off through a data-logger. The BMP results were as follows: Phoenix 264,18 NmL/g VS, Kwa-Mashu 147,96 - 170,50 NmL/g VS and Verulam 181,79 NmL/g VS. The electrical energy potential was estimated where Phoenix showed an electrical energy potential of 7 kWh, Kwa-Mashu’s Mash-S1a - c and Mash-S2a – c had 4,51 and 3,91 kWh, respectively and Verulam had a potential electrical energy of 4,81 kWh.

Keywords: Municipal wastewater, Sludge Production, wastewater characteristics, Sludge Treatment, biogas utilization, Anaerobic digestion; biochemical methane potential tests; energy recovery.

List of Abbreviations

ALK	Alkalinity
AD	Anaerobic Digestion
BMP	Biochemical Methane Potential
BMW	Bayerische Motoren Werke
BNR	Biological Nutrient Removal
BOD	Biochemical Oxygen Demand
BTU	British Thermal units
CH_4	Methane
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
CSTR	Continuously Stirred Tank Reactor
DBFZ	Deutsches Biomasse Forschungs Zentrum
DM	Dry Matter
DTI	Department of Trade and Industry
EBPR	Enhanced Biological Phosphorus removal
GC	Gas chromatography
GHG	Greenhouse Gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (German Society for International Cooperation)
IBM	International Business Machines
IDC	Industrial Development Corporation
IDM	Industrial Demand Side Management
IDM	Integrated Demand Management
kWh	Kilowatts hour
LCFAs	Long Chain Fatty Acids
MGD	Million gallons per day,
MLSS	Mixed Liquor Suspended solids
NEM:WA	National Environmental Waste Act
NEMA	National Environmental Management Act
NGO	Non-Governmental Organization
NWMS	National Waste Management Strategy
OLR	Organic Loading Rate
PAOs	Phosphate Accumulating Organisms

PHAs	Polyhydroxylalkanoates
SABIA	Southern Africa Biogas Industry Association
SAGEN	South African-German Energy Programme
SALGA	South African Local Government Association
SBP	Specific Biogas Production
SBR	Sulphate reducing bacteria
SDG	Sustainable Development Goals
SIR	Substrate to Inoculum Ratio
SRT	Solid Retention Time
SGY	Specific gas yield
SMY	Specific methane yield
SSTs	Secondary sedimentation tanks
SPSS	Statistical Package for the Social Sciences
TDS	Total Dissolved solid
TS	Total Solids
TSS	Total Suspended Solid
VFAs	Volatile Fatty Acids
VS	Volatile Solids
VSS	Suspended Volatile Solids
WAS	Waste Activated Sludge
WHO	World Health Organisation
WWTP	Wastewater Treatment Plant

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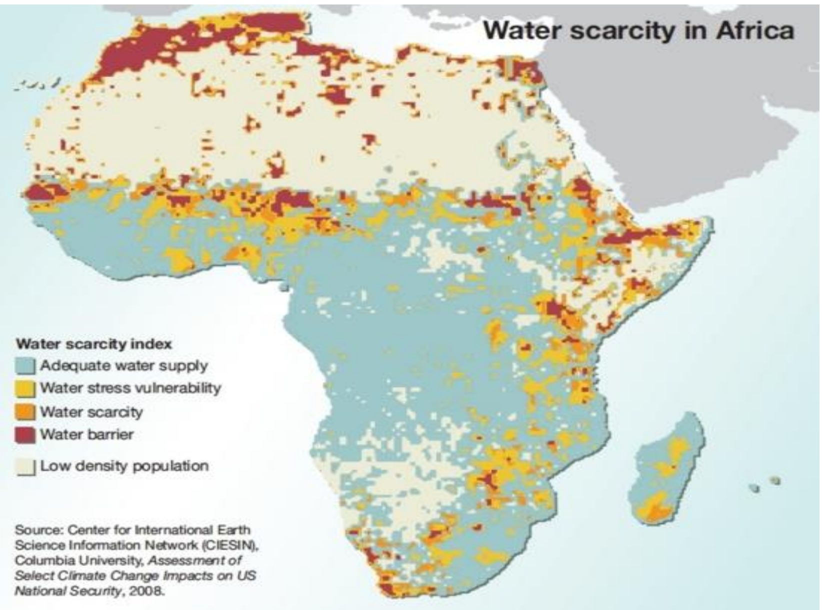
CHAPTER 1

A literature review was carried out to provide knowledge and insights on the sustainability of wastewater treatment plants. As such this literature review covers the following: 1) an overview of wastewater treatment and sludge treatment 2) an overview of conventional activated sludge treatment and wastewater characterisation 3) an overview of anaerobic digestion.

1. Introduction

The rapid population growth rate, urbanisation and industrialisation, are increasing the demand for the available water resources. Globally South Africa ranks at number 30th in the list of driest countries in the world. It is estimated that 4.0 billion people live in water-scarce areas, which is about two-thirds of the population (Vörösmarty *et al.*, 2000)**.** Most of the water-scarce countries are located in Africa as per Figure 1.



Source: Center for International Earth Science Information Network (CIESIN), Columbia University, *Assessment of Select Climate Change Impacts on US National Security*, 2008.

Figure 1.1: Water-scarce countries in Africa

1.1 Pollution sources

The rapid rate of population growth and urbanisation has increased urban waste. Wastewater or raw sewage which contains dissolved as well as suspended matter is water that has been associated with anthropogenic activities by households or industry (Mara and Horan, 2003). Wastewater needs to be treated prior to being discharged into natural water however, it is estimated that 70% of the wastewater from municipalities is being discharged without treatment (Tchobanoglous and Kreith, 2002). The municipal wastewater treatment plants (WWTPs) are pollution point sources containing a variety of harmful pollutants. Chemicals, microorganisms, nutrients, and heavy metals are subsequently carried from their sources to the water bodies. Globally nutrients are a major pollutant resulting in eutrophication caused by the continuous use of fertilizers (Mara and Horan, 2003). Diffuse sources which emanate from diverse sources are also concerning. Stormwater runoff carries significant pollution including pesticides.

1.2 Processes in the treatment of wastewater

Wastewater treatment aims to transform the harmful materials in the wastewater into lesser harmful products for the environment and protecting public health. Figure 1.2 below shows different levels and series of treatment steps in wastewater treatment (Guo et al., 2019). These are primary, secondary and tertiary or advanced treatment or a combination of all the stages (Mara and Horan, 2003). When the wastewater is to be re-used, heavy metals, refractory organics and inorganics need to be removed.

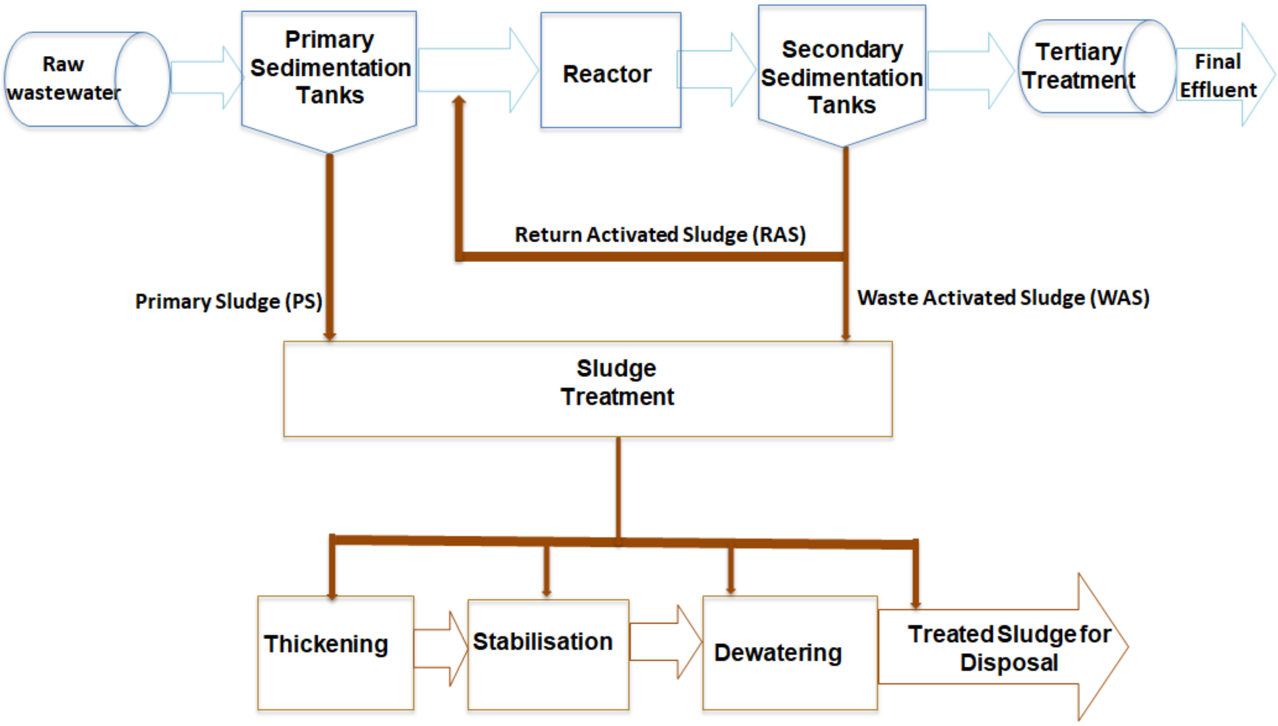


Figure 1.2: A simplified layout of the wastewater treatment processes

1.2.1 Primary treatment

The primary wastewater treatment processes involving physical unit processes incorporate preliminary stage. Screens or racks which vary in size remove objects like sticks, rags and other floatable materials that may cause operational problems. during primary treatment, it is estimated that 25 to 50% of the chemical oxygen demand (COD) is removed together with a concentration of 50 to 70% of the suspended solids (SS) and about 65% concentration of the oil and grease (O&G) in the influent (Chernicharo and Sperling, 2005). The colloidal and dissolved solids cannot be removed at this stage whilst solids gravitate to the bottom and are referred to as the raw or primary sludge and are carried for further processing primarily in the anaerobic digesters. The primary effluent is carried over to the aerators in the conventional activated sludge system (Metcalf & Eddy, 2013).

1.2.2 Secondary treatment

The secondary wastewater treatment processes involving chemical and biological unit processes in the WWTPs are aimed at the removal of biodegradables and suspended solids (Chernicharo and Sperling, 2005). Typical activated sludge processes consist of the bioreactors (aeration tanks), the sedimentation tanks and the recycle stream. Large volumes of air are provided to the aerobic microorganisms - mixed liquor suspended solids (MLSS) in the reactor from beneath to ensure proper mixing. About 2 mg/l of dissolved oxygen is recommended for adequate respiration (Chernicharo and Sperling, 2005). On completion of aeration, the MLSS is then separated from the clarified effluent which is taken to the secondary sedimentation tanks (SSTs) also known as the final clarifier. The MLSS, also known as biomass, is the separated solids that have gravitated in the secondary clarifiers to the bottom. These are pumped back to the aeration tanks as return activated sludge to treat the influent wastewater stream (Metcalf & Eddy, 2013).

1.2.2.1 Conventional activated sludge

Conventional activated sludge is the oldest biological process for wastewater treatment which is widely used in municipalities. The secondary treatment processes employ biological mechanisms where it is estimated that the Chemical Oxygen Demand (COD) and Total Suspended Solids (TSS) over 85% can be removed (Mara and Horan, 2003; Ma *et al.*, 2015).

Nutrients are a concern in modern wastewater treatment due to eutrophication which depletes the oxygen in the water body resulting in the loss of some aquatic life forms. The secondary stage, however, is not designed to remove nutrients but modifications can be made to meet stricter effluent discharge standards (Metcalf & Eddy, 2013). The influent in the municipal WWTPs typically contains about 5 – 9 mg/l and 40 mg/l of total phosphorus (TP) and total nitrogen (TN), respectively.

A. Biological nitrogen removal

The biological nitrogen removal (BNR) process is premised on the sequential processes of nitrification and denitrification. Nitrogen removal occurs under aerobic conditions employing chemoautotrophic bacteria which require longer SRT whilst denitrification occurs under anoxic conditions with the help of heterotrophic bacteria which require shorter SRT (Tchobanoglous et al., 2002). In the aerobic zone, ammonia is converted to nitrites which are then converted to nitrates. The nitrates (NO_3) formed are then reduced to molecular nitrogen gas which escapes to the atmosphere (Chernicharo and Sperling, 2005).

B. Biological phosphorus removal

The biological phosphorus removal (BPR) process operates within 2 – 10 SRT days, assisted by phosphate-accumulating organisms (PAOs) which can store excess phosphorus (Tchobanoglous et al., 2002). Longer SRT will trigger nitrification. Under anaerobic conditions, the PAOs convert organic matter into Polyhydroxyalkanoates (PHAs) compounds which are energy-rich polymers. The PAOs settle with the sludge and get wasted with the mixed liquor as the waste activated sludge atmosphere (Chernicharo and Sperling, 2005).

C. Other modifications of the activated sludge system

Other variations include extended aeration; sequencing batch reactors and activated sludge system with nutrients removal (Chernicharo and Sperling, 2005).

1.2.3 Tertiary treatment

Wastewater may still contain large amounts of microorganisms that might be harmful to humans after the secondary stage and will require disinfecting. The most widely used disinfecting process is chlorination before the effluent is discharged to receiving environment. Other disinfecting processes are ultra-violet (UV) light, ozonation, and bromine chloride additions. Maturation ponds store final effluents for a final ‘polish’ before discharge and provide a buffer in the event of a breakdown at a plant. The disadvantage, however, is that the process takes longer and the ponds require a much larger land area to retain the sewage (Chernicharo and Sperling, 2005).

1.3 Sludge treatment

Sludge treatment improves the dewaterability and digestibility of sludge and is comprised of biological, chemical and mechanical technologies. Municipal wastewater treatment plants produce sewage sludge that mainly comprises water containing suspended and dissolved solids. Thickening of the sludge is normally applied first where sludge is reduced to as little as a third of its initial volume (TSS) (Mara and Horan, 2003; Ma *et al.*, 2015). The dewatering technologies use filter or mechanical presses which is more advanced than the sludge drying beds. Other sludge technologies include biological processes - aerobic digestion (e.g. composting) and anaerobic digestion.

1.3.1 Anaerobic digestion

Anaerobic digestion (AD) has been around for a long time and is thus a matured technology (Turovskiy and Mathai, 2005). Compared to aerobic digestion, AD stabilisation is most commonly favoured due to the high degree of waste stabilisation, minimal sludge production, low nutrient and energy requirements by the system. Anaerobic systems, however, can be unstable and this instability is usually due to potential feed overload, the presence of inhibitory factors as well as fluctuations in temperature.

The anaerobic digestion (AD) process is a biological process that converts the organic matter to produce methane-rich biogas, supernatant and digestate. Biogas comprise mainly methane (CH_4) and carbon dioxide (CO_2) and other trace gas like hydrogen sulphide (H_2S). The biogas produced can be recovered to produce energy resulting in an environmentally friendly and cost-effective process (Mata-Alvarez, Macé and Llabrés, 2000). The biogas produced has an energy value proportional to the methane content hence a higher methane content is an indicator of biogas of good quality (Abdel-Hadi, 2008). The biogas quality is critical for power production and depends mainly on the methane content ranging from 60 – 70% (Khandelwal and Mahdi, 1986). The CO_2 and H_2S in the biogas should be low since they lead to lower biogas yields. Also during the AD COD is converted into biogas hence 1 m^3 of biogas produced is equal to 0,35 mL CH_4/g mole COD at a standard temperature of 0 ^oC and pressure, 1.0 atm (Metcalf & Eddy, 2013).

1.4 Wastewater characteristics

Compositions of wastewater are becoming diverse and complex thus characterisation is important in selecting the appropriate wastewater treatment processes (Wijaya and

Soedjono, 2018). Wastewater constituents can be categorised as physical, chemical or biological. These properties, however, are connected and are a risk to the human life as well as to the receiving environment (Wijaya and Soedjono, 2018).

The physico-chemical parameters include the physical and chemical properties such as pH, chemical oxygen demand (COD) and/or biochemical oxygen demand (BOD), total solids (TS) which include - total dissolved solids (TDS) and total suspended solid (TSS), dissolved oxygen (DO), total nitrogen (TN) and its variations as well as total phosphate (TP) and its variations (Akpor *et al.*, 2011.) Also includes minority substances such as metal, toxic material and detergent. Physical parameters that are of interest in wastewater include solids, temperature, turbidity and colour amongst others (Metcalf & Eddy, 2013).

Chemical characteristics are of great significance and are mainly concerned with the organic and inorganics - nitrogenous and phosphorus compounds (Ekama, Wentzel and Sötemann, 2006). The wastewater comprises about 70% of organic constituents while the inorganic component is about 30%. The organic constituents include protein, carbohydrates, fats, oils, greases, chemicals and at times nitrogen. The inorganic non-metallic constituents include the pH, alkalinity, chlorides and other constituent gases, originating mainly from the water supply and additions during both domestic and industrial use.

The main pathogens found in raw wastewater typically include bacteria, viruses, protozoa and helminths (Metcalf & Eddy, 2013). These microbiological populations found in domestic wastewater are excreted mainly by humans hence they reflect the health conditions of their source communities. *Escherichia coli* (E. coli) is easy to identify and enumerate and thus has been widely adopted as an indicator of faecal pollution (Tchobanoglous et al., 2002).

1.5 Motivation for the study

Anaerobic digesters make up a significant part of sludge treatment in municipal WWTPs. The incorporation of these units provides an opportunity for municipalities to reduce their energy demand and to generate electricity and heat in the WWTPs. The current practice, however, is to flare the biogas into the atmosphere without opportunities to recover the biogas for use in the WWTP being fully explored. This results in the release of greenhouse gases due to biological processes associated with the advanced wastewater treatment technologies.

Sustainable management of wastewater is at the centre of the circular economy. There are more positives to improving the way we manage wastewater, with potential co-benefits to societies and the environment with the potential to produce bioenergy and bio-fertilizers using the biogas and digestate, respectively.

This research project considered three (3) major WWTPs, namely: Kwa-Mashu, Phoenix and the Verulam WWTPs. The comprehensive comparative assessment as proposed in this research will factor in empirical proof of treatment efficiency, Green House Gases (GHGs) emissions, energy consumption, and potential recovery of energy while factoring variations in influent quantity (seasonal variations), quality (physicochemical characteristics) informed by plant feed (domestic and industrial catchment areas), plant design and socio-economic factors and resources.

This study seeks to contribute towards the three major constructs of sustainability: economy, environment and social development.

1.5.1 Problem statement

Currently, the energy supply of most operations of the municipal WWTPs is from the national grids, using fossil-fuel sources. Advanced wastewater treatment which employs biological processes are a technology of choice in most municipalities however, they are energy intensive. It is estimated that 60 - 70% of the energy is used for aeration which is an integral part of wastewater treatment and pumps while heating up the digestion tanks during anaerobic digestion, also uses significant energy (Mara and Horan, 2003). As a result, the municipal WWTPs are identified as sources of anthropogenic GHG emissions and these exacerbate climate change and cause air pollution.

1.5.2 Research questions

a. What is the quality and property of the influent wastewater in the 3 selected WWTPs?
b. What is the treatment efficiency of the 3 selected WWTPs (as defined by COD removal)?
c. What is the biogas and methane potential of the wastewater feeds and the feasibility to capture and utilize the biogas for power generation in the WWTPs?

1.5.3 Research aim

South Africa is committed and cognisant of a developmental agenda that prioritises obligation towards wastewater treatment sustainability however, most municipalities in SA still focus on wastewater collection and treatment rather than resource recovery.

As such this study aims to assess the eco-efficiency of the case WWTPs in EThekwini municipality, factoring treatment efficiency, reduction in GHG emission and potential for energy/bio commodity recovery, towards defining a gold standard for local WWTPs.

1.5.4 Research objectives

To be able to achieve the aims, the following objectives would guide this study:

a. To make a comparative analysis of the physicochemical characteristics of wastewater feed in the selected WWTPs.
b. To make a comparative analysis of the baseline treatment efficiency (in terms of COD reduction) of case WWTPs.
c. To determine the biogas yield and estimate the energy generation potential of the WWTPs.

1.6 Thesis Outline

This thesis covers the following: **Chapter two** outlines the AD fundamentals and describes the four biochemical reactions involved, operating parameters guiding the anaerobic digestion, different types of anaerobic digesters and their working principles. **Chapter three** outlines the methods and experiments carried out during this study. **Chapter four** gives the results of the experiments performed and a discussion on these. **Chapter five** provides conclusions based on the results of this study.

CHAPTER 2

A literature review was conducted to provide in-depth knowledge and insights on the eco-efficiency of the wastewater treatment plants (WWTPs) which could be transformed to serve as both energy sinks as well as water and energy recovery facilities (WERF). The review outlines the AD fundamentals and describes the four biochemical reactions involved, operating parameters guiding the anaerobic digestion process, different types of anaerobic digesters and their working principles and covers the following areas: 1) an overview of wastewater treatment with a focus on conventional activated sludge (CAS), sludge production and sludge treatment technologies including anaerobic digestion 2) anaerobic digestion fundamentals, biochemical reactions and operating parameters, the design methods, 3) renewable energy with a focus on biogas, wastewater treatments plants and the potential to recover the biogas and the biogas utilisation in various applications including in the WWTPs, the recent developments globally including the biogas market to reduce the impact of the problems and techno-economic viability of biogas projects.

2.1 Introduction

Rapidly growing population globally and urbanisation resulting in a high consumption rate of resources are global challenges. Sewage and solid management and disposal are the biggest human and environmental problem globally due to ineffective waste management systems. Most municipalities, still commonly treat sewage sludge as a waste stream which ends up in landfills without further processing and being used as a resource Chen et al., 2020; Płuciennik-Koropczuk et al., 2017). Sludge stabilisation using anaerobic digestion helps to reduce the pathogens and odours whilst it produces biogas as one of the by-products. Thus anaerobic digestion integrates waste management and energy management which is an effective, affordable, environmentally friendly method that also provides a renewable source of energy. The Agenda 2030 for Sustainable Development Goals (SDGs) which was adopted by the United Nations in 2015, represents a philosophical standpoint, which emphasizes process sustainability and treatment efficiency as key pillars of safe and adequate water provision to water indigence in developing countries (United Nations, 2015).

Traditionally wastewater treatment focussed on producing good effluent quality. Hence the use of advanced wastewater treatment processes, which include conventional activated sludge processes are used in most municipalities due to relatively higher treatment efficiencies. Secondary treatment processes are, however, energy-intensive due to biological processes. It is estimated that 0.13 – 0.79 kWh per m^3 of wastewater is the total energy required where about 60% of this is attributed to aeration, accounting for 25% of the total wastewater treatment costs (Gu et al., 2017). The energy supply to the operations of the WWTPs however, is mainly from fossil fuel sources. As such, WWTPs are identified as sources of greenhouse gas emissions (GHGs), mainly associated with carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4).

Thus the wastewater treatment plants (WWTPs) employing conventional activated sludge (CAS) treatment processes have high energy requirements for aeration and heating of digesters during the anaerobic digestion to stabilise the sludge. During the operations of the WWTPs, water and energy use are intrinsically linked such that a symbiotic relationship is formed resulting in a water-energy nexus dynamic (Gleick et al., 2011). The WWTPs however, produce biogas as one of the by-products of the fermentation processes during anaerobic digestion. The biogas can be recovered and used in the ADs which will render the WWTPs energy self-sufficient. As such municipal WWTPs could be transformed to serve as both energy sinks as well as water and energy recovery facilities (WERF).

As seen in Figure 2.1 there is a paradigm shift from the traditional WWTPs to new models of WWTPs, which incorporate the combined heat and power (CHP) unit. The biogas produced from the AD process can be used in the gas turbine or internal combustion engines (ICE) in the CHPs to produce electricity and heat. Only up to 40% of energy is being used in the AD-CHP systems due to their high utilisation rate of the fuel (Sandino et al., 2010; (Uddin & Wright, 2022). The waste heat, which is a valuable asset is captured and used to generate steam and this can be used to heat the mixers in the digester. Fuel cells based CHPs are mainly used in industrial applications, using natural gas or biogas. These systems can achieve up to 85 - 90% efficiency (η) of combined electrical and thermal with zero emissions (Ellamla et al., 2015). Hence in comparison to other energy-saving technologies fuel cells are regarded as more sustainable since only water is produced as a by-product. About 1 m^3 biogas assumed to be 60% methane (CH_4) is estimated to have a calorific value (energy content or energy released upon combustion) of 6 (5.54) kWh, which is an equivalent of 21 – 25 MJ/m^3, at standard pressure and temperature (Biogas Basisdaten Deutschland, 2008). This is an equivalent of about 0.5 – 0.6 l of diesel. About 1 m^3 of pure methane, however, has a calorific value of around 10 (9.94) kWh, which is an equivalent of 35.8 MJ/m3, while carbon dioxide has zero energy content (Petit et al., 2007). Assuming a

35% efficiency, it is estimated that 1 m^3 of biogas has the potential of producing 2.14 kWh of electrical energy and 2.9 kWh of heat (Fachverband Biogas, 2009). This integrated system approach has the potential to assist the WWTPs to be energy self-sufficient to meet both the energy demands of the plant and thus be carbon neutral. Also, the steam captured and re-used contributes to the energy-saving potential of the plant while facilitating the concept of a circular economy.

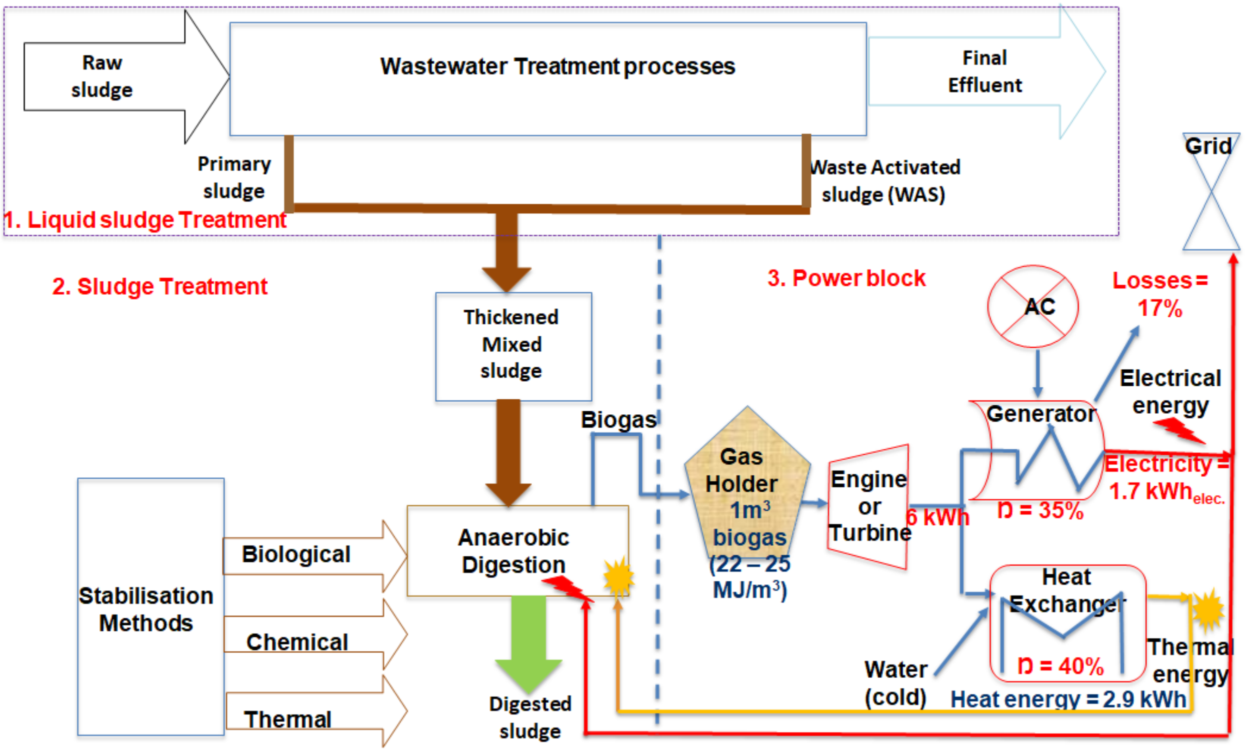


Figure 2.1: A simplified overview of a WWTP with a CHP scheme

2.2 Sludge treatment technology options

Sludge treatment technologies are applied to increase the solids content, and improve the dewaterability and digestibility of the sludge.

1. Thickening is the simplest, inexpensive process and can reduce water content and increase the volume of sludge considerably, achieving 5 - 6 wt% dry sludge (Uggetti et al., 2009).
    - Gravity thickening - this process is simple however, the final solids concentration achieved depends on the proportions of primary and secondary sludge contained (Cheremisinoff, 1994).

- Gravity belt thickeners - are used for all types of sewage sludge while activated sludge can be thickened to 5 % Dry Matter (DM) (von Sperling et al., 2005).
- Dissolved air flotation (DAF) - is used on primary and waste activated sludge (Butler et al., 1997). Equipment costs are lower but energy costs are higher (von Sperling et al., 2005).

2. Dewatering is a physical unit process where the moisture contained in the sludge is reduced, producing a highly concentrated cake (Ruiz et al., 2010).
    - Centrifuging – these are simple to operate devices however, require large areas of land and have high investment costs (Cantet et al., 1996).
    - Drying beds – these are natural, simplest techniques that have been in use for a long time on small-to-medium-sized plants (Bukhari, 2002).
    - Filter belt – it follows the same principle as the gravity belt thickening process and can achieve in the range of 30 – 40% solids concentration (Cheremisinoff, 1994).
    - Filter press – as high as 30 to 45 % moisture reduction can be achieved however investment requirements are quite high (McFarland, 2001).

3. Stabilisation aims to reduce the fermentation of the putrescible matter, eliminating pathogens and the emission of odours.
    - Anaerobic digestion – it is aimed at reducing, stabilising, and partially disinfecting the treated volume of sludge.

2.3 Biochemical reactions

Anaerobic digestion (AD) is the biological decomposition process accomplished by different groups of microorganisms working in synergy. During the AD, biogas is produced which can be recovered as an energy source, digestate which can be used as a feedstock in the fertilisers and supernatant liquor (SNL). The biogas is a mixture of mainly methane (CH_4) and carbon dioxide (CO_2) as well as other trace elements (de Mes et al., 2003). Different substrates are used to produce biogas which contains carbohydrates, proteins fats, cellulose and hemicelluloses thus rendering it environmentally and economically viable.

2.3.1 Anaerobic Digestion pathways

During digestion, the large polymeric compounds contained in the organic material are insoluble and are normally not readily available to be used by microorganisms. The organic fraction of these complex compounds are converted to simpler components (Rohstoffe, 2012). The polysaccharides, proteins and fat are converted into simpler molecules. Each group of microorganisms performs a separate task in the overall AD process and they are: hydrolytic; acidogenic, acetogenic and methanogenic organisms. Figure 2.2 below shows the four biochemical reactions:

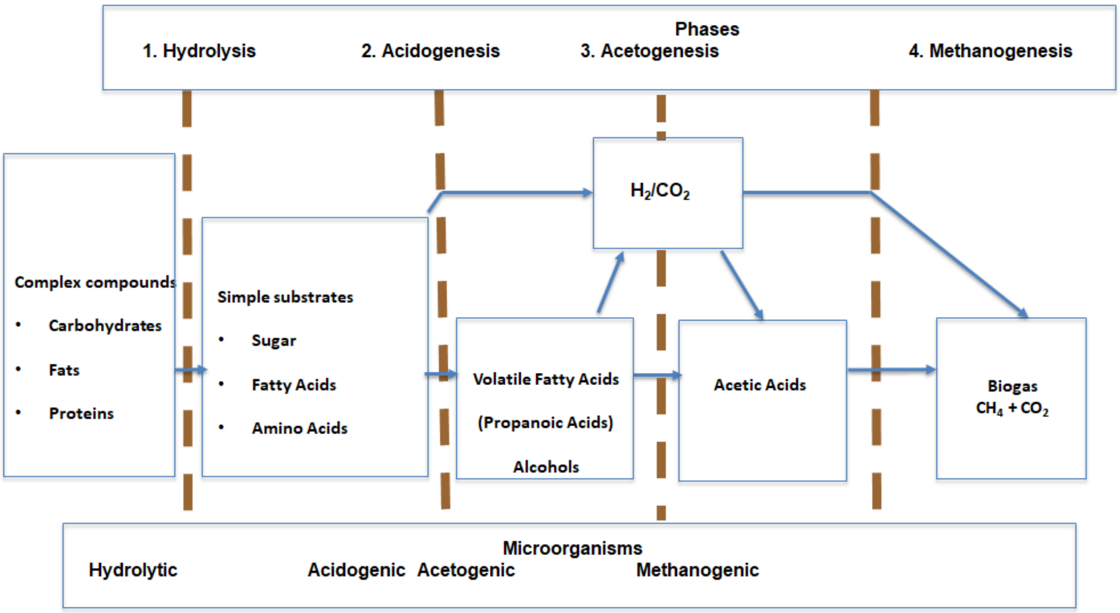


Figure 2.2: Flow diagram of AD pathways

a. Hydrolysis

The carbohydrates, proteins, and lipids are first hydrolyzed and converted into relatively simple sugars and acids. The carbohydrates are broken into monosaccharides, proteins into amino acids and lipids (Vavilin et al., 2008). All these reactions are executed by a group of facultative anaerobes (Weiland, 2010). The hydrolysis stage does not result in the stabilisation of the organic waste. It is mainly for acid fermentation where the organic molecules are disintegrated and rearranged (Appels et al., 2008).

b. Acidogenesis

Hydrolysis which is a slow process is critical for the initiation of the fast-paced acidogenesis reaction. Acidogens are involved in the second stage and responsible for breaking down dissolved organic pollutants in wastewater into fatty acids. During the acidogenesis, the intermediates of the hydrolysis step are fermented to volatile fatty acids (VFAs) - acetic acid, butyric acid, and propionic acid as well as alcohols, lactic acid, and ammonia. The VFAs are largely influenced by the pH levels.

c. Acetogenesis

During the acetogenesis, VFAs and alcohols cannot be directly converted to methane hence the VFAs are first broken down into compounds that are then further digested (oxidised) by acetogens to produce mainly acetic acid and hydrogen (Appels et al., 2008). The accumulation of hydrogen is potential inhibition of the metabolism of the acetogens.

d. Methanogenesis

During methane fermentation, organic material is converted into methane and carbon dioxide by methanogenic bacteria. Methanogenesis is critically pH dependent and involves the use of either acetic acid or hydrogen and carbon dioxide pathways to produce the final products (de Mes et al., 2003).

2.3.2 Operational parameters

Anaerobic digestion microorganisms are sensitive and the four main biochemicals which are inter-depended can be affected by several environmental factors. The biochemical methane potential yields require special conditions and thus monitoring of operating parameters is critical. Biochemical methane potential (BMP) tests are performed at a lab scale under specific conditions to assess the methane potential and biodegradability of the substrates (Angelidaki & Ellegaard, 2003). Table 2.1 contains typical AD operational parameters that are being monitored and values that are recommended to avoid potential inhibitions during the digester performance (Droste, 1997).

Table 2.1: Typical AD parameters

Parameter (mg/l)	Typical operational guidelines for mesophilic digestion
Sludge feed	Sludge concentration of 5% total solids
Temperature control	Uniform temperature in the range 32 - 37°C (close to 35°C)
pH control	pH 7 - 7.5
Solids retention time (SRT)	15 - 25 days
Volatile Acids	Typically in the range 50 - 300 mgℓ $^{-1}$ as acetic acid
Alkalinity	Typically in the range 2 000 - 3 000 mgℓ $^{-1}$ as CaCO3
Volatile acids/alkalinity ratio	Should be < 0.3
C:N ratio	A ratio of 20 - 30:1 is regarded as optimal

I. Temperature

Temperature is the most critical physical parameter and operates within three temperature ranges. The psychrophilic range operates at less than 15 °C, the mesophilic at 15 to 45 °C temperature range and the thermophilic range operates at 45 to 65 °C mainly based on the microorganism group involved (Nijaguna, 2006; Vindis et al., 2009)

Mesophilic organisms are sensitive and can only withstand temperature fluctuations only up to +/−3 °C. Digestion at the mesophilic range is slow and can take between 10 and 30 days. Most anaerobic digestion processes at WWTPs operate in the mesophilic range and are easier to maintain (Vindis et al., 2009; Jeong et al., 2014).

Solids retention time (SRT) of thermophilic digesters ranges between 5 and 12 days at increased loading rates which results in higher biogas production due to accelerated substrate biodegradability while pathogens removal is improved (Angelidaki & Ellegaard, 2003). These systems are, however, unstable, prone to ammonia inhibition and are energy intensive. In a study, two systems were examined both operating with the same organic loading rate (OLR) of 15 kg COD/m^3.d with one operating under thermophilic and another under mesophilic conditions. The biogas production results for the thermophilic and the mesophilic digester were 20.0 l/d and 13.5 l/d, respectively and this supported the view above that at thermophilic temperatures the conversion is faster (Jeong et al., 2014).

II. Organic Loading Rate

The Organic Loading Rate (OLR) is one of the critical parameters used to evaluate the performance of the digesters. The OLR refers to the mass of organic material fed to the digester per digester volume per unit time. The OLR is mathematically expressed as in equation 2.1:

$$\text{OLR} = \frac{C}{HRT} \qquad \text{Equation 2.1}$$

where:

- OLR is expressed as kg VS or COD per m^3 per day
- C is the organic content (volatile solids or chemical oxygen demand)
- HRT is the hydraulic retention time (d) and expressed in hours (or sometimes days),

The control of the OLR is critical since higher than optimal OLR can cause toxicity to the digester affecting the stability of the AD process. Digester microorganisms require an optimum feeding rate at optimum intervals, otherwise, if they are overfed they become inefficient. Operationally the OLR and HRT are inversely proportional hence to reduce the OLR, the HRT needs to be increased. It is not desirable, however, to increase HRT since higher HRTs increase the digester volume and thus the plant's capital expenses (Meegoda et al., 2018). Higher OLR can also contribute to the accumulation of VFAs, causing a synergistic imbalance between methanogens and acidogenic and acetogenic anaerobes (Ahring, 1995). Thus, to control the VFA, an optimal OLR must be achieved.

III. Hydraulic Retention Time

Hydraulic retention time (HRT) is the amount of time that a liquid sludge is in the system. This depends on the volume of the digester and the flow rate of the influent in the system and can be expressed as in equation 2.2:

$$\text{HRT} = \frac{V}{Q} \qquad \text{Equation 2.2}$$

where:

- HRT is hydraulic retention time (d) and is usually expressed in hours (or sometimes days),
- V is the volume of the aeration tank or reactor volume (m^3), and
- Q is the influent flow rate (m^3/d).

Methanogens have a slow growth rate and thus should be provided sufficient time to ensure optimal conversion. At significantly lower HRTs, there is a possibility of washout of biomass out of the system however, longer HRT requires large reactor volumes (Metcalf & Eddy Inc. et al., 2003). The HRT becomes limiting when the bacteria is not replenished at the same rate as it is being removed.

IV. Solids Retention Time

The Solid Retention Time (SRT) is the input rate of organic material per unit volume of the digester. Operationally the SRT describes the average time the solids are held in the system [mass of solids inside the digester (kg)/mass of solids withdrawn (kg/d)], expressed as in equation 2.3:

$$\text{SRT} = \frac{QxCOD}{V} \qquad \text{Equation 2.1}$$

where:

- Q: Influent flow rate [m^3/d];
- COD: Chemical Oxygen Demand [$kgCOD/m^3$];
- V: Individual reactor volume [m^3];

Microorganisms require time to reproduce thus the SRT is a critical parameter in the design of the digester volume. The following conditions were observed in a study on a semi-CSTRs reactor (Appels et al., 2008):

- SRT < 5 days: not enough for stable digestion, methanogens would still be adjusting and maybe washed out whilst VFAs are still in abundance;
- 5 days < SRT < 8 days: VFA concentrations are not lowered at a sufficient degree
- 8 days < SRT < 10 days: stable digestion with low VFA levels, lipids start breaking down
- SRT > 10 days: highly stable digestion with significantly reduces sludge constituents

V. Potential inhibitions caused by intermediate products

These refer to inhibitions largely caused by intermediate products (NH_3, VFA, LCFA, etc.) that are formed during anaerobic digestion (Uddin & Wright, 2022). Thus, the combined impact of NH_3, VFA, LCFA accumulation and pH fluctuations have a significant effect on biogas production. These inhibitions would lead to digester failure if the process design is not well adapted to the substrate properties so that difficult-to-degrade compounds, are completely degraded. During the acetogenesis stage, the high accumulation of molecular hydrogen inhibits the conversion of LCFA, into methane which would have formed at the hydrolysis stage during the degradation of lipids (Angelidaki & Ellegaard, 2003; Uddin & Wright, 2022). This exerts pressure on the bacterial effect and may result in irreversible inhibition.

a. Ammonia

The inorganic nitrogen in the digester exists as ammonium (NH^{+4}) and free ammonia (FA). The build-up of ammonia-nitrogen can result in a decrease in specific microbial activities as the FA is inhibitory. It can diffuse into the cells of microorganisms thus disrupting the entire microbial community structure (Wang et al., 2017). The total ammonia-nitrogen (TAN) at concentrations from 1.7 to 14.0 mg/l has the potential to affect the methane formation negatively. The influent wastewater with ammonia concentration (NH_3-N) of less than 200 mg/l is, however, beneficial for the AD process since it provides the essential nutrient (Chen et al., 2008).

In addition, high concentrations of ammonia-nitrogen and free ammonia (FA) may result in high pH due to undetected accumulation of volatile fatty acids (VFAs). This is unusual since normally when VFAs are high the pH is reduced which gives a clear indication of an inhibited system. In their studies however, Angelidika et al, have shown that reducing the pH and temperature within acceptable ranges can increase the methane yield (Angelidaki & Ellegaard, 2003).

b. Nutrients

Nutrients in the raw material play a critical role in the gas generation hence their deficiency affects the performance of the digesters. Nitrogen, and phosphorus including sulphur are regarded as macro-nutrients whilst iron, cobalt, nickel, molybdenum and selenium are regarded as micronutrients. Macronutrients are important for cell growth and accelerate the metabolism of microorganisms. In their studies, Henze and Harremoes (1983), regarded a ratio of C:N:P:S (600:15:5:1) and a ratio of 7:1 for N:P optimal (Henze & Harremoes, 1983). Methanogenic bacteria require macronutrients as well as micronutrients to function. Iron, due to its oxidation-reduction properties is significant in methanogenesis (von Sperling et al., 2005). Literature shows that some substrates can benefit from the use of micronutrients resulting in increased biogas production. In the studies performed by Wang et al, where distilled water and nutrient/buffer solution were used, whilst the degradation of the substrate was faster, there was however, a slight difference in the final methane yield (Wang et al., 2017). It was noted though that occurred when nutrient-rich substrates like digested sludge were used. As such the need for nutrients is determined by the type of substrate used. Hence nutrient-rich substrates can be co-digested with substrates that are nutrient-deficient to augment the nutrients but also to improve microorganisms diversity (Mata-Alvarez, 2003). For instance, energy crops are slow to degrade due to their complex nature hence they require a long retention time and as a result bigger digesters are required. This can be averted by the pre-treatment of such substrates to break down their biomass structure which improves biogas production (Uddin & Wright, 2022). Also, this results in more cost-effective investments as smaller digesters are relatively cheaper.

c. C:N ratio

Substrate concentration varies in the substrates used for digestion. The carbon: nitrogen ratio is an important parameter to evaluate the performance of the digester. A balanced ratio of C:N ratio of 20 - 30:1 is regarded as optimal for a good digester performance (Wang et al., 2017; Henze and Harremoes 1983), however, recommended C:N ratios of 350:7 and 1000:7 for highly loaded and lightly loaded systems, respectively (Henze & Harremoes, 1983). Carbon and nitrogen, the latter preferred over carbon are required for energy sources and for the growth and metabolism of microorganisms, respectively (Uddin & Wright, 2022). Thus low concentrations of carbon and nitrogen are not desirable whilst high substrate concentrations will lead to the build-up of intermediate products. For instance, if the ratio is increased nitrogen will be depleted resulting in a decrease in biogas production. Conversely, the low C:N ratio leads to ammonia (NH_3) accumulation which is inhibitory. Sewage sludge C:N ratio, however, is in the region of 10 – 20 hence they are ideal for co-digestion (Chen et al., 2008).

d. pH levels

The optimum pH level is 7.0 since various microorganisms have diverse pH preferences while according to other studies, the optimum pH of anaerobic digestion is between 6.5 – 7.5 (Conant et al., 2008). Methanogenic bacteria require a pH range between 6.5 and 7.2 as they are sensitive to pH fluctuations whilst fermentative microorganisms can function in a wider range of pH between 4.0 and 8.5 (Kougias et al., 2014). Acidic conditions can prevail during methanogenesis inhibiting the biogas production due to loss of buffering capacities and the VFAs formation (Conant et al., 2008). Operationally the use of too much raw sludge results in acid fermentation while the pH drop slows down the methane fermentation (Yu & Fang, 2002). Thus, the situation can be rectified and higher pH levels can prevail by stopping to feed the digester so that methanogens will be able to consume excess VFAs.

e. Alkalinity

Alkalinity provides buffering capacity in the digester that prevents rapid change in pH and can range between 1500 and 5000 mg/L $CaCO_3$ (Long et al., 2012). Otherwise, the accumulation of organic acids (VFAs) formed would drive the pH down thus inhibiting the bacteria.

f. Heavy Metals

Heavy metals, are a major inhibitory challenge as they bind to cellular cells hence contributing to reactor failures (Buitrón et al., 2001). The presence of toxic pollutants inhibits anaerobic microorganisms' activity which results in longer reactor start-up time and potential reactor failure. It does appear that the acid-forming bacteria, also get inhibited by heavy metals (Hickey et al., 1989; Lin, 1993).

Methanogens are considered more sensitive to toxicity among anaerobes (Gautam et al., 2013). When the sulphate is reduced to sulphide, methanogens are also reduced (Maillacheruvu et al., 1993). The sulphate-reducing bacteria (SRB) competes with methanogens for COD, hence the kinetics get complicated. Some studies have reported that thermodynamically, the kinetics would favour the SRB (Widdel & Bak, 1992). Hence only after the SRB demand for the COD has been met, the remaining COD would be made available for the methanogens to use for conversion to methane. Whilst the sulphide is inhibitory at a significantly high level, however, at lower concentrations, say less than 20 mg/l, the methanogenesis is not inhibited (Metcalf & Eddy Inc. et al., 2003).

2.4 Major types of anaerobic digesters

There are many anaerobic digester designs however, the two major types are those with fixed dome roofs and floating covers whilst the other digesters are variations based on them. The working principle of both digester designs is similar and both do not include a mechanism for mixing or heating the produced biogas (Surendra et al., 2014).

2.4.1 Indian floating dome digester

Developed in India in the 1960s, the Indian floating dome was originally called Khadi and Village Industries Commission (KVIC) is cylindrical or dome-shaped with a floating drum where the gas is stored (Surendra et al., 2014). It is made up of concrete and steel where the rest of the digester is buried underground and only the cover is above ground see figure 2.3. The drum placed on top of the digester, can move up and down based on the level of the gas at the top of the reactor. This digester requires specialised labour for installation and as such has high investment costs (Cheng et al., 2014).

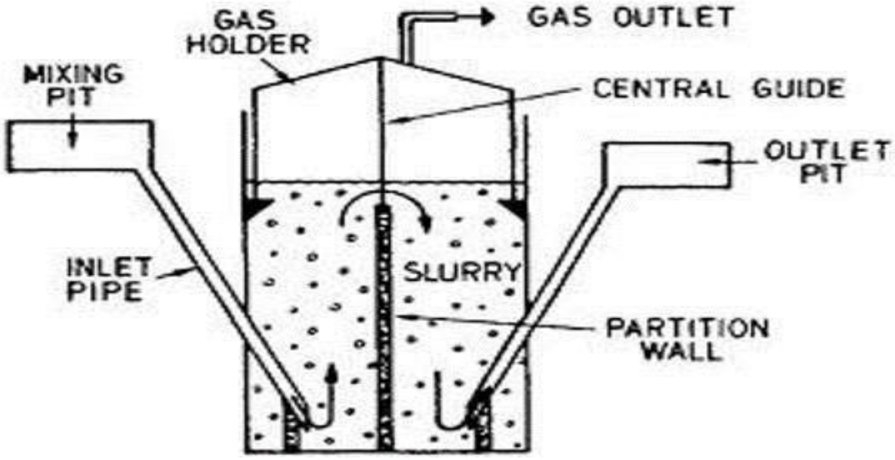


Figure 2.3: A schematic diagram of an Indian-type digester (Surendra et al., 2014)

2.4.2 Fixed dome digesters

The Chinese or fixed dome digester, (see Figure 2.4) is one of the widely used digesters with a cylindrical chamber where biogas accumulates in the upper part of the chamber (Sasse et al., 1991). It has a feedstock inlet and an outlet where, as biogas pressure builds up due to the level of the slurry and the expansion chamber, part of the feedstock is pushed into the compensation tank. Fixed dome construction is labour intensive, has high investment costs and requires specialised skills for maintenance.

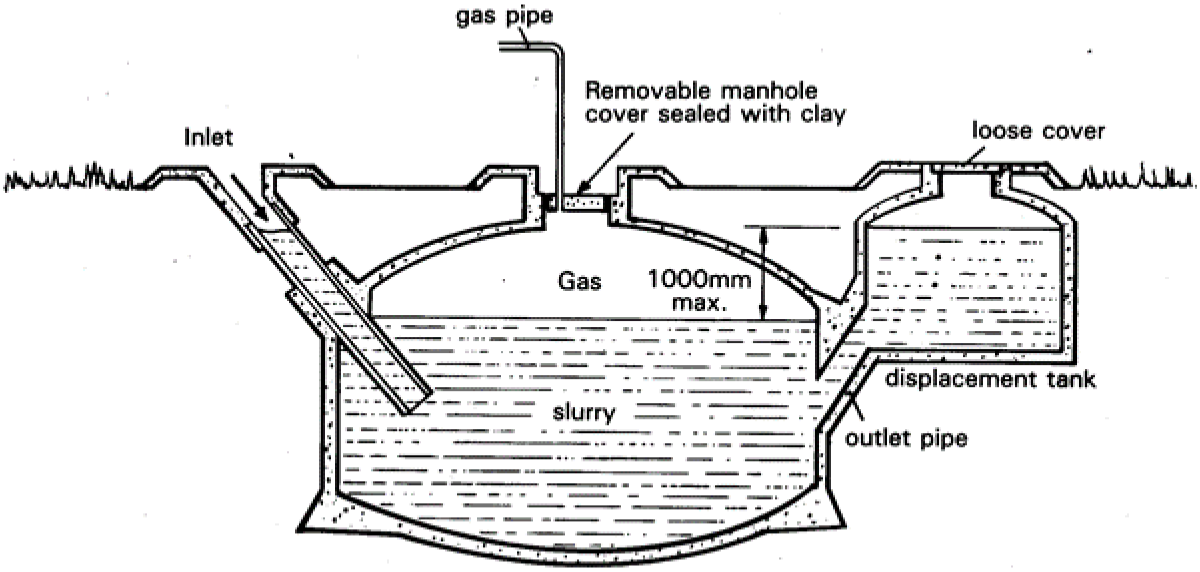


Figure 2.4: Schematic diagram of a fixed-dome digester (Sasse et al., 1991).

2.4.3 Classifications of digesters

There are several types of anaerobic digesters with one or more stages where all biochemical reactions take place. The classifications as shown in Figure 2.5 include the feeding mode, the reactor type, solids/moisture content (Metcalf & Eddy Inc. et al., 2003)

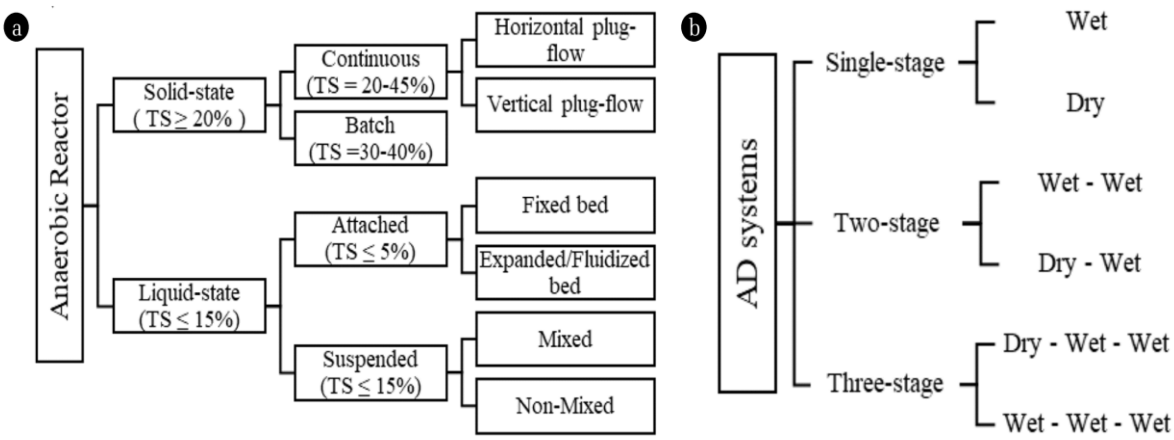


Figure 2.5: The classifications of the digester

A. Single-stage digesters

These have one reactor where all four biochemical reactions take place under the same operating conditions and are the simplest, easy to build and operate digester. The digester can be fed as a batch process where substrates are left to digest and after a pre-determined time, the reactor is stopped, emptied, re-filled with new feedstock and re-started. Batch processes require more upfront capital. Continuous process unlike the batch process requires a more complex design and can be operated as semi-batch, or semi-continuous. During the continuous process, the reactants are continuously fed and the digested products are removed with minimum digester downtime, whilst the biogas is constantly produced.

Generally, single-stage systems are associated with lower biogas yield compared to systems.

a) Mixed system

This system can handle non-homogenous substrates with a solids content of 3 - 10 % (Uddin & Wright, 2022). Continuous mixing of the feedstock helps to keep the solids in suspension to avoid any thermal dead spots or toxic compounds accumulating. The digester design consists of a steel rector where the produced biogas accumulates at the top of the digester. The tank can be above or underground with heat exchangers to maintain the digestion temperature thus reducing the retention time to 10 – 25 days (Uddin & Wright, 2022). This system is more expensive to operate and maintain but this is offset by higher biogas production.

b) Non-mixed

The non-mixing system is simple, cheap to construct, operate and maintain whereas the digester consists of a lagoon with an impermeable cover for the biogas produced. It is operated at warm room temperatures used for high moisture content sludge, and liquid manure with 3 % or less total solids thus requiring large volume lagoons (Uddin & Wright, 2022).

B. Two-stage high-rate digester

The two-stage digestion is aimed at optimizing all the anaerobic digestion steps. In this arrangement there are two different reactors, for performing hydrolysis and methanogenesis separately hence their growth characteristics are very different (Appels et al., 2008).

First reactor - hydrolysis/acidogenesis:

- It's called an "acid-phase digester" where hydrolysis and acidogenesis take place;
- It has a retention time of 1- 2 days;
- Operates in the pH range between 5.5 - 6.5;
- It can be operated under both mesophilic and thermophilic conditions;
- No stabilisation takes place and as such methane generation is negligible.

Second reactor - methanogenesis:

- It is referred to as a "methane-phase digester";
- It has a retention time of 10 days;
- It can be operated under mesophilic temperature conditions.

The two-stage AD digesters are usually operated as high-rate systems to separate the supernatant liquor (SNL) with minimal gas recovery. The first tank also called the primary digester in the two-stage digesters is fitted with the mixing and the heating equipment and is mainly used for digestion. The second tank also called the secondary digester is normally not heated or mixed and thus serves as a storage. The primary and secondary tanks can have the same capacity including the heating and mixing equipment. In this case, they will both serve as a standby digester (Appels et al., 2008)

C. Three-stage digester

The three-stage system is more complex requiring consistent feeding and has higher operating and maintenance requirements. The hydrolysis, acidogenesis/acetogenesis and methanogenesis reactions take place in different reactors while the system result in improved odour at a lower retention time thus achieving overall higher performance.

2.5 Renewable energy

Historically, the growing energy demand globally has been largely met with fossil fuels, which have been identified as a source of greenhouse gas (GHG) emissions contributing to climate change. It is estimated that the global average concentration of GHGs in 2020 was 417 parts per million (ppm) (Joanne & Hunt, 2009). Energy is a critical input to the economy, for the production of goods and services. Thus, it is required for economic development where these interdependencies, create an economic-energy-GHG nexus. Between 2000 and 2015 there has been an increase of more than 50% in gross final energy consumption (Khan et al., 2019). As can be seen in Figure 2.6, as human population growth, basic needs and energy consumption of societies increase resulting in a rampant rise in anthropogenic GHG emissions (Energy Agency, 2020).

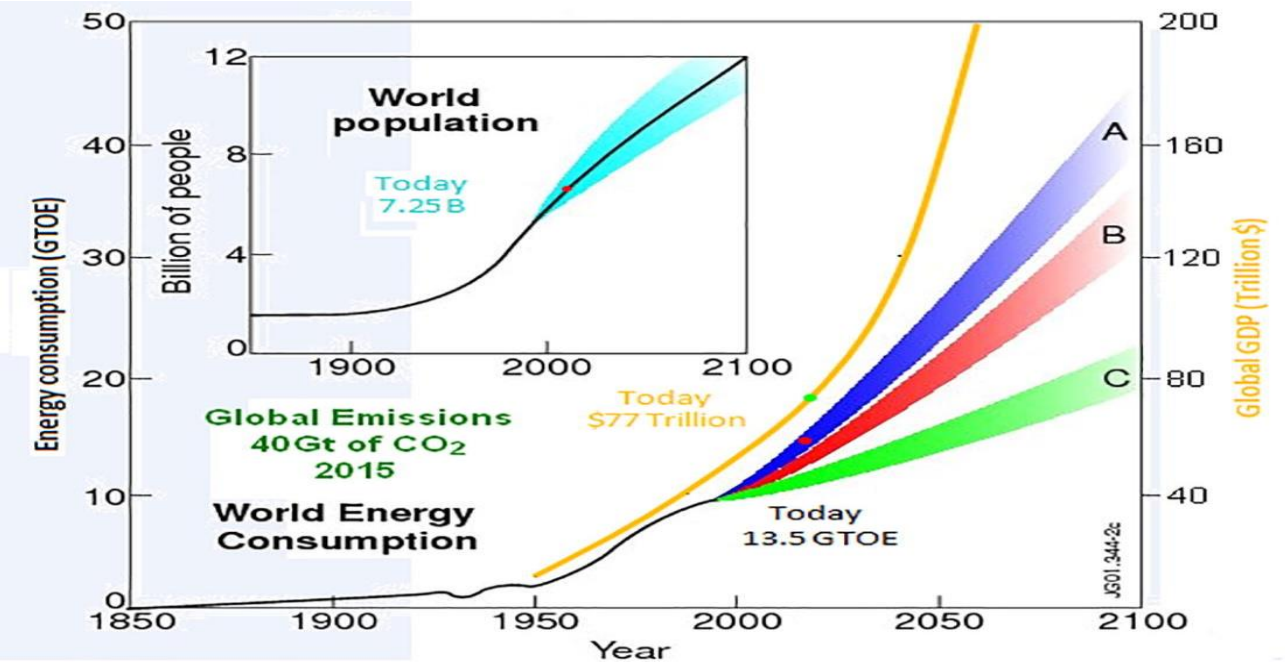


Figure 2.6: A graph of world population vs energy consumption, GHG and GDP (Energy Agency, 2020).

Sustainable development, however, involves the availability of adequate resources, particularly energy services, to satisfy the basic needs of an individual and society for improving social welfare and economic development. Against the backdrop of this, there has been an increase in the share of renewables which can be an alternative to reduce GHGs emissions in support of low-carbon economic development. Hence renewable energy remains a viable solution where it is projected that by 2027, the renewable energy capacity will grow by 2 400 GW globally, creating a diverse energy mix comprising solar, wind, biomass, nuclear and hydrogen (Energy Agency, 2020). New technologies and processes require efficiencies to emerge at a faster pace and scale.

2.5.1 Biogas energy value

Biogas is a renewable energy carrier, defined by its methane value. The quality of biogas dioxide varies and the ratio of methane to carbon is depended on the composition of the substrate. A typical biogas composition contains 60 - 70% Methane (CH_4), 30 – 40% Carbon Dioxide (CO_2) and other trace elements such as Hydrogen Sulphide (de Mes et al., 2003). Biogas as a fuel has low efficiency as compared to fossil fuels such as diesel and petrol. For example biogas when used in spark ignition engines, it produces less than 20 kW output compared to 60 kW original output when petrol is used (Mukumba et al., 2016). This is because of the impurities in the biogas which are not combustible thus resulting in low conversion of biogas to electricity. There are various technologies to upgrade biogas by removing impurities and improving its efficiency as a fuel. Hydrogen sulphide is harmful as it is converted to corrosion-causing acids. For optimum performance, the H_2S should be lower than 250 ppm (Sandino et al., 2010). A higher methane content in the biogas thus is more desirable to optimise the gas conversion. Methane is a highly flammable gas and its content in biogas needs to be at least greater than 50% of the total composition for the generation of electricity (Fachverband Biogas, 2009). The biogas once produced during AD can be converted into electricity through combustion in a gas engine or a turbine.

The high heating value (HHV) and the low heating value (LHV) both describe the heat contents of the biogas. The HHV or gross calorific or gross energy value is the amount of heat released when one (1) m^3 of biogas is combusted while the LHV or net calorific value omits condensation. The energy content of biogas is directly linked to the methane concentration which is assumed to be 60% methane. Thus it is estimated that 1 m^3 of biogas produced has an energy content of 6 kWh, an equivalent of 21 – 25 MJ/m^3, at standard pressure and temperature (Biogas Basisdaten Deutschland, 2008). Meanwhile, a typical 1 m^3 of pure methane has a calorific value of around 10 kWh, while carbon dioxide has zero (Petit et al., 2007). About 30 - 40% of the energy in the fuel is used to produce electricity while the remaining energy becomes heat. Thus 1 (one) m^3 of biogas has the potential of producing 2.14 kWh of electrical energy and 2.9 kWh of heat (Fachverband Biogas, 2009)

The amount of biogas, Q_{biogas} and methane F_{CH4}, depends on the chemical composition of the organic waste hence the precise ratio of CH_4 to CO_2 in biogas varies. Thus the energy from biogas can be converted to electricity using a variety of electrical efficiency (η_{elec}) values of biogas. These can vary between 25 % and 43 % depending on the technology used. Normally 25 % is used for smaller generators and 43 % for large turbines. Microgas turbines have a lower electric efficiency (25 – 31%) but have a good part loading efficiency and the exhaust heat available at at least 270 °C after the recuperator and can be used in the process of steam production (Schmid et al. 2005). Fuel cells are operated at temperatures between 80 and 800 °C resulting in higher electric efficiency (Ahrens & Weiland, 2007). The catalysts which are critical for converting methane into hydrogen are very sensitive to impurities thus an efficient gas cleaning method is required. The investment costs in the fuel cell CHPs are much higher than for engine-driven CHPs. To calculate the electricity production potential, equations 2.4 or 2.5 below can be used:

$$E_{elec} = Q_{biogas} \times F_{CH4} \times CP_{CH4} \times \eta_{elec} \qquad \text{Equation 2.2}$$

where:
E_{elec} is the electrical energy produced per tonne of organic residues, in KW/tres,
Q_{biogas} is the amount of biogas obtained from the organic residues of a biodigester, in m^3,
F_{CH4} is the methane contained in the biogas, in percentage,
CP_{CH4} is the specific heat of methane (KWh/m^3),
η_{elec} is the electrical efficiency in percentage.

$$e_{biogas}\,(kWh) = E_{biogas}\,(Btu) \times 0{,}000293\,(kWh/Btu) \times \eta_{elec} \quad \text{Equation 2.3}$$

where:
e_{biogas} is the total electricity that can be generated from biogas, in kWh,
E_{biogas} x is the unconverted raw energy in the biogas (in BTUs),
η_{elec} is overall conversion efficiency.

2.6 Biogas utilisation

Biogas is an excellent fuel for a large number of applications and can also be used in Combined Heat and Power (CHP) to produce heat and steam, electricity generation/co-generation, used in transport as vehicle fuel, and in the industry in the production of chemicals. In electricity production, it can be upgraded and used as a replacement for fossil fuels and contribute to national grids.

Domestically, biogas can be used primarily for cooking and lighting whereas biogas stoves are used displacing solid, high-emission fuels like firewood and charcoal. The use of fuel wood especially in developing countries accounts for 54% of deforestation whilst worldwide deforestation is responsible for 17 – 25% of all anthropogenic GHG emissions (Khan et al., 2019). Thus, the use of biogas in place of wood could see the global avoidance of 4.5 metric tons of CO_2 emissions, that could have been released to the atmosphere.

The main components in the CHP are the heat recovery and the generator which converts the chemical energy of the fuel into electrical energy. Electric power and heat are the most important commodities. In the CHP, 30 - 40% of the energy in the fuel is used to produce electricity where the waste heat is captured, reducing almost half of wasted energy. The CHP technology can deliver up to 85 - 90% efficiency (combined electrical and thermal) and have lower emissions (Ellamla et al., 2015). In Europe, the use of biogas in large-scale applications for electricity generation through combined heat and production (CHP) engines is well established (Simet Anna, 2016). In South Africa, only 13% of its energy is used for space heating and 32% for hot water (Fachverband Biogas, 2009). Internal combustion engines (ICE) based CHPs are a technology of choice in Germany with 4 000 biogas plants which include diesel engines, gas motors and gas turbines and are more suitable for small-scale co-generating applications (Fachverband Biogas, 2009). Fuel cells used in CHP applications can use natural gas or biogas. Fuel cells are destined to be the future power plants playing a critical role in green hydrogen production, available with capacities from 5 to 2,800 kW (Energy Agency, 2020). Heat can be recovered to produce hot water for domestic applications, low-pressure steam and absorption chiller for cold water. Hydrogen production is very efficient, producing only water as a waste product, see equation 2.6:

$$2H_2 \text{ (gas)} + O_2 \text{ (gas)} \longrightarrow 2H_2O \text{ (vapor)} + \text{Energy} \qquad \text{Equation 2.4}$$

Biogas can be applied in farming where it can alleviate energy poverty, especially for rural communities. Biogas applications have the potential to play a significant role in the agricultural sector. There are approximately 4,000 agricultural biogas production units that were operated on German farms (Fachverband Biogas, 2009). Cow dung, goat dung, sheep dung and donkey dung are among the substrates that are in abundance in rural communities.

Biogas can replace natural gas even in the industry where it can also be used as feedstock for the production of chemicals.

In the transport sector, biogas can be odourised and pressurised where it can be mixed with natural gas and be used to fuel vehicles. The biogas can also be used with diesel and maintain as high as 90% of the efficiency of the diesel engine.

2.6.1 Techno-economic feasibility of biogas plants

The technical, social and economic aspects as well as government and institutional arrangements are all critical and should be factored in before one develops biogas projects. It is suspected that the rising prices of fossil fuels and the environmental imperatives on the other hand have been contributing to the decline of coal consumption (Energy Agency, 2020). Thus the techno-economic analysis helps to evaluate the favourability and profitability of the biogas projects. There is a mature technology and reliable market for biogas. To assess the economic viability of biogas, however, biogas must compete not only with other renewables but with electricity generation from fossil fuels as well (Amigun & von Blottnitz, 2010). Technically the electricity generation component of a biogas power plant is not so different from a normal generator set used for fossil fuels. It is, however, generally more cost-efficient to run bigger biogas plants than smaller ones.

The payback period refers to the time it takes to recover the capital invested on annual returns. The payback period which is one of the indicators used, is critical in determining the investment potential. It is calculated, using equation 2.7:

$$n = \frac{\text{capital investment}}{\text{annual returns}} \qquad \text{Equation 2.5}$$

where:
n = payback period (years)

Literature in most cases though contains case studies with information from biogas power plant producers referring to payback periods of only 1.5 – 2.5 years, which are ideal but not realistic. Other studies show more realistic figures based on medium and large plants (>50kW) power generating plants. They show that assuming a Deutsches Biomasse Forschungs Zentrum (DBFZ) tariff scheme (~0.15 US$/kWh), payback periods of 6 years under very favourable conditions and 9 years for unfavourable but still economically viable investments, respectively are more realistic (Kartha et al., 2005).

2.6.2 Biogas development in South Africa – challenges and opportunities

South Africa is faced with energy security whilst it is endowed with a lot of biomass resources and other substrates. Energy is becoming the single most critical performance indicator in South Africa, with potentially far-reaching economic, social and environmental consequences (Scheepers and van de Merwe-Botha, 2013). Electricity generation from biogas in Africa including in South Africa, however, has not really captured the market energy due to various reasons. Biogas is still in its infancy in South Africa however, South Africa was one of the first countries in the world in the 1940s to develop digesters as part of sludge management at WWTPs (Amigun & von Blottnitz, 2010). In South Africa, fixed dome and balloon digesters are commonly used. Most biogas projects in South Africa were built as pilot digesters and ceased to operate within ten years after being commissioned (Turpie et al., 2008).

Lack of education and expertise to operate these systems including training on feeding and the maintenance of the digesters to avoid system failure is a big challenge in South Africa.

The previously installed digesters were treated as demonstration units only and as such there was a lack of ownership of systems by communities. Meanwhile, it is estimated that some three billion people around the world, rely on traditional biomass resources for energy (United Nations, 2015). These are mainly found primarily in rural areas of developing countries. Hence in line with the 2030 Agenda Sustainable Development Goals (SDG), it is important that together with environmental issues but also ethical-socio-economic challenges in developing countries are also addressed. Paramount to these are gender and energy poverty. According to estimates, the use of biogas could result in cost savings of R1 808 per household, an equivalent of 8,6 % of the household income per year in South Africa (Biogas, 2015). This translates to a gross national annual cost saving of up to R4,5 billion, thus biogas can be a cost-effective, healthy alternative energy source as well.

Biogas, however, can play a significant role in meeting the country's energy needs and provide a considerable contribution to the national grid. It is estimated that biogas can contribute 3 gigawatt (GW) or 4GW to the national grid in South Africa (Biogas, 2015). In the rural areas, there are opportunities for biogas to supply isolated grids and provide electricity for cooking and lighting. In South Africa, more than 70 % of low-income households, rely on sources of energy to satisfy their basic energy needs (SABIA & SAGEN, 2016). Meanwhile, more affluent communities, who have universal access, rely mainly on electricity. Special gas mantle lamps, typically consume about 0.07 – 0.14 m^3 of biogas per hour under a gas pressure of 70 – 84 mm of water, with satisfactory results (Surendra et al., 2014). These lamps can then be used to provide better lighting instead of candles that are also associated with fire accidents, especially in shack dwelling communities. Since in most cases cooking is usually performed indoors without proper ventilation, use of biogas could be a good substitution of fuel wood as a source of energy with added improvement of human well-being through reduced levels of indoor smoke and better lighting. The World Health Organization (WHO) estimates that 1.5 million pre-mature deaths per year (over 4000 deaths/day) are directly associated with indoor air pollution due to use of solid fuels especially among women and children who are traditionally responsible for cooking.

It is estimated that biogas generation in South Africa has the potential to displace 2 500 MW of grid electricity. The Uilenkraal biogas plant was one of the first large scale biogas projects in South Africa. The project involved use of 1 200 lactating cows that provided manure which was co-digested with urine and wastewater slurry (Marius Claassen Supervisor & Basson, 2015). Meanwhile, Bronkhorstspruit Biogas Project, commonly known as Bio2Watt was the first commercially operational biogas project using manure with supplements from the abattoirs. About 4,5 MW of electricity is generated by the project with the uptake by BMW where it provides 25 - 30% of their energy demands (Biogas, 2015).

Electricity grid connection and appropriate feed-in-tariffs costs are critical factors informing investment. Using the example of Germany again and other industrialised countries, only guaranteed feed-in tariffs have led to a breakthrough. In Germany basic feed-in-tariffs ranged from 0.10 – 0.2 US$/kWh$_{el.}$ for plants up to 150 kW (Energy Agency, 2020). In fact, studies are showing that biogas power plants are not commercially viable without subsidies or guaranteed high prices (~0,20 US$) for the produced outputs. In Africa none of the biogas pilot plants have been installed without international technical and financial support. Hence though biogas technology can be a solution to South Africa energy needs, the designing and installation of digesters require high initial costs. It is estimated that the installation of a 10 m^3 fixed dome digester requires at least R80 000 in South Africa (Biogas, 2015). Thus, government support and intervention through subsidies and other forms is needed. There are various programmes amongst these is the joint rebate programme led by Eskom and the Department of Trade and Industry (DTI) and others under the Industrial Development Corporation (IDC). These are offering various interventions including finance with low interest rates to serve as incentives in the green technology investments. Eskom's Integrated Demand Management (IDM) in 2013, proposed that for every kWh generated by a biogas plant in South Africa between 18h00 and 20h00 weekdays for the first three years of operation, Eskom will contribute R1.20 (Ruffini, 2013). Thus subsidies as well as the establishment of appropriate feed-in tariffs are crucial to stimulate the biogas market.

Although the government seem supportive of biogas expansion, energy policies and regulatory framework are very complex and have been cited as the biggest barrier to helping stimulate the biogas industry in South Africa (Biogas, 2015). On contrary, Germany made a breakthrough and became profitable in power generation plants from biogas mainly due to its progressive policies and government support including Japan with developing policies such as SPIRIT21 (Sewage Project, Integrated and Revolutionary Technology for Twenty-First Century) and Sewerage Vision 2100 (Energy Agency, 2020). In South Africa, whilst the National Environmental Management Act (NEMA) provides the overarching regulatory framework, there are a whole lot of other different sets of legislation to comply with. These include the National Environmental Management: Waste Act (NEM: WA), the National Environmental Management: Air Quality Act (NEMAQ), and the National Waste Management Strategy (NWMS). Furthermore, there are others related like the National Water Act (Act No. 36 of 1998), the National Heritage Resources Act (Act No. 25 of 1999), the National Gas Act (Act No. 48 of 2001) and associated municipal by-laws that have to be complied with as well. These make the process complex and cumbersome. As a result, the National Biogas Platform which is an initiative that comprises government departments, non-governmental organisations (NGOs) and project developers, has since developed a regulatory tool to guide developers and decision-making authorities in an effort to simplify and streamline the process.

There is also a lack of research and development as well as support from biogas experts in South Africa (Amigun & von Blottnitz, 2010; United Nations, 2015). New knowledge in biogas technology is required and currently, the country is relying mostly on research work done outside Africa. Extensive research work to identify opportunities and constraints in biogas technology in South Africa is required.

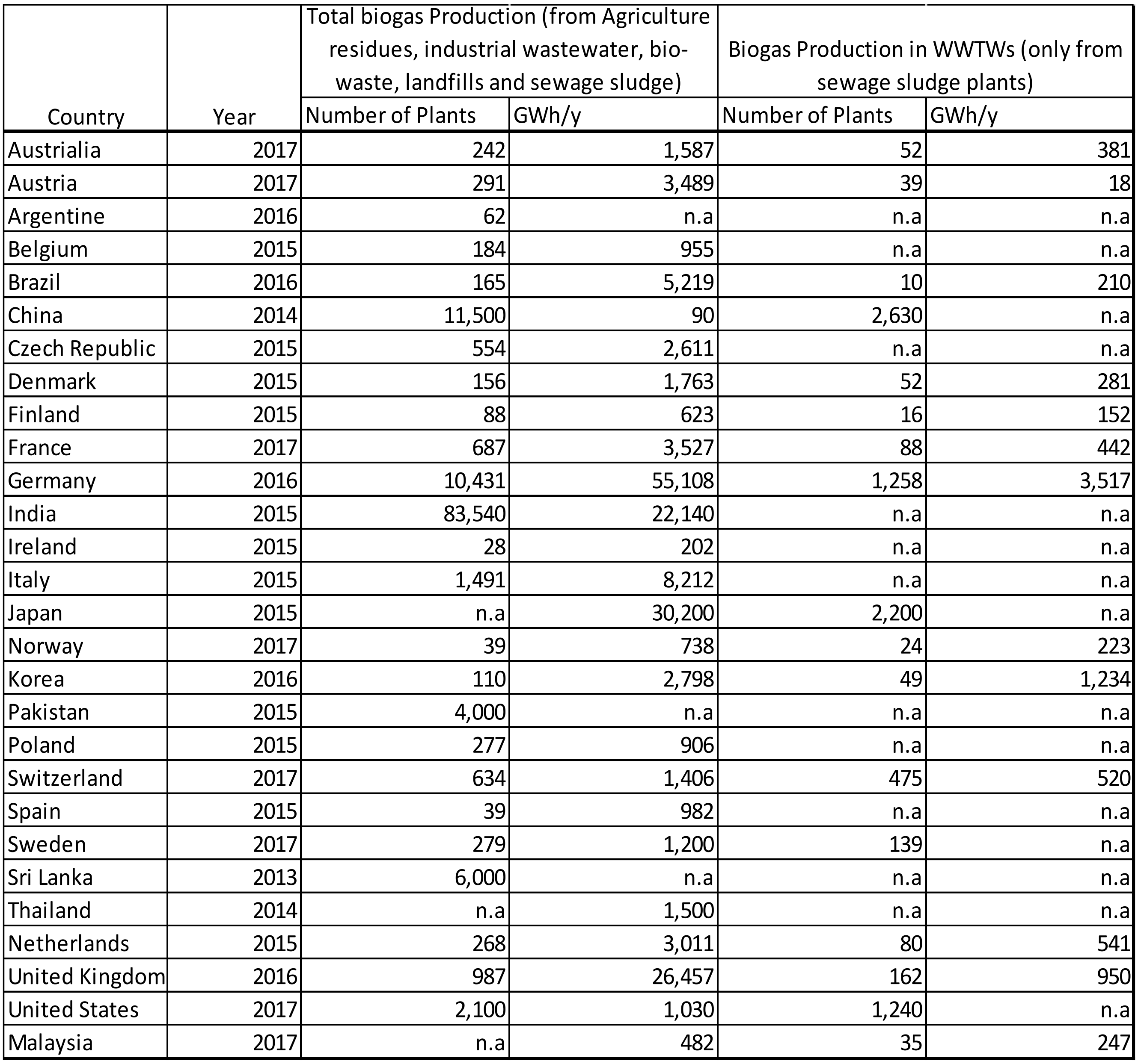
The use of fire wood used for cooking especially in developing countries is responsible for 17 – 25% of all anthropogenic GHG emissions (Khan et al., 2019). Firewood and kerosene which are the most common traditional fuels used for cooking, if replaced with biogas can result in overall GHG emission reduction. It is estimated that the produced biogas has the potential to substitute 727 million dry metric tons of firewood and 42 billion litres of kerosene per year in developing countries (Surendra et al., 2014). Thus annually 293 million metric tons of CO_2 equivalent GHG emissions can be mitigated from Africa.

The current electricity pricing levels for biogas do not reflect its most valuable component, namely: biogas-generated power is fully dispatchable. Thus biogas can supply electricity on demand at any time of the night or day, especially during peak hours when there is the highest demand for energy. This inherently higher value should be exploited further and leveraged. According to The Market Intelligence Report, biogas has electricity generating and heating potential with a current market value of more than R450 million and R18 billion in South Africa (Biogas, 2015). Furthermore, biogas is safe, it is 20% lighter than air with a density of 1.15 – 1.25 kg/m^3, thus it will rise upward in an event of a gas leak. It also has an ignition temperature in the range of 650 - 750 °C which is higher than petrol and diesel thus the risk of fire and explosion is minimal (Deublein & Steinhauser, 2008). Despite these significant economic, environmental, health and social benefits biogas has not permeated especially the rural communities of developing countries where it would make the greatest impact.

2.8 Anaerobic digestion in municipal wastewater treatment

The operations of the municipal WWTPs incorporate the conventional wastewater processes with the energy supply normally from fossil-fuel sources. On the other hand, conventional wastewater treatments use AD to stabilise wastewater resulting in biogas as one of the products. The main feedstock for anaerobic digestion (AD) around the world includes sewage sludge due to its high methane component (Bachmann, 2015). Furthermore, the stabilisation of wastewater has been practised for a long time. In the 1890s in the city of Exeter, UK the first full-scale application was developed using sewage and methane to heat the digestion tanks (Khan et al., 2019). Table 2.2 shows the installations of the AD systems globally. Germany is leading the biogas technology development globally. In 2016 it had a total of 10,431 biogas plants with an installed capacity of 55 108 GWh/y with 1 258 WWTPs generating 3,517 GWh/y of electricity (Simet Anna, 2016). China and India are in the lead in the developing countries. In Japan, 280 out of 2,150 WWTPs incorporate anaerobic digestion system.

Table 2.2: Anaerobic Digestion plants globally at WWTPs



Country	Year	Total biogas Production (from Agriculture residues, industrial wastewater, bio-waste, landfills and sewage sludge)		Biogas Production in WWTWs (only from sewage sludge plants)	
		Number of Plants	GWh/y	Number of Plants	GWh/y
Austrialia	2017	242	1,587	52	381
Austria	2017	291	3,489	39	18
Argentine	2016	62	n.a	n.a	n.a
Belgium	2015	184	955	n.a	n.a
Brazil	2016	165	5,219	10	210
China	2014	11,500	90	2,630	n.a
Czech Republic	2015	554	2,611	n.a	n.a
Denmark	2015	156	1,763	52	281
Finland	2015	88	623	16	152
France	2017	687	3,527	88	442
Germany	2016	10,431	55,108	1,258	3,517
India	2015	83,540	22,140	n.a	n.a
Ireland	2015	28	202	n.a	n.a
Italy	2015	1,491	8,212	n.a	n.a
Japan	2015	n.a	30,200	2,200	n.a
Norway	2017	39	738	24	223
Korea	2016	110	2,798	49	1,234
Pakistan	2015	4,000	n.a	n.a	n.a
Poland	2015	277	906	n.a	n.a
Switzerland	2017	634	1,406	475	520
Spain	2015	39	982	n.a	n.a
Sweden	2017	279	1,200	139	n.a
Sri Lanka	2013	6,000	n.a	n.a	n.a
Thailand	2014	n.a	1,500	n.a	n.a
Netherlands	2015	268	3,011	80	541
United Kingdom	2016	987	26,457	162	950
United States	2017	2,100	1,030	1,240	n.a
Malaysia	2017	n.a	482	35	247

In South Africa, the first municipal digesters built date to as far back as the 1940s and this was to be followed by some installations in the 1970s and 1980s (Amigun & von Blottnitz, 2010). The focus of these installations though then was sludge management instead of biogas production. Currently due to environmental concerns, biogas production from AD including in WWTPs is of growing interest (Turovskiy & Mathai, 2005). As such anaerobic digesters (AD) are a significant part of sludge treatment in municipalities in South Africa which presents municipalities with an opportunity to recover the biogas and render the municipal WWTPs environmentally and economically sustainable. Biogas is estimated to contain 4,800 kWh of chemical energy hence this will reduce energy demand while generating electrical and heat energy (Gikas, 2017).

There are 850 AD systems in total in the municipal WWTPs, with 56% of these installed in Gauteng and among these is the Northern Waste Water Treatment Works (WWTW) of Johannesburg Water (Department of Water, 2022). The Northern WWTW was completed in 2012 and is capable of producing 1.1 MW which represents 18 % of the plant’s power requirements (Biogas, 2015). Biogas produced could be used to provide electricity for the up and downstream treatment processes in the WWTP. Most of the energy needs of the operations of the WWTPs however, are still met with fossil fuel sources and the biogas is being flared into the atmosphere. Opportunities are still not being fully explored to recover the gas which can provide power and heat thus rendering the WWTPs self-sufficient. Co-digestion which improves the methane yield by diluting the inhibitory effects of substances while it increases microbial diversity and synergy is not being practised much in South Africa (Mata-Alvarez, 2003).

In rural areas housing developments, schools and clinics are normally not connected to a wastewater system. Thus, they could treat their sewage wastes by AD in order to produce electricity or gas and use it as fuel for cooking and heating purposes (SABIA & SAGEN, 2016). This could, in addition, provide socio-economic benefits and waste management options including to mitigate against any potential pollution of groundwater by pathogens.

CHAPTER 3

This chapter outlines the methodologies and procedures used to analyse the raw data of the operations and water quality in the 3 wastewater treatment plants (WWTPs) in eThekwini municipality. The raw data is based on the actual operations from January 2019 to December 2019. Characterisation of the wastewater samples was done at the eThekwini Scientific laboratory in Pinetown, Durban whilst the Biochemical methane potential (BMP) tests were done on the Automatic Methane Potential System (AMPTS II) at Unisa laboratory, in Johannesburg.

3.1 The Study Area

eThekwini Municipal Area (EMA) is located within the Province of KwaZulu Natal in the east of South Africa covering a land area of 2 297 square kilometres. Below (Figure 3.1) is a map of eThekwini Municipal showing locations of wastewater treatment plants (WWTPs). The eThekwini municipality in Durban operates a total of 27 Wastewater Treatment Plants (WWTPs), treating a total of 460 Ml/day of sewage (Ethekwini Unit, 2017).

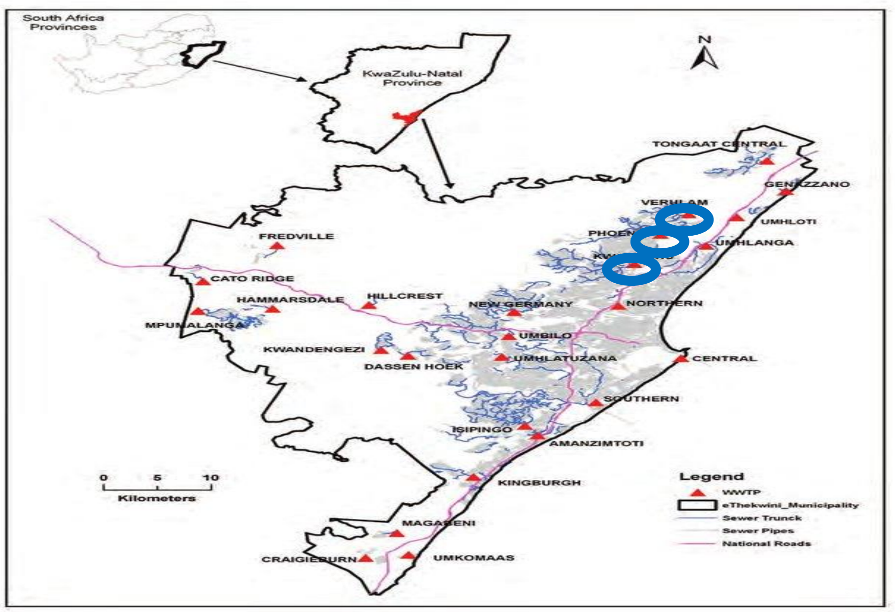


Figure 3.1: A map of the eThekwini municipality WWTPs (Ethekwini Unit, 2017.)

In this study, we focused on three major WWTPs, namely: Kwa-Mashu, Phoenix and the Verulam. Table 3.1 shows the details of the locations. Kwa-Mashu and Phoenix are located about 25 km from Durban and about 12 km apart from one another. Verulam is located about 27 km north of Durban.

Table 3.1: A summary of the locations of WWTPs

WWTP	Location (GPS Coordinates)
Verulam	-29.645804260692486, 31.063600510810822
Kwa-Mashu	-29.72965619567206, 31.00895676896177
Phoenix	-29.67982, 31.03789

3.1.1 Description of the 3 WWTPs

Kwa-Mashu WWTP

The plant has a design capacity to treat 65 Ml/d of wastewater however, it was receiving in the range of 59 Ml/d wastewater flows from 3 feeding lines, namely: Ntuzuma – 9 Ml/d, Phoenix line 1 and 2 – 22 Ml/d and 25 Ml/d, respectively. The feeds are made up of 60% domestic waste which is from surrounding residential areas and the commercial sector. The remaining 40% is partially treated effluent from the surrounding industries and these are:

- Food & Beverages Industries
- Metal Finishing
- Paint Manufactures
- Pulp and Paper
- Chemical Processing
- Adhesive Manufacture
- Workshop and Truck Yard
- Drum Services/Recycling
- Panel Beating
- Textile Industries
- Printing Industries

Verulam WWTP

The plant has a total of 12 Ml/d which consists of an 8 Ml/d Bardenpho-type activated sludge unit (old works) and a 4 Ml/d circular activated sludge plant (new works). The 4 Ml/d comes online once the influent wastewater exceeds the 8 Ml/d capacity. The Plant treats on average 4 – 5 Ml/d, mainly from about 21 000 households however, there are high incidents of industrial pollution, particularly the dyes from the textile industry. The treated effluent is chlorinated and pumped to a pond which discharges into the Umdloti River. The industrial effluent discharged to Verulam includes:

- Soap Manufacturer
- Food and Beverage
- Textile Industry
- Concrete Mixing
- Stationery Manufacturer
- Laundry
- Hospital Package Plant
- Paint Manufacturer
- Plastic Recycler
- Ground Water Remediation
- Laundry Services
- Printing Industry
- Workshop and Truck Yard
- Car Wash

Phoenix WWTP

This WWTP currently treats approximately 29 Ml/day of raw sewage from the Phoenix and Ottowa areas in the north of the municipality. Phoenix sewage is mainly from the recently developed Cornubia mixed development which is made up of 70% of the domestic waste and 30% is from the surrounding industries, which include:

- Panel Beaters
- Workshops and Wash Bays
- Food and Beverage
- Printing Industry
- Plastic Pallet Manufacture

3.2 Sampling

The samples at the 3 WWTPs were collected with the help of the eThekwini municipality plant operators. Samples are taken as frequently as possible from various locations due to the variability of the composition of the wastewater and to assess the potential impact, trend or disturbances. Desirable sampling points are those where there is the greatest mixing of the wastewater but also clearly marked and accessible. Hence the influent wastewater samples are preferably taken at the Head of Works (HOW), due to the high turbulent flows. The final effluent discharge samples were taken at the maturation ponds. The samples were taken hourly from Monday to Friday since the laboratory is not available on weekends.

During sampling latex gloves are worn to ensure there is no contamination of samples. Grab or composite samples were collected however; it must be noted that the grab samples are representative of the wastewater conditions at the time of sample collection. Hence their analysis cannot be used to evaluate the long-term performance of the wastewater treatment. The volumes of each grab sample are proportional to the amount of the wastewater flow at the time the sample was taken. Meanwhile, composite samples are taken by continuous sampling or by mixing discrete samples. During periods of low or zero flow, there were no samples taken for that particular period. Composites were collected in 20L plastic bottles while the 300 ml wide-mouthed Nalgene plastic bottles (see figure 3.2a) were used for grab samples. Samples were clearly labelled so that they could be easily identified from other samples in the laboratory. Automatic samplers are used or alternatively, manual sampling (Figure 3.2b) is done by dipping the container in the wastewater stream so the mouth of the container faces upstream.

Figure 3.2: Diagrams of the a) Empty Nalgene wide-mouth bottles b) Sample collected

Samples were preserved at or below 4°C to reduce the biological activity during storage and transporting and those that could not be stabilised by chemical addition or any method were immediately analysed.

3.2.1 Sample analysis Data

Once the samples were collected, they were then taken to the laboratory EWS Scientific Services Laboratory, in Pinetown, Durban for analysis. The samples are accompanied by the document with the following information:

- Date of sampling;
- Time of sampling;
- Location and name of sampling site (include GPS coordinates if available);
- Job or project number;
- Name of the sampler;
- Container pre-treatment and preservations added;
- Other observations that may affect the method or results of the analysis.

During each step of handling of the samples, a copy of the final completed Chain of Custody form is issued by the laboratory to confirm receipt and handling of the samples as part of the analytical report.

One year’s worth of operating data for the 2019 calendar year was used in this study for the 3 WWTPs that were assessed. The data included influent/effluent for different parameters as well as the rainfall data. Numerous plots of the operating data and rainfall data were plotted to establish correlations between average rainfall intensity and average flow rate, Q and also between average flow rate, Q and average influent concentrations of key parameters.

The correlation between rainfall and inflow was analysed using Pearson’s Correlation Coefficient “r”. The test measures the relationship or association between two variables. Coefficient values range between +1 to -1, where a +1 value indicates a positive relationship while -1 indicates a negative relationship and zero (0) indicates no relationship. IBM SPSS statistical tool was used to measure correlations.

3.3 Physico-chemical analysis

The typical physical characteristics include; temperature, taste, odour, colour, turbidity, dissolved solids etc. The chemical characteristics include; pH, hardness, alkalinity, acidity, chlorides, dissolved oxygen, and chemical oxygen demand (COD). The biological characteristics include; faecal Coliform (FC), Total Coliform (TC) etc. The standard analytical methods that were used to analyse various parameters are approved methods as outlined in the APHA Standard Methods (2005) (American Public Health Association, 2005). The parameters that were measured in these categories and the procedures used include the following:

3.3.1 Physical Characteristics

Total Solids

Total solids (TS) in the wastewater sample refers to all the matter that remains as residue upon evaporation to 103 to 105°C. Total solids content in wastewater exists in three different forms:

(a) suspended solids
(b) colloidal solids and
(c) dissolved solids.

Procedure

A 100 ml well-mixed sample was poured into a graduated cylinder and transferred to a pre-weighed dish (recorded the weight) and evaporated. The dish and sample were then dried at 103 – 105 °C for 1 hour in an oven and weighed. The dish was cooled in a Thermo Scientific™ Nalgene™ Transparent Polycarbonate Classic Design Desiccator from USA to ambient temperature for 20 – 30 minutes and re-weighed. The increase in the TS was then calculated as per equation 3.1 below:

$$\text{TS (mg/l)} = W_{total} - W_{dish} \times \frac{1000}{\text{ml of sample}} \qquad \text{Equation 3.1}$$

where:

W_{dish} is the weight of the dish (mg)
W_{sample} is the weight of the wet sample and dish (mg)
W_{total} is the weight of dried residue and dish (mg)

Dissolved Solids

This is the filtrate that is remaining after filtering a sample containing dissolved solids. When sewage is passed through a 2.0 µm filter, the filtrate is not clear but is turbid, because of the presence of filterable solids. This filterable-solids fraction consists of colloidal solids as well as dissolved solids.

Procedure

Samples were stirred with a magnetic stirrer and then transferred onto a glass-fibre filter (2.0 µm) with an applied vacuum. Samples were washed with three successive 10 mL of deionized water. This was followed by suction for about 3 min after filtration. Filtrate (with washings) were transferred to a weighed evaporating dish and evaporated to dryness in a drying oven (Memmert UN30-230V 32L, TE Equipment, New Jersey, USA). Samples were then cooled in a desiccator.

Suspended solids

The total suspended solids refer to the portion of total solids that are retained by a filter (non-filterable) paper when measuring total solids. The suspended solids may be further subdivided into settleable solids and non-settleable solids.

Procedure

A 100 ml well-mixed sample was poured into a 250 ml beaker. The sample was then filtered through a weighed standard glass-fibre filter (2.0 µm). The dry Gooch crucible and the residue retained on the filter were dried in an oven maintained at 103 to 105°C for at least 1 hour. The sample was then removed from the oven and cooled in a desiccator and its weight was determined. The increase in weight of the filter represents the total suspended solids. To obtain an estimate of total suspended solids, equation 3.2 was used:

$$\text{SS (mg/l)} = (\text{Weight of filter + residue}) - \text{weight of filter} \times \frac{1000}{\text{ml of filtered sample}} \qquad \text{Equation 3.2}$$

Settleable Solids

Settleable solids are the material that settles out of suspension within a defined period or that will settle to the bottom during a test.

Procedure

Well-mixed samples (one from the influent and another one from the effluent) were poured into the 1L Imhoff cone and filled to the mark. The samples were then allowed to settle for 45 minutes at the bottom and the volume of settleable solids was recorded in ml per litre of sample.

Volatile Solids (VS)

The total solids in wastewater are further categorised as fixed solids (ash) and volatile solids (organics). The residues of total, suspended, or dissolved solids tests can be used to determine the VS.

Procedure

The sample obtained from the TS test was used by placing 100 grams of the dry residues on the Gooch crucible and these were weighed. These were further ignited at 550°C in a Thermo Scientific™ Muffle furnace, made in the USA for 30 minutes. The sample was then cooled in a desiccator for 20 – 30 minutes then taken to the weighing balance and its weight was recorded. The loss of weight on ignition is due to decomposition or volatilization and represents the volatile solids. The VS was then calculated as per equations 3.3 and 3.4 below.

$$\textit{Volatile Solids (mg/l)} = W_{total}\,(mg) - W_{volatile}\,(mg) \times \frac{1000}{\textit{ml of sample}} \quad \text{Equation 3.3}$$

or

$$\text{Volatile Solids (\%)} = \frac{W_{total} - W_{volatile}}{W_{total} - W_{crucible}} \times 100 \quad \text{Equation 3.4}$$

where:

$W_{crucible}$ is the weight of the crucible (mg)

W_{total} is the weight of dried residue and crucible (mg)

$W_{volatile}$ is the weight of residue and crucible after ignition (mg)

The remaining solids represent the fixed total, dissolved, or suspended solids while the weight lost on ignition is the volatile solids. This was then stored in a desiccator until needed.

3.3.2 Chemical Characteristics

Chemical oxygen demand (COD)

This refers to the amount of oxygen needed to consume the organic and inorganic materials. Potassium dichromate ($K_2Cr_2O_7$) is considered the best oxidant due to its strong oxidizing ability. The 5 Closed Reflux laboratory coulometric methods are popular, and faster and were used where a rough estimate of a colour sample by taking three wideband readings along the visible spectrum is obtained. The amount and colour of the light absorbed depends on the properties of the solution. Hence it can find the concentration of substances since there is a linear relationship between absorbance and concentration, based on the principles of the Beer-Lambert Law (Beer’s Law). Thus, the DR 3900, Hach's benchtop colourimeter (Hach South Africa (Pty) Ltd, Johannesburg, South Africa) was used to read the COD concentration also using commercially available vials.

Procedure

Potassium hydrogen phthalate (KHP) was used as a standard reference for the colometric analysis. Most wastewater samples will fall in the high range, so standards of 100, 250, 500 and 1 000 mg/L were prepared (Lapara et al., 2000). A COD reactor/heating (150°C) block was preheated and a colorimeter are turned on so that both instruments were allowed to stabilize. The analytical standard procedure is for 50 ml of the wastewater sample which was placed in a 500-ml refluxing flask. The vials contained 25 ml potassium dichromate ($K_2Cr_2O_7$), a strong oxidant in a 5 ml mixture of 50% concentrated sulfuric acid and silver sulfate (Ag_2SO_4) as a catalyst. Prior to the analysis, it was determined if the sample contained 1 g/l of chloride. If so, then 1 g of mercuric sulfate ($HgSO_4$) was used by heating it to eliminate chloride interference. A blank sample was selected by adding all reagents to a volume of distilled water. The three vials were marked with known standard levels. Two vials were then marked for the wastewater samples, to make a duplicate run. Wastewater samples of 2 mL were added to each vial. In the case of the blanks, 2 mL of deionized water was added. Each vial was mixed well and placed into the reactor block for two hours. After two hours, the vials were removed from the block and placed on a cooling rack for about 15 minutes. The colorimeter was set and calibrated accordingly. The pre-prepared vials come in low-range (3-50 ppm) or high-range (20-1500 ppm) however, both were used given the variety of the wastewater samples analysed. Based on the amount of oxidation, the vials can change colour from orange to green (see Figure 3.3 below) when dichromate is being reduced to chromium salts (green). Then each vial was placed in the unit and the COD concentration was read.

Figure 3.3: A set-up of the COD vials used during the COD test

Oxygen Consumed

Potassium permanganate (Kr_2MnO_4) which is a strong oxidising agent was used to quantitatively determine the oxygen consumed in a wastewater sample. The analysis can be done by titration and the value determined is known as the *permanganate value* (PV4). The analysis can be used to evaluate the efficiency of the wastewater treatment.

Procedure

Using diluted wastewater 100 ml of samples and sulfuric acid solution (5.0 mL) were added to a 20 mL Erlenmeyer flask on a ratio of (1:3). With a pipette 10 mL of potassium permanganate solution (0.01 mol/L) was accurately added. The solution was heated in a boiling water bath for 30 minutes, making the water surface higher than the surface of the sample. A sodium hydroxide solution of 10 mL (0.01 mol/L) was added immediately into the flask. The mixed solution is titrated using standard potassium permanganate solution (0.01 mol/L) to reddish colour and the amount of potassium permanganate consumed is recorded on a 715 Dosimat exchange unit, made by Metrohm Ltd, in Switzerland. Chemical oxygen demand is determined by calculating the amount of potassium permanganate consumed by the difference method.

Nitrogen compounds analysis

Total Nitrogen (TN) which is regulated, is the sum of nitrate-nitrogen (NO_3-N), nitrite-nitrogen (NO_2-N), ammonia-nitrogen (NH_3-N) and organically bonded nitrogen. In the 3 WWTPs, the organic nitrogen is not analysed and in the 2 WWTPs, the ammonia free is measured in both the liquid treatment and the sludge treatment.

(a) Ammonia Nitrogen or Free Ammonia:

Ammonia nitrogen, exists either as ammonium ion (NH^{4+}) or ammonia gas (NH_3) in an aqueous solution. The titrimetric procedure for the determination of ammonia nitrogen was used where the samples were first treated by the preliminary distillation into boric acid absorbing solution. The ammonium concentration of the boric acid solution was titrated with a strong acid titrant to the pale lavender end-point of the methyl red-methylene blue indicator.

Procedure

Distillation

A borosilicate Kjeldahl glass flask of 800 mL capacity that was attached to a vertical condenser so that the outlet tip may be submerged below the surface of the receiving acid solution of boric acid. The pH was measured with the Thermo Scientific Orion Star A111 Benchtop pH Meter, which can measure the pH value and temperature for the sample. About 500 mL water and 20 mL borate buffer solution were added with 6N NaOH solution to a distillation flask to adjust the pH to 9.5. The receiving flask contained 50 mL of 0.04N H_2SO_4 while the solution was distilled at a rate of 6-10 mL/min until 200 mL of distillate was collected. The distillate was diluted to 300 mL with reagent water.

Titration

A 100 ml of wastewater sample was selected and a colour indicator was added to the sample. The sample was titrated using 0.02N sulfuric acid until the indicator turns to a pale lavender colour. The amount of acid used for the colour change is proportional to the ammonia present. The entire procedure using an ammonia-free distilled water blank was repeated.

Phosphorus

Phosphorus exists in aqueous solutions as orthophosphate, polyphosphate, and organic phosphate and the sum of all these three phosphorus species is regarded as total phosphorus. The most common class of methods for determining aqueous phosphorus concentrations, especially in routine wastewater analysis, are colorimetry-based methods and orthophosphate anion is determined by photometry. Orthophosphate is quantified by means of a photometer at 880 nm using phosphate calibration solutions of known phosphate concentrations.

Total Phosphate

Total phosphorus is determined by oxidation as well as hydrolysis prior to orthophosphate analysis.

Procedure

To determine total phosphorus, 100 ml of sample was digested using a persulfate digestion method. The digestion converts the condensed phosphate and organically bound phosphate to orthophosphate. The sample is then analyzed as described above in the orthophosphate procedure.

Orthophosphate

Procedure

Ortho-phosphate was determined using colorimetric methods where chemical reagents are used to develop the colour. The spectrophotometer was also used to measure the absorbance of the sample. The intensity of the colour of the sample after treatment is proportional to the amount of orthophosphate found in the sample.

pH analysis

The pH measurement can be done with the use of equipment that includes a pH meter with pH and reference electrode or combination electrode and standard buffers for meter calibrations. An Orion Star A111 Benchtop pH Meter, from Thermo Scientific Fischer in Massachusetts, USA was used with standard buffers of 0 to 14. The lower values (than 7) indicate high acidity and higher than 7 values indicate low acidity (more alkaline) whilst a pH of 7 indicates neutral.

Procedure

Before the measurements were taken, the pH meter with pH and reference electrode and standard buffers for meter calibrations was used. The most common buffers for calibration 4 (for acidic samples), 7 and 10 (for base samples) were selected. All the calibration data was recorded including the temperature of buffers. After ensuring that the pH was properly calibrated, 100 ml of samples from various sample locations in the sewage and sludge treatment were transferred into the beaker. The electrode was placed in the samples while stirring slowly. The electrode was left for approximately 1 - 2 minutes and once the readout had stabilised the pH was recorded.

Alkalinity

Alkalinity is usually made up of carbonate, bicarbonate, and hydroxides and it is the measure of a solution's capacity to react with a strong acid, usually sulfuric acid (H_2SO_4) to a predetermined pH. The higher the alkalinity is; the more neutralizing agent is needed to counteract it. Alkalinity was determined by the Potentiometric titration method. The alkalinity is measured both in the sewage as well as the sludge before its final disposal.

Procedure

Collected samples from the sewage and sludge treatment were used where 100 ml of samples were poured into the beaker. The pH meter was adjusted to 7 buffer then the pH was measured. A Thermo Scientific Orion Star A111 Benchtop meter was used. Then the sample was titrated with 0,02 N H_2SO_4 whilst stirring the sample during titration. When the pH read 8,3 the mls of acid used were recorded. It was noted that when the pH is more than 8.3 it contained normal alkalinity. Titration continued until a pH of 4,5 was recorded and the mls of acid used recorded. The alkalinity measurements were calculated as:

$$\text{Total alkalinity (mg/l } CaCO_3) = \text{Total mls of acid used} \times 10 \qquad \text{Equation 3.6}$$

3.3.3 Microbiological characteristics

Faecal coliform

Microbiological parameters of wastewater are extremely important for judging their pathogenic potential. The principal microorganisms of concern however, in wastewater include bacteria, fungi, algae, protozoa, worms, rotifers, crustaceans and viruses (Tchobanoglous & Schroeder, 1985). Methods for the detection of pathogenic microorganisms are tedious and complicated and are not recommended for routine use

(Greenberg et al., 1985). Therefore, indicator organisms are determined with the coliform group being a principal indicator of faecal bacteria. The analysis of the coliform group is thus given in the form of faecal coliforms units (FCU)/100 ml of wastewater sample. *Escherichia coli* (*E. coli)* is the most widely adopted potential indicator for faecal contamination in wastewater. In general, there are three techniques used to count the bacteria, namely: the membrane-filter technique, the solid medium technique (plate count method) and the liquid medium. The membrane-filter technique (MFT) was applied since it is more rapid, requires less glassware and is not labour-intensive, however, the cost of consumables is high. The membrane filtration technique is based on the principle that special filter discs with small pore sizes will retain bacteria cells which can be made to grow out to visible colonies by incubating the filter discs on a nutrient medium. Coliform organisms ferment the lactose in this medium, producing a green metallic sheen.

Procedure

Samples were sourced from the maturation ponds of the WWTPs (only 2 of the 3 WWTPs measured the E. coli) of interest where regulated 100 ml of the treated samples were used. A membrane filter with 0.45 µm (filter discs of 0.2 - 0.8 um can be used) pore width was used to filter the sample. The filter was removed from the filtration unit and transferred to a small petri dish containing a sterile absorbent pad saturated with a suitable culture medium. Commercially prepared media in liquid form (sterile ampule or other) may be used however, 1.5 g of the Endo-type media were used. Endo agar (E5399 Endo Agar, Merck KGaA, Darmstadt, Germany) medium can cause the growth of recognizable coliform colonies that can be counted after incubating at 35°C within 24 hours. The filter membrane was placed face-up on a specific broth designed to allow colonies of the indicator organisms to grow. After incubation in the inverted position, the bacterial colonies were counted and the counts were related to the volume which had been filtered. The results are counted as follows:

$$\text{Number of colonies per 100 ml} = \frac{\text{no. of colonies x 100}}{\text{volume of filtered (ml)}} \qquad \text{Equation 3.7}$$

3.4 The Biochemical methane Potential Test (BMP)

The biochemical methane potential (BMP) tests were used to determine the biogas potential of the collected substrates. The conventional BMP assays involve incubating a substrate with anaerobic bacteria for a period of 30 to 60 days commonly at 37°C whilst monitoring the production of biogas. The conventional test is, however, time and labour-consuming hence in this study, the Automatic Methane Potential Test System (AMPTS) II method was used.

3.4.1 AD Sample collection

Sewage samples were collected from various samples as shown in Figure 3.4 below.

Figure 3.4: Sludge samples used from different sample points

3.4.2 AD Sample locations

The WWTPs of interest in this study were: Kwa-Mashu, Phoenix and Verulam plants where samples were taken at various locations as per Table 3.2 below. The samples were then tightly sealed to avoid leakages, and kept in cool conditions before being transported to the Unisa, Florida campus, Johannesburg where the experiments were performed.

Table 3.2: Descriptions of sample locations

WWTPs	Description of the sample point	General Remarks
Kwa-Mashu	Thickened sludge from DAF feeding the primary digesters	The thickeners were off-line
	Primary sludge feeding the thickener	Visually the sludge looked diluted due to recent rains then
	The secondary digester cells feeding the dewatering plant	The levels in the digested sludge sump were low, the pump was started to get the flow up
Phoenix	Primary sludge feeding the primary digesters	The RAS pump was off.

	Secondary digesters	The digesters were offline
Verulam	Primary sludge to primary digesters	The RAS pump was offline
	Digested sludge from secondary digester cells	Digested sludge diverted to drying beds (no chemicals for the dewatering)

3.4.3 Automatic Methane Potential Test System (AMPTS) II method

Batch-fed AD experiments using the Automatic Methane Potential System (AMPTS II) have been widely used. The AMPTS test is highly automated and thus, is less labour-intensive, produces high-quality data since there is minimal human interface and can measure ultra-low biogas flows (Holliger et al., 2016; Raposo et al., 2011). The anaerobic digestion of the seven (7) feedstock samples was carried out in an AMPTS® II, Bioprocess Control, Sweden, shown in Figure 3.5 below.

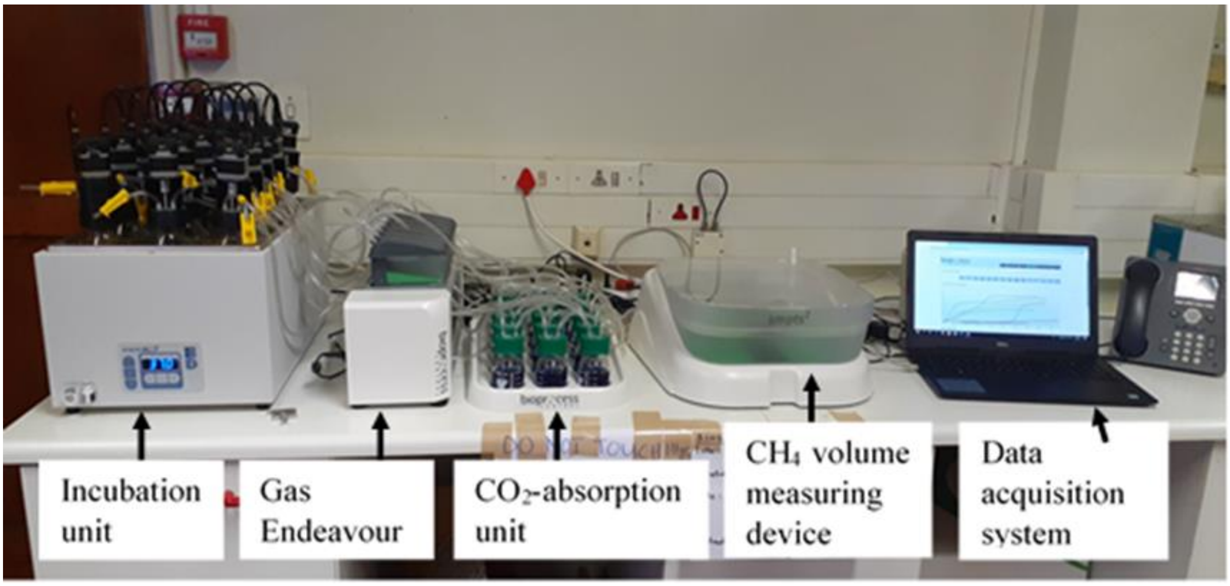


Figure 3.5: Pictorial view of the experimental unit

3.4.4 Characterisation of AD Feedstock

Before starting any BMP test, the substrates were characterized about Total Solids (TS) and Volatile Solids (VS).

Total Solids

To determine the Total Solids (TS) content of each sample, wet-measured amounts (100 g) of samples were placed on the crucibles. These samples were then placed in a preheated oven set at 105 °C for 24 hours. The dried sample was then removed and put in a desiccator to cool. Using a measuring balance, this was then re-weighed. The TS was then calculated using the equation:

$$TS\ (\%) = \frac{mdried}{mwet} \ x\ 100 \qquad \text{Equation 3.8}$$

Volatile Solids

The Volatile Solids (VS) content of the sample was determined by burning the residue. The weighed (20 g) dry matter (mdried) was placed on a crucible for about two hours at 550 °C in a pre-heated thermostatically controlled muffle oven for 2 hours. The samples were then removed from the oven, cooled and the residues were weighed. The VS were determined using the equation:

$$VS\ (\%) = \frac{mdried - mburned}{mwet} \ x\ 100 \qquad \text{Equation 3.9}$$

3.4.5 Experimental Procedure

The reactors with a total volume of 500 mL and their rubber stirring caps were thoroughly cleaned to prevent contamination. Each reactor bottle was then labelled accordingly (e.g. blank, positive control tests etc.). The potential entrained moisture was flushed out of the relevant tubing by using an air-filled 50 mL syringe, and fragments of other material were cleaned by soaking the tubing in a weak sodium hypochlorite solution. The reactors were purged with 40: 60% nitrogen-CO_2 mixture (or pure nitrogen can be used, depending on availability) for about 0.5 – 2 mins to create the anaerobic conditions. The purge ports were fitted with shortened pieces of clear PVC tubing that can be opened and closed during the purging of each bottles' headspace.

The reactors were prepared to a working volume of 400 mL where experiments were performed in triplicates. The required volumes were measured with glass measuring cylinders and beakers. The substrates were used in 12 bottles which contained primary and thickened sewage samples and the 3 remaining bottles contained only inoculum samples. As indicated earlier, digested sludge from the secondary digesters was used as inoculum. The proportions of loaded feedstock and inoculum into each vessel were varied. The CO_2-adsorption units' alkaline solutions consist of alkaline Thymolphthalein solution, which was prepared at 0.4% by dissolving 120 g of NaOH in 250 mL DI water. The complete alkaline solution was then prepared by adding 5.0 mL of 0.4% Thymolphthalein to 1.0 L of 3.0 M

NaOH. Thymolphthalein pH indicator was used to absorb CO_2 and H_2S in the CO_2 – absorbing unit.

The AMPTS II software was used to input the test conditions for each set of triplicate tests. On the system's Experiment web page input data such as ISR and the volatile solids (% w/w) or COD (g/L) content were inputted on the system, which displayed the calculated proportions of substrate and inoculum to add per bottle per test type. The Inoculum: Substrate ratio (ISR) of 1.0, 1.2 and 1.3 were used based on both samples' organic contents (VS or COD).

The reactor bottles were placed in the water bath and each biogas outlet port was connected to the Gas Endeavour (GE) unit via clear PVC tubing. All gas line connections to the GE and AMPTS II units were checked to ensure no gas leaks would occur. The water bath and the flotation unit were filled up to the required water level and AD was set to run at ± 37 ^{o}C. Once all reactors' gas lines were made secure each DC motor head was connected with power cables. The main power cable protruding from the motor controller unit was then connected to one of the reactor's motor heads to interpret speed signals from the GE and AMPTS II, as well as for controlling stirring speed. Reactors were agitated for 60 mins at 60 rev/min after every 2 hours over 30 days.

Gas is measured through water displacement using flow cells that generate and record a digital pulse for every 2 ml of gas that flows. The automatic logging of data was initialized on the AMPTS II computer which captures the biogas production (NmL/d) and cumulative biogas potential volume (Nml). Experiments were terminated when the mean daily biogas production over three consecutive days was less than 2 % of the cumulative biogas potential. An integrated embedded data acquisition system was used to record, display and allow the downloading of the results (raw data) in CSV or Excel file format.

CHAPTER 4

This chapter presents the findings from experimental work carried out as outlined in the methodologies described in Chapter 3. The results would be provided with the associated discussions. The analysis includes the characterisation of the conventional wastewater treatment processes (defined as preliminary, primary, and secondary treatment) performed in eThekwini Scientific Laboratory Services. The sludge feedstock characterisation for bench-scale tests for biogas estimations was done on the AMPTS at the Unisa laboratory, in Johannesburg.

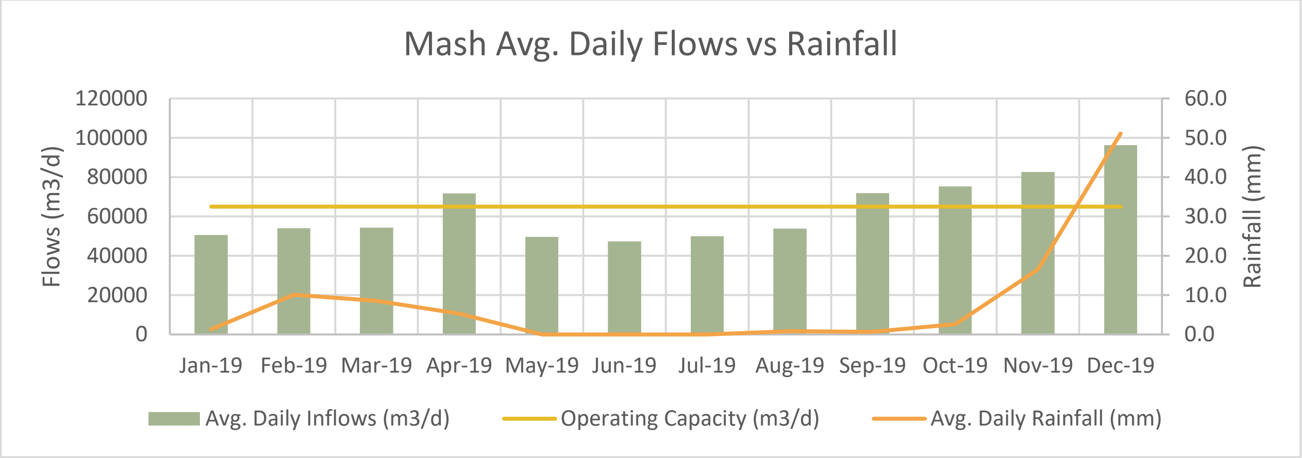
4.1 Influent wastewater and wet weather flows

Municipal sewage flows emanate from domestic and industrial wastewater and these may include storm water run-off contributing to the total quantity of the wastewater. The wet weather flows treatment systems are designed almost similar to conventional activated sludge systems with the key differences being the intermittent flows (Tchobanoglous et al., 2002). Sewage systems are categorised as Sanitary Sewer Systems (SSS) or Combined Sewer Systems (CSS) based on their capacity to deal with stormwater during wet weather events. The CSS are more common in affluent, subtropical regions where all rainwater discharge is directed to sewers (Lele et al., 2015).

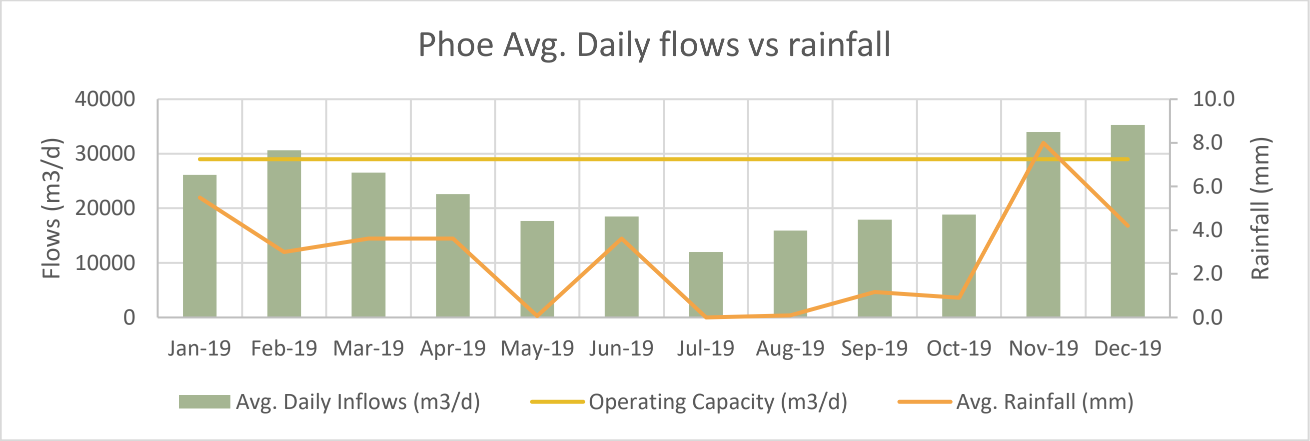
Inflow and infiltration (I/I) are two mechanisms that stormwater can enter the wastewater treatment plants (WWTPs) flowing through manholes, cracked and/or leaking pipes, and improper connections (Water Environment Federation. Sanitary Sewer Overflow Cooperative Workgroup, 1999). The I/I is unwanted and can account for a substantial amount entering the sewer system. In South Africa the rainfall is both spatial and temporal with the rainy season mostly in October through to April with December, January and February regarded as the wettest months (Mengistu et al., 2021). The rainfall is not consistent hence it is possible to have rainfall outside the rainy periods.

The influent in the 3 WWTPs included domestic, industrial contributions and stormwater run-off. As such the flow patterns of the influent will vary in composition and flow rates due to diurnal and seasonal variations. This can be attributed to the behavioural patterns of the communities and the rainfall patterns. Thus, the operating data for the 3 WWTPs analysed where total monthly sewage flows and the rainfall data were used to get the average daily flows. Figure 4.1, shows plots of the influent flows vs rainfall for Kwa-Mashu WWTP, which has a total design capacity of 65 MGD with anticipated 2030 future flows of 90 MGD; Verulam WWTP, which has a design capacity of 8 MGD and an additional 4 MGD circular activated sludge plant, the latter operating when the influent wastewater exceeds 8 MGD and Phoenix WWTP that has an operating capacity of 29 MGD:

a)



b)



c)

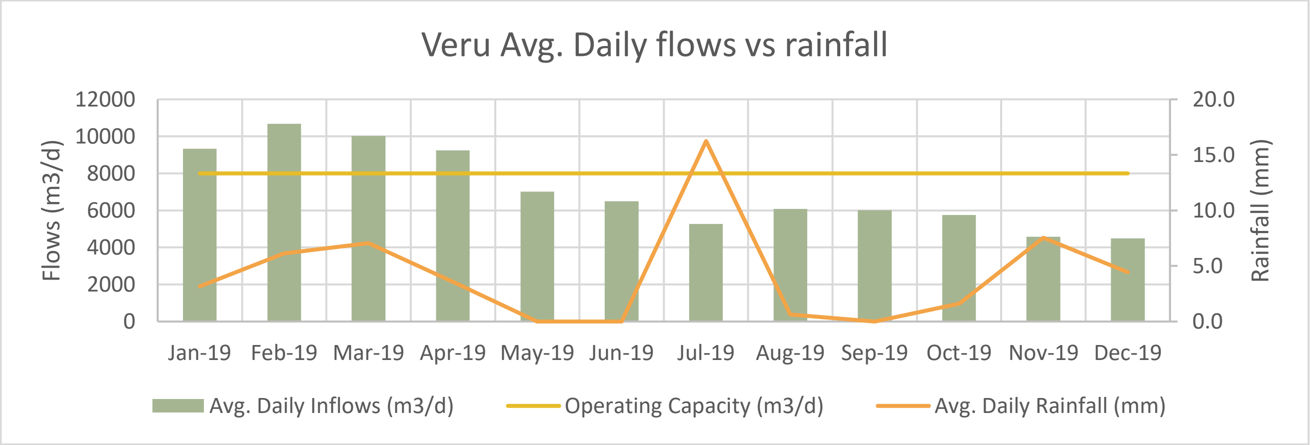


Figure 4.1: Average daily flow rates vs Rainfall as a function of time in a) Kwa-Mashu WWTP (Mash) b) Phoenix WWTP (Phoe) and c) Verulam WWTP (Veru).

In Kwa-Mashu and Phoenix WWTPs though not pronounced during the rainy months the average daily sewage flow increases were observed as well as the rainfall increase. From October to December Mashu WWTP influent flows increased as the rainfall increased, hence the sharp spikes in both the influent and rainfall curves. The average daily flows in October, November and December, were exceeded by 14%, 21% and 33% respectively. A study showed that during one particular storm event showed that the flow to the activated sludge treatment plant was approximately 3.08 times the dry weather flow (DWF) (Berthouex & Fan, 1986a). In April the flows were high however, the rainfall received was relatively not that high compared to February where average rainfall of 10,1 mm was recorded.

Phoenix also recorded high inflows in the summer months, with November and December where 34 MGD and 35 MGD, respectively recorded. These increases in the wastewater flows corresponded with the average rainfall of 8 mm and 4,2 mm recorded in November and December, respectively. Similarly, in February the influent flows were high.

As indicated some catchments receive rainfall outside the rainy season. In Verulam for instance the highest influent flows were recorded in February and March. In July however, an average rainfall of 16,2 mm, was recorded hence the sharp spike in figure 4.1c above. From January to April as well as in November substantial rainfall was registered.

Using the IBM SPSS statistical package, a statistical analysis for the 3 WWTPs was performed with the results contained in Table 4.1. Accordingly, Verulam WWTP showed a weak/small correlation (negative relationship) between rainfall and inflow, while Phoenix WWTP also had a weak/small correlation (positive relationship). On the other hand, Kwa-Mashu WWTP showed a strong/large correlation.

Table 4.1: Pearson’s Correlation Coefficient

WWTP	Pearson’s Correlation Coefficient	Description
Verulam	-0.42	Weak/small Negative linear relationship
Phoenix	0.164	Weak/small Positive linear relationship
Kwa-Mashu	0.756	Strong/large Positive linear relationship

Thus these observations confirmed the seasonal variations as a result of the impact of the rainfall on the influent flows volumes in the 3 WWTPs.

4.2 Stormwater impact on the influent wastewater quality

Storm water run offs to the municipal WWTPs not only add to the total influent flow rate but also change its water quality. Stormwater carries pollutants which impact the treatment capacity and failure not to have capacity, may result in a short-term risk of non-compliance by the WWTPs (Tchobanoglous et al., 2002). The characterisation of the influent wastewater flow is critical to assess the capacity to treat the additional pollutant loading related to stormwater contribution. Table 4.2 shows the comparison between the constituent composition of the stormwater runoff and untreated municipal wastewater with industrial contributions. Meanwhile Rouleau et al (1997), in their investigations on stormwater events, found that the wastewater flows also impacted the particulate matter (Rouleau et al., 1997a). Thus, the discrepancy in the concentration of the pollutants in the stormwater run-off can be attributed to the diluting effect on the quality of the wastewater.

Table 4.2: Comparison of stormwater run-off and municipal wastewater

Parameter	Unit	Stormwater Runoff	Municipal Wastewater
Total Suspended Solids (TSS)	mg/L	67 - 101	120 - 370
Chemical Oxygen Demand (COD)	mg/L	40 - 73	260 - 900
Total Kjeldahl Nitrogen (TKN)	mg/L	0.43 - 1.00	20 - 705
Fecal Coliform (FC) Bacteria	MPN/100mL	10^3 -10^4	10^5 -10^7
Phosphorous	mg/L	0.67 - 1.66	4 - 12

To characterise influent wastewater, COD, NH_3 and SS were evaluated as shown in Figure 4.2 a – c plotting flows) vs influent concentrations over the 12 months' period:

a.

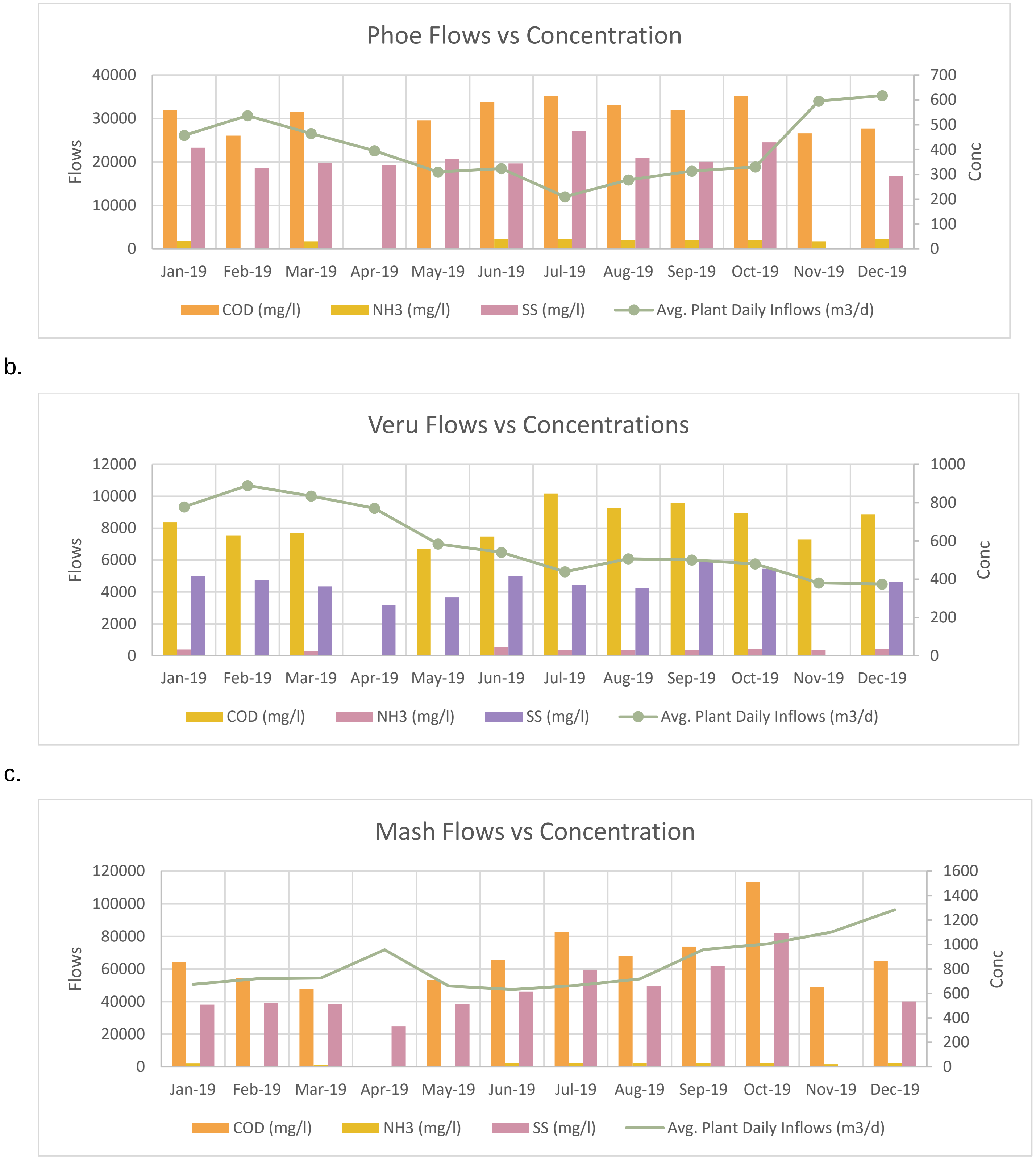


Figure 4.2: Plots of average inflows and concentration (COD – chemical oxygen demand, NH_3 – ammonia and SS – suspended solids vs time a) Verulam WWTP (Veru) b) Phoenix WWTP (Phoe) c) Kwa-Mashu WWTP (Mash).

Kwa-Mashu WWTP generally receives about 60% of its influent from both domestic wastewater and industrial wastewater from 11 various industries (refer to Chapter 3 Section 3.1.1). The effluent from the leather industries known to be using chemicals like chrome and caustic soda as well as effluent from food industries are known for high COD content. The COD and the SS were variable during the sampling period, in July and October however, with COD concentrations at 1 099 and 1 553 mg/l, respectively which were also in line with the increase in the daily averages but not the rainfall. In July rainfall of zero (0) was recorded though in October 51.1 mm (the highest for the year) was recorded. Meanwhile, the COD levels in Phoenix and Verulam WWTPs were also fluctuating throughout the sampling period. Phoenix recorded the maximum concentration for COD of 615 mg/l which corresponded with the average rainfall of 3.6 mm and Verulam 849 mg/l corresponding with 16.2 mm in July/October and July, respectively.

The increases in the COD concentrations do not show any correlation between the rainfall and the COD increases as some increases occurred during the dry seasons. It should be noted, however, that the 3 WWTPs assessed treat both domestic wastewater, the stormwater run-off and also receive the trade effluent contributions from the surrounding industries. As can be seen in Table 4.3 below, compared to domestic wastewater in Table 4.2, the influent with industrial contributions is characterised by high concentrations of carbon dioxide (COD), ammonia (NH_3) and suspended solids (SS) (Metcalf & Eddy Inc. et al., 2003):

Table 4.3: Typical composition of the municipal wastewater

Parameter	Concentration (mg/l)		
	Strong	Medium	Weak
Total solids	1200	700	350
Total Dissolved Solids (TDS)	850	500	250
Suspended solids	350	200	10
Nitrogen (as N)	85	40	20
Phosphorus (as P)	20	10	6
Chloride	100	50	30
Alkalinity	200	100	50
Grease	150	100	50
BOD_5	300	200	1

The ratio of BOD_5:COD used for raw domestic wastewater is normally 0.5:1, for municipal raw wastewater the biodegradability index varies from 0.4 to 0.8 and for industrial wastewater, the ratio of 10:1 will apply (Metcalf & Eddy Inc. et al., 2003). Thus, the 3 WWTPs assessed did not conform to the domestic wastewater concentrations and their COD concentrations were in line with those in literature (Table 4.2), confirming industrial wastewater contributions. In a study on fifteen well-operated WWTPs, it was found that high influent flows resulted in 11% more in BOD, which was also an indication of high content of organic fraction due to industrial contributions (Berthouex & Fan, 1986a). High COD concentrations in the influent wastewater are beneficial to the AD process though.

In Verulam the NH_3 concentration ranged between 30 and 44 mg/l, in Phoenix 31 to 41 mg/l and Kwa-Mashu the concentration was between 17 and 33 mg/l, which were all within the range for the untreated sewage. The highest NH_3 in the 3 WWTPs did not, however, correspond with the increases in either the average daily flows or the rainfall. The only exception was in Kwa-Mashu where the highest NH_3 occurred in December when the plant also received the highest flows and rainfall. Generally, ammonia, which is the most used form of inorganic nitrogen, is found in the influent in the WWTPs due to the ammonification and hydrolysis taking place in the sewer system (von Sperling et al., 2005). The ammonification and hydrolysis involve the conversion of the rapidly biodegradable soluble nitrogenous matter by heterotrophic bacteria and the conversion of slowly biodegradable particulate matter by autotrophic bacteria, respectively. At a concentration of less than 200 mg/l in the influent, it is regarded as beneficial for the AD (Wang, 2016). Notably in February, there were no measurements for NH_3 in the 3 WWTPs which coincided with high influent and rainfall flows recorded in the same month. The most common source of NH_3-rich wastewater is the fertiliser run-off from the municipal WWTPs. The influent NH_3 concentrations in the 3 WWTPs do not show a strong presence of industrial contributions in terms of Table 4.2. Thus the presence of NH_3 can be attributed to the transformations in the sewer system.

Investigations to elucidate the relationship between flow rate and influent wastewater characteristics have not been well documented in the literature. Regarding the suspended solids (SS) characterisation in the influent Berthouex and Fan (1986) in a study they conducted found that high influent flows resulted in 19% in TSS plant upsets (Berthouex &

Fan, 1986b). These consisted of TSS and COD, along with a dilutional effect on dissolved pollutants such as ammonia (Rouleau et al., 1997a). In our study, the 3 WWTPs recorded high concentrations of SS in the influent. The concentration of the SS in Kwa-Mashu ranged between 331 and 1 095 mg/l while Phoenix and Verulam had the highest concentrations of SS at 476 and 493 mg/l, respectively. The SS concentrations in the 3 WWTPs assessed were different from those found in the literature (Table 4.2 and Table 4.3), they were higher than those with industrial contributions. Some authors report that in municipal wastewater about 57% of the influent COD contains suspended solids (Berthouex & Fan, 1986b). Suspended solids in the industrial wastewater are associated with food processing factories and car wash operations, which are found in the catchments of the 3 WWTPs. Thus the 3 WWTPs SS concentrations were higher probably due to the contributions from industrial wastewater as well as from the fraction of the influent COD which was high in the first place.

The total phosphorus (TP) includes orthophosphate, polyphosphate, and organic phosphate. The influent characterisation of the total phosphorus was done by plotting the influent concentrations of orthophosphate and TP vs the time during the 12 months sampling period, in Figure 4.3.

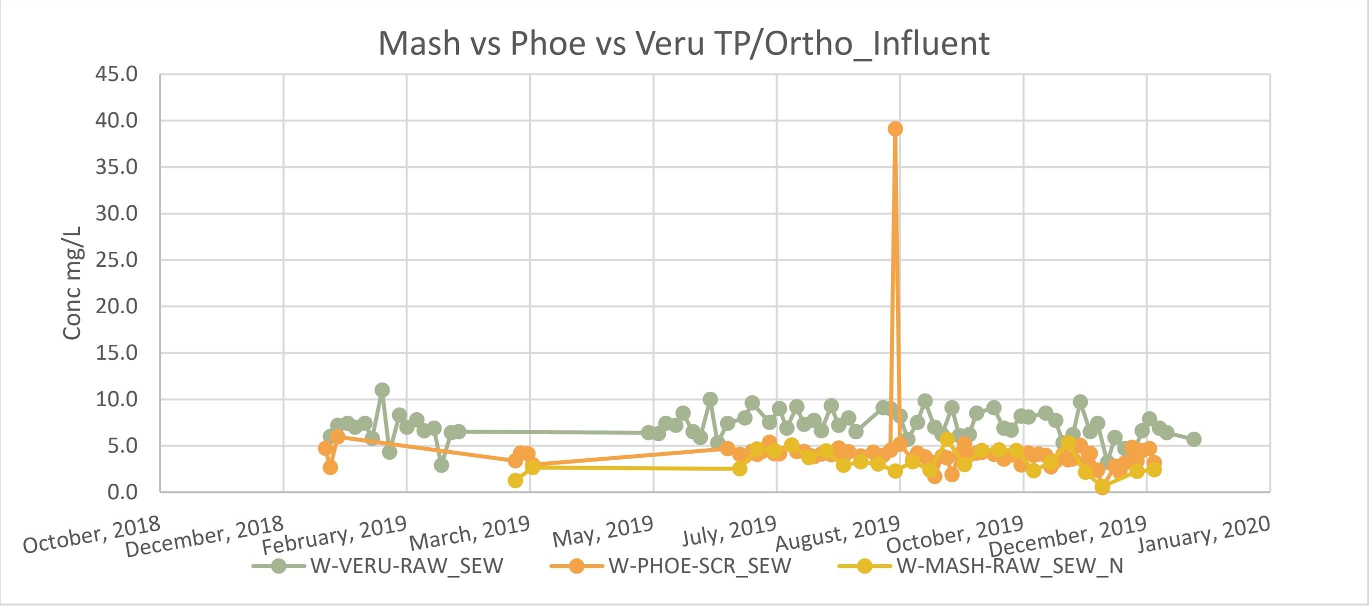


Figure 4.3: Graph of phosphorus concentration expressed as Total Phosphate and Orthophosphate in Verulam (Veru), Phoenix (Phoe) and Kwa-Mashu (Mash) WWTPs.

Typical concentrations of orthophosphate in municipal wastewater are between 4 – 12 mg/l (refer to Table 4.2) above. Thus, the total phosphorus concentrations, which included all the 3 forms in the 3 WWTPs assessed did not vary much throughout the seasons. They ranged from 10 mg/l with an outlier of 39.12 mg/l recorded in the Phoenix WWTP on the 21st August 2019. Compared to other types of wastewater, they were higher. Phosphorus compounds are generally associated with diverse non-point sources from the use of chemicals in the fertilisers in the agriculture sector and domestic wastewater. Phoenix receives 70% domestic wastewater and 30% industrial contributions (refer to Chapter 3 Section 3.1.1). Thus, the high levels in the influent can be attributed to the use of phosphate-based detergents from domestic usage.

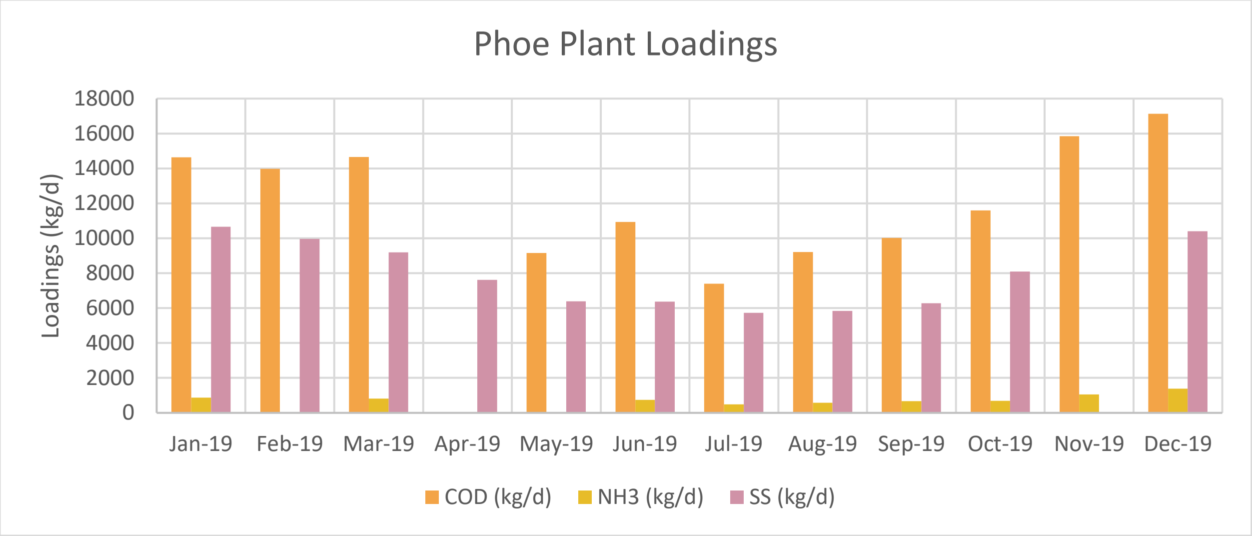
Thus, though the stormwater impacts on the quality of the influent wastewater in the short term including on the treatment capacity of the WWTP, there were no significant correlations between the influent pollutants loads and the rainfall in the wastewater. Therefore, the variations in the pollutant's loads could be attributed to the industries in the catchment of the 3 WWTPs.

4.3 Wastewater Constituent Mass Loading

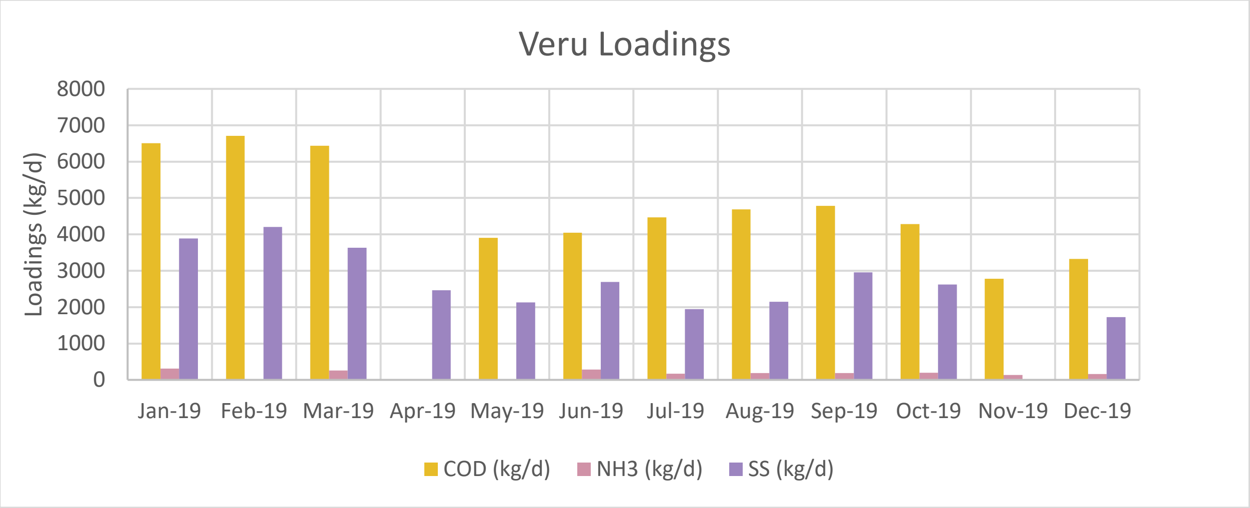
There are different types of loading rates and the wastewater constituent mass loadings are at least as important as hydraulic loading rates Siegrist et al., (1984). Loading rates are critical in the design process of treatment units to better understand the behaviour of the system however, they can still be applied to existing WWTPs. The values of the actual loading rates which are likely to be different from the desired target even if the input flow or the input concentrations are to be controlled are compared with the recommended values from the literature which are specific to each process.

Mass organic loading is determined by using the formula contained in Appendix B, meaning that they factor in the flow rates. Mass loading (kg/d) is applied to the plant-influent wastewater flowrates (Q) but it can also be applied to the effluent to assess the performance of the WWTP. The loads were plotted against the concentrations over the sampling period as shown in Figure 4.4 below. The parameters that were assessed in the 3 WWTPs were COD, SS, and NH_3 over the 12-month assessment period.

a)



b)



c)

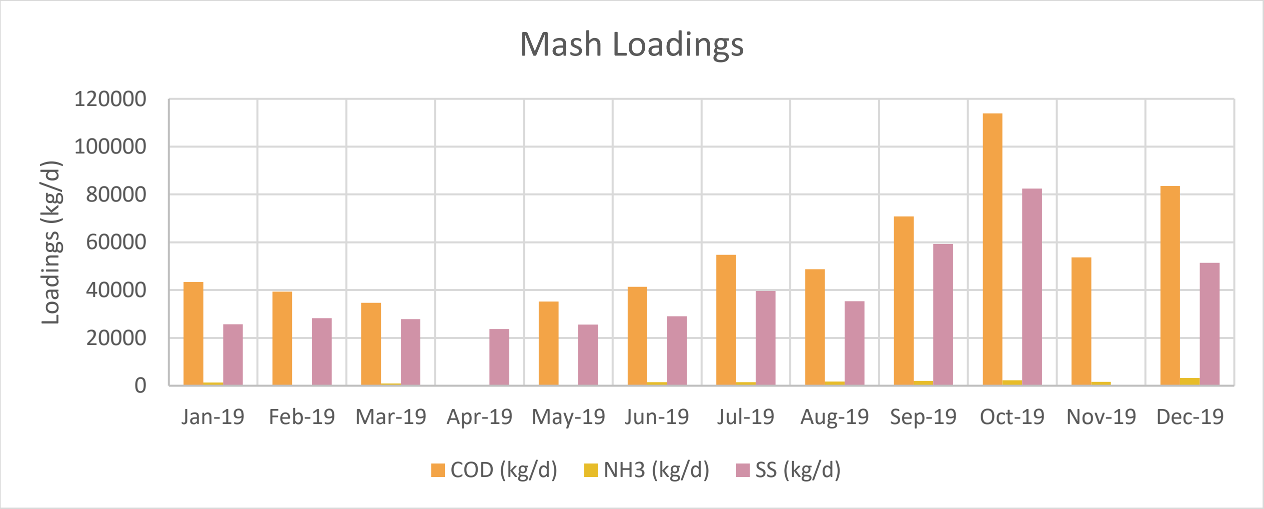


Figure 4.4: Mass Loadings as a function of time in a) Phoenix WWTP (Phoe) b) Verulam WWTP (Veru) c) Mash Kwa-Mashu WWTP (Mash)

The analysis of the 3 influent parameters, viz.: COD, SS and NH_3 for Kwa-Mashu during the summer months are high. The COD loading rates for the 3 WWTPs were high in October with Kwa-Mashu having the highest COD loading at 113 856 kg/d (as was seen in figure 4.2 c) followed by Phoenix and Verulam at 11 597 and 4 279 kg/d, respectively. Kwa-Mashu in October recorded rainfall of 81 mm whilst in the same month its influent COD concentration load was 1 513 mg/l, the highest in that year. This suggests that the significant increase in the influent load is due to wet weather flows. The influent mass loads in the WWTP examined by Rouleau et al (1997) for TSS, BOD, and NH_3 were found to be 10, 7, and 1.2, respectively times greater than the dry weather loads (DWL) Rouleau et al., (1997b). Thus, these two factors, hydraulic load due to seasonal variations and the industrial wastewater could be attributed to the high mass COD loading in the 3 WWTPs assessed.

Turbidity is related to the SS concentrations, thus the measure of SS indicates a high microbial load (Tchobanoglous et al., 2002). The highest loads in SS were 82 447 mg/l in October for Kwa-Mashu, at Phoenix 10 656 mg/l in January and at Verulam 4 206 mg/l in February, which were in wet seasons. This suggests that the loads increased with seasons and the performance of the 3 WWTPs might be impacted accordingly.

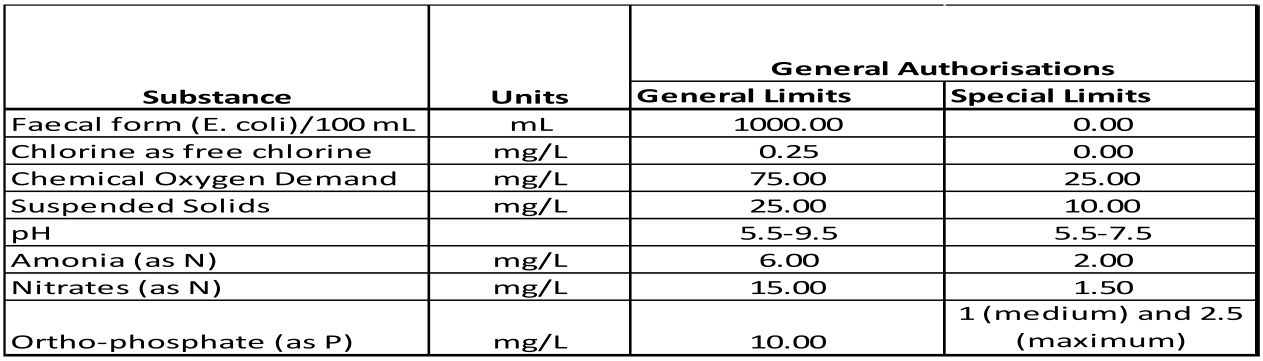
Meanwhile, Phoenix NH_3 loads were the highest at 1 376 mg/l in December, in Verulam 313 mg/l in January and Kwa-Mashu 3 178 mg/l in December. Most of the nitrogen in the influent is in the ammonia form. These increased loads for all the parameters were recorded during the wet seasons thus confirming the correlation between loads and the seasonal variations.

4.4 Treatment Efficiency – Percentage removal

Compliance of final effluent with regulatory standards is critical hence wastewater needs to be adequately treated prior to being discharged into the environment. In South Africa, the compliance of a plant to regulatory standards is critical to improve treatment processes hence the regulatory standards are used to measure the quality of the effluent processes (Agyemang et al., 2013). Hence monitoring of indicator parameters before the final effluent is discharged to the receiving water body assists in protecting the environment. Table 4.3 below shows the parameter values according to the South African General Authorizations (GA) for general and special limits.

Plant performance may fluctuate throughout the year. Whilst the influent flow rates are commonly used for design purposes; however, for performance assessment, both the average influent and effluent flow rates are normally used. As such this study analysed the influent and final effluent data of the 4 key parameters: COD, oxygen consumed (PV4), NH_3 and SS were analysed in the 3 WWTPs to determine their treatment efficiency, see Figure 4.4 a – c. Table 4.4 below was used to assess the effluent removal in the 3 WWTPs.

Table 4.4: South African General Authorizations (GA) for general and special limits



Substance	Units	General Authorisations	
		General Limits	Special Limits
Faecal form (E. coli)/100 mL	mL	1000.00	0.00
Chlorine as free chlorine	mg/L	0.25	0.00
Chemical Oxygen Demand	mg/L	75.00	25.00
Suspended Solids	mg/L	25.00	10.00
pH		5.5-9.5	5.5-7.5
Amonia (as N)	mg/L	6.00	2.00
Nitrates (as N)	mg/L	15.00	1.50
Ortho-phosphate (as P)	mg/L	10.00	1 (medium) and 2.5 (maximum)

The municipal wastewater effluents contain high amounts of organic matter and if discharged into natural water bodies, would be harmful to aquatic species. High COD in the effluent will deplete the receiving environment of the dissolved oxygen leading to mortality and hence it is also a good indicator to evaluate the treatment efficiency of the WWTP (Edokpayi et al., 2017).

The oxygen consumed (PV4) test is a measure to test the strength and the quantity of oxygen consumption in the wastewater. The standard potassium permanganate is used as an oxidant to liberate the oxygen in the wastewater (Edokpayi et al., 2017). The test, however, does not give the total oxygen needed for the biological oxidation of all or the bulk of the organic matter.

Suspended matter present in sewage tends to blanket the stream thereby interfering with the spawning of fish and reduction of aquatic biota. The Suspended Solids (SS) in the influent assist to assess the water quality whilst in the effluent it assesses plant performance processes (Agyemang et al., 2013).

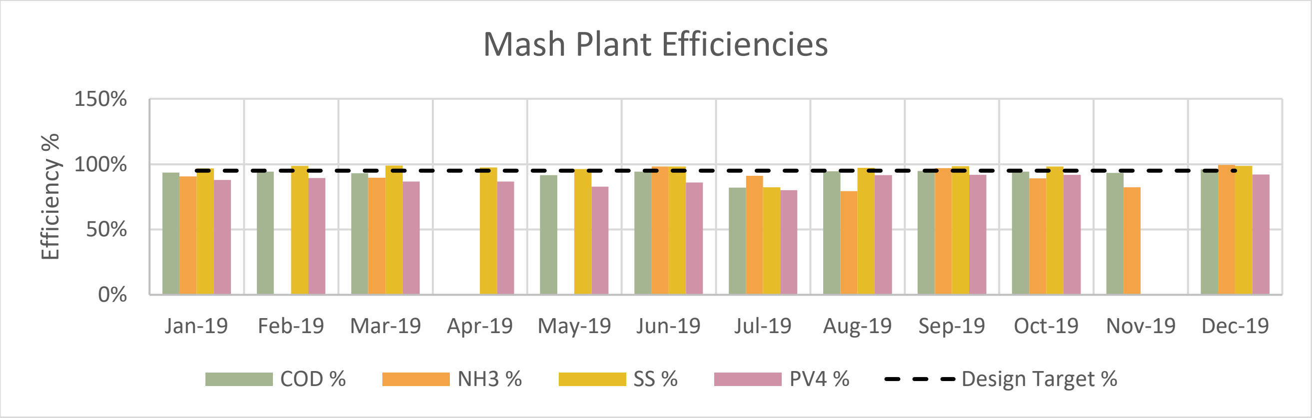
Ammonia exerts pressure on the wastewater by depleting dissolved oxygen and when discharged with the effluent it affects the aquatic ecosystem hence it is advisable to remove it. Conventional activated sludge secondary treatment processes incorporate nitrification into the treatment process. During nitrification the oxygen demand of the system increases, to supply to the activated sludge system (Agyemang et al., 2013).

The treatment efficiency which is the rate the key parameters (COD, PV4, NH_3 and SS) are being removed or reduced was determined, using equation 4.1 below, by analysing the influent and final effluent data (Appendix A and B). The desired treatment efficiency target for each parameter was set at 95% for all the 3 WWTPs that were assessed.

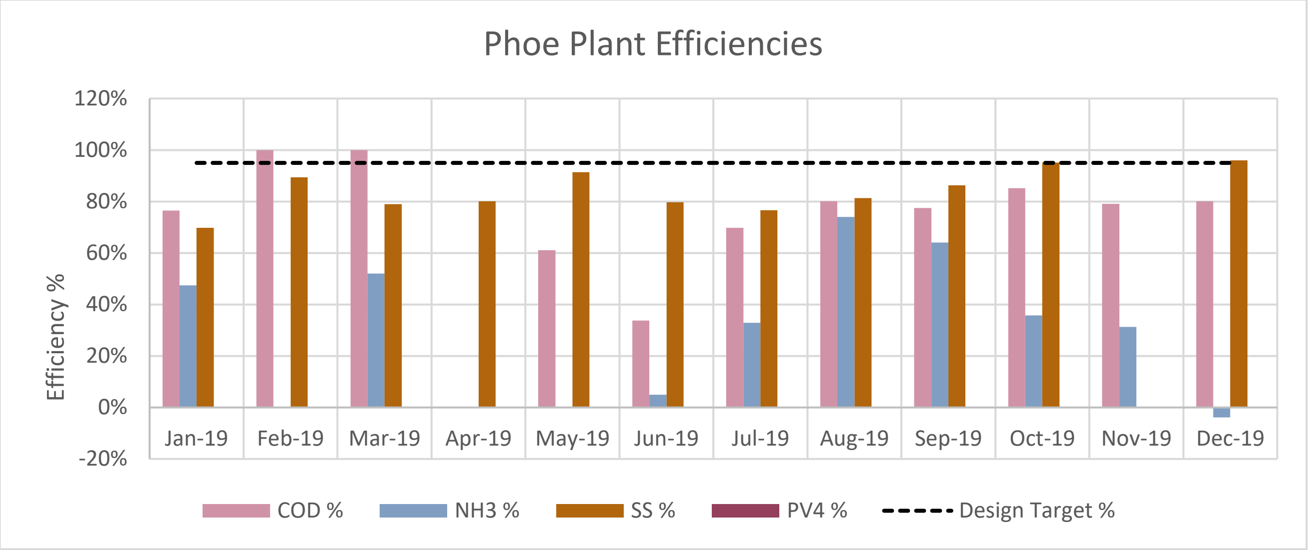
$$\text{Per cent Removal (\%)} = \frac{\text{Influent} - \text{Effluent}}{\text{Influent}} x\ 100 \qquad \text{Equation 4.1}$$

In order to plot the graphs, figures 4.5 a–c the influent and effluent data in Appendix C was used where the removal percentage of each parameter was compared to the design target set by the licence conditions of the 3 WWTPs:

a.



b.



c.

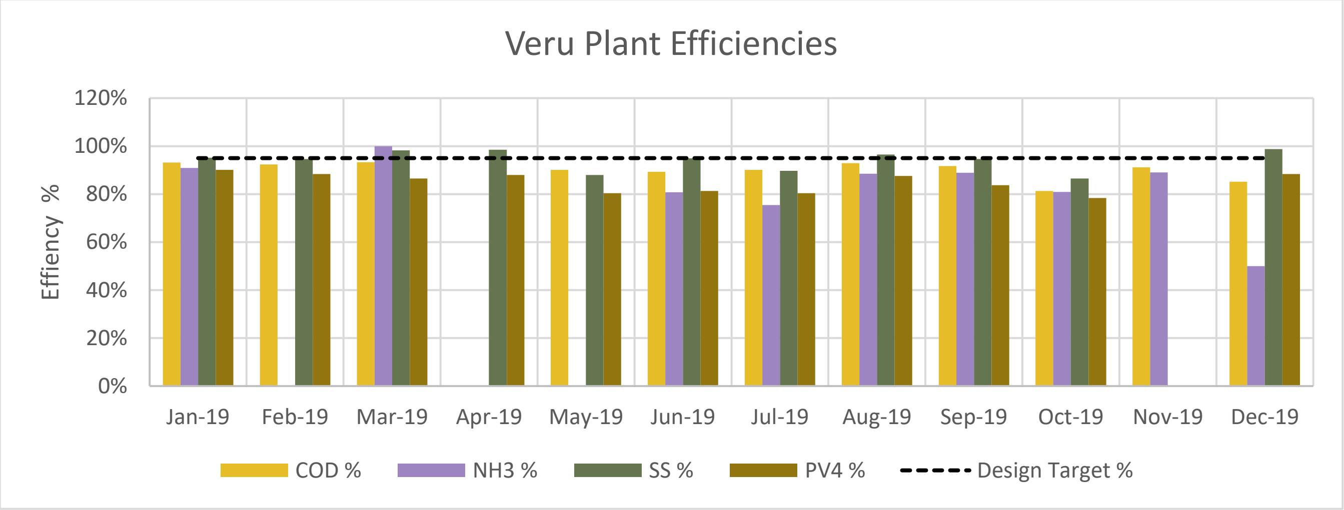


Figure 4.5: Plots of Plant Treatment Efficiencies in terms of concentrations of COD, NH3, SS and PV4 as a function of time in a) Kwa-Mashu b) Phoenix c) Verulam WWTTPs

The 3 studied WWTPs displayed varied concentrations and flows in both the influent and the effluent, used to calculate mass loadings as such their overall plant treatment efficiencies were varied as well. In a study by Phang et al (2000), BOD, COD and TSS concentrations in the final effluent of the wastewater as high as 910 - 1300, 780 - 5130 and 19 - 20000 mg/l could be found Phang et al., (2000).

Kwa-Mashu WWTP contained high concentrations of COD and was the highest whilst Phoenix in comparison to the other 2, had relatively lower concentrations of COD in the influent. Kwa-Mashu however, performed better than the rest in the removal of the COD in the effluent in all the seasons, ranging from 82 – 96% whilst the influent COD concentration was relatively high ranging from 719,4 mg/l – 960 mg/l. It must be noted that in April there were no records taken for the COD in the influent. The 96% COD removal efficiency, of Kwa-Mashu was achieved in December, however, this was when the total monthly rainfall received was the highest (1 584 mm). The total monthly COD influent received in December was, however, the lowest (719,4 mg/l).

In their study, Giokas et al (2002) investigated the effect of influent wastewater flow variation on treatment plant performance Giokas et al., (2002).

The 3-year study concluded that treatment plant performance decreased during increased flows that were associated with rainfall events. Decreased performance at high flows was primarily attributed to decreased detention times in the treatment processes.

The performance of Kwa-Mashu suggests that the seasonal variations are not the only contributing factors to its performance. In activated sludge processes, the retention time and the biomass rate (food-to-mass ratio, F/M) are important, a higher F/M ratio results in a lower SRT. Hence, for municipal wastewater which is normally designed for 20 – 30 days, they operate at 0.10 – 0.05 g BOD/g VSS.d F/M ratio while for systems with 5 – 6 days SRT they operate at 0.3 – 0.5 g BOD/g VSS.d F/M ratio (Metcalf & Eddy Inc. et al., 2003). Thus, the treatment efficiency is related to the COD concentration as well as the SRT. This could not be attributed to significant rainfall that was registered in that month either.

As indicated COD in Phoenix WWTP was generally low including in the influent. The treatment efficiency, however, was still low, ranging between 34% to 100% in February and in March. In February and March, the graphs show 100% results. It should be noted, however, that these were default values since there were records of final effluent data in February and March 2019. Again same as Kwa-Mashu the removal target was not met in April since there were no influent records. Thus, the highest true treatment efficiency achieved was 85% recorded in October.

Verulam COD removal ranged from 85% to 93% whilst according to figure 4.1c in April it received an average daily flow of 9 249 m^3/d and thus exceeded its operating capacity. The conditions applicable to the plant performance in Kwa-Mashu can be attributed to Phoenix and Verulam.

Adequate time is required for floc formation to facilitate biomass growth thus solid retention time is critical. Thus at 20 ^{o}C temperatures and 10 ^{o}C between 2.5 to 3.0 and 3.0 to 5.0 days are required, respectively for flocs to form (Metcalf & Eddy Inc. et al., 2003). Thus, effluent SS concentration of less than 30 mg/l is aimed for.

The SS removal efficiency in Kwa-Mashu was exceptionally well above the design target of 95% for most times except for July where the parameter removal was 82% while in February and March, it achieved 99% removal.

The SS removal reduction in Phoenix and Verulam ranged between 70 - 98% and 87 – 99%, respectively. The lowest removal efficiency in Phoenix was recorded in January which also corresponds to the low removal efficiency of COD. The same was observed in Verulam and Kwa-Mashu WWTPs. It should be noted that in November the SS parameter removal target for all 3 WWTPs was not met due to a lack of both influent and final effluent data which could be due to operational challenges.

Suspended solids can be estimated from the COD fraction, where it is estimated that in municipal wastewater about 57% of the influent COD is comprised of the SS (Berthouex & Fan, 1986b). Thus the removal performance of the SS can be attributed to the amount of COD found in the influent.

Nitrification, is generally accomplished in the biological secondary treatment process. The operations of these processes, however, can be modified. This results in increases in the sludge age as well as the retention time. Also, when the process includes AD, it must be noted that the centrate from the AD processes to the secondary treatment may contain a significant amount of NH_3 (Metcalf & Eddy Inc. et al., 2003).

Phoenix's overall plant ammonia removal was consistently low during the entire sampling period. It ranged between -4% in December 2019 and the highest removal for NH_3 was 74% in August. It was observed that it had received an average total monthly NH_3 concentration of 39 mg/l in the influent whilst the effluent concentration was higher, 42.5 mg/l (refer to appendix C and D). The low treatment efficiency is also explained by the fact the effluent had exceeded the Guideline's general limits of 6.00 mg/l for general and special limits of 2.00 mg/l (see Table 4.3 above). The NH_3 removal in the other 2 WWTPs was also not in compliance in most cases. In Verulam though, the lowest it achieved was 50% NH_3 removal efficiency it never met the 95% design target, nor the effluent limits. It only got 91% in January 2019 thus meeting the general limits by achieving the 3.1 mg/l NH_3 discharge. Kwa-Mashu removal efficiency for NH_3 ranged between 72% and 99%, exceeding the design target 3 out of 9 times it was measured. Interestingly it only exceeded the general effluent discharge limits of 6.00 mg/l once in August, discharging at 6.5 mg/l.

Thus, it could be argued that the increased NH_3 in the effluent in most cases could have been due to poor nitrification or the increased recycle flows of the centrate from the AD processes. Nitrification is sensitive to pH, thus it could be that the pH was low.

Together with the COD and the BOD, the PV4 is also amongst the parameters used to test the strength of the wastewater. Unlike the COD test, the Permanganate Value (PV4) test is the oxygen absorbed (OA) with the aid of Potassium permanganate (Kr_2MnO_4), hence also known as the OA. Though simple in the PV4 test some compounds are only partially oxidised test hence a full COD test is universally accepted and preferred (Metcalf & Eddy Inc. et al., 2003). Table 4.5 below illustrates the response of the values for COD, BOD and PV4 to pure organic compounds:

Table 4.5: Comparison of BOD, PV, and COD, adapted from Metcalf & Eddy Inc et al (2003)

Substrate	Values as per cent of theoretical		
	BOD	PV	COD
Benzene Sulphonic Acid	63,6	0.00	91,6
Acetic Acid	58,0	0.00	93,5
Phenol	69,7	80,1	96,0
Ethyl Alcohol	69,9	4,7	95,9
Acetone	67,5	0.00	92,2
Toluene	39,2	0.00	60,0
Diphenyl Guanidine	2,3	59,6	101,6

Some municipalities, like eThekwini municipality, perform both tests even though the PV4 is for benchmarking. The effluent discharge limit for the PV4, is 10 mg/l for general limits only.

The oxygen consumption in the wastewater is an indication of the presence of a high microbial load in the final effluent.

The PV4 removal in Phoenix WWTP showed default results during the monitoring period because only the final effluent (Pond 6) is being measured. It must be noted, however, that the effluent at this sampling point the maximum PV4 value recorded was 12.9 mg/l in January. In Kwa-Mashu and Verulam WWTPs the PV4 test was done in the raw sewage and other sampling points. Kwa-Mashu has 3 ponds in series and thus the final effluent is tested in Pond 3. In Verulam, the treated effluent is chlorinated and pumped to a pond which discharges into the Umdloti River. Though the removal efficiency results were slightly below the target, with Kwa-Mashu and Verulam achieving the lowest removal efficiency of 80% and 78%, respectively. The total monthly in the final effluent concentrations streams of both WWTPs complied with both the general limits during most of the sampling period. It was also observed in the 3 WWTPs that the values of PV4 are always slightly lower than the removal efficiencies of COD. It should be noted that the maturation ponds facilitate microbial removal and do not increase BOD removal (von Sperling et al., 2005). Thus the underperformance could be attributed to the compounds that were not oxidised.

4.5 Microbiological characteristics

A wide range of microorganisms are found in wastewater and if found in water or wastewater leaving any treatment plant, this signifies inadequate treatment. In municipal systems, the detection of more than 10% of samples in a given sampling period is concerning. Consecutive samples from the same site, that are positive for total coliforms, indicate changes in the quality of the water. Hence it is important to assess the effluent before it discharges into the receiving environment, ideally at the maturation ponds. *Escherichia coli* (E. coli) is commonly used as a preferred indicator for faecal contamination in wastewater (Tchobanoglous et al., 2002).

a)

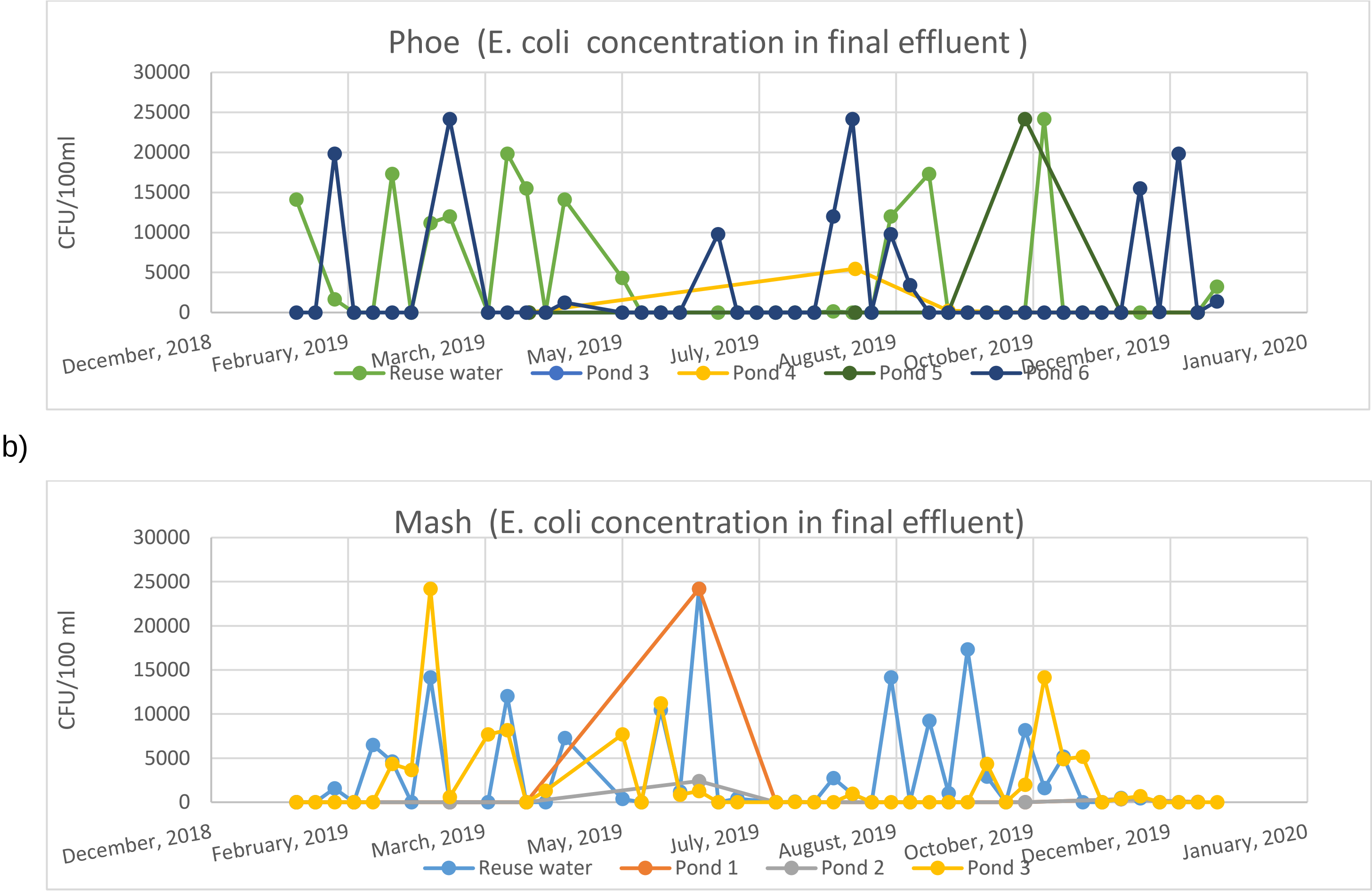


Figure 4.6: Analysis of E. coli in the final effluent in a) Phoenix (Phoe) WWTP b) Kwa-Mashu (Mash) WWTP

Even after secondary treatment, the final effluent may still contain large amounts of harmful microorganisms. Maturation ponds serve to provide a final polish of the effluent before it is discharged to the receiving environment. Due to exposure to UV sunlight, they are able to achieve microbial removal of more than 99% can be achieved (Tchobanoglous et al., 2002).

Only 2 of the 3 WWTPs assessed perform tests for the E. coli only the final effluent streams and the re-use water and not the influent wastewater. Thus, we could not determine the microbial reduction during the study period, only its presence in the final effluent and the reclaimed water.

The *E. coli* levels both in Kwa-Mashu and in Phoenix recorded the highest levels of around 25 000 CFU/100 ml in March. Kwa-Mashu has 3 ponds in series with the final effluent stream, in pond 3 In Phoenix there are 4 ponds in series, where the final effluent stream before discharge is monitored in pond 6. Wastewater limit values applicable to the discharge of wastewater into a water resource is 1 000/100ml level for general limits and 0 for special limits. Conventional activated sludge generally achieves low microbial efficiencies however, it is reported in literature that the final effluent in most cases has more coliforms than the influent concentration. This is argued that the influent pH is low thus the environment is not conducive for the bacteria whilst in the final effluent (von Sperling et al., 2005). Thus the final effluent sampling points, pond 3 and pond 6 of Kwa-Mashu and Phoenix, show non-compliance for the major part of the year. In Verulam, the *E. coli* was not monitored even in the final effluent.

The presence of E. coli in re-use water is not desirable as it can pose a danger to the workers. E. coli is mostly associated with domestic wastewater as opposed to industrial contributions.

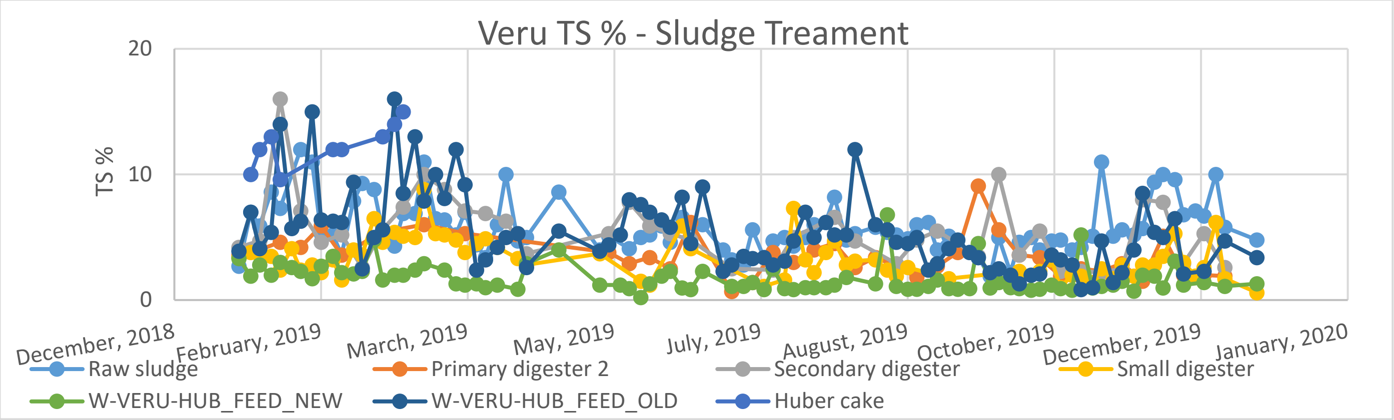
Stormwater run-offs also carry higher amounts of pathogens including chemicals. Thus, the WWTPs systems that are linked to stormwater are also impacted in terms of the wastewater influent (Q_w) characteristics. This can result in a short-term risk of non-compliance if the treatment facility does not have adequate capacity to treat the additional pollutant loading generated by the stormwater contribution (Tchobanoglous et al., 2002). This will impact the treatment performance of the facility.

4.6 Sludge treatment

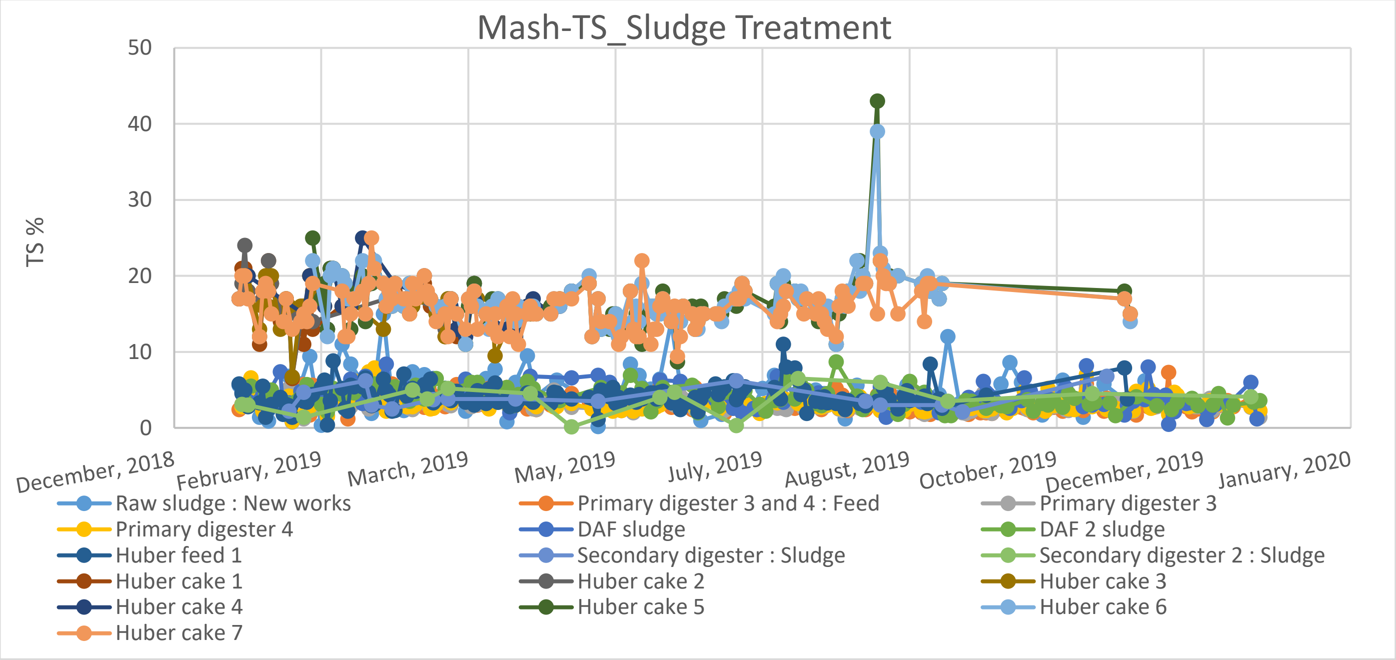
4.6.1 Total Solids Analysis

The total solids (TS) is one of the critical parameters to assess anaerobic digestion. Dewatering is a physical unit operation aimed at reducing the moisture content of sludge and producing a residue that can be handled like a solid. Residues with minimum solids content varying between 16% and 30% have been reported (Ruiz et al., 2010). Dewatering techniques can be mechanical e.g. filter press, centrifuge and belt press (McFarland, 2001).

a)



b)



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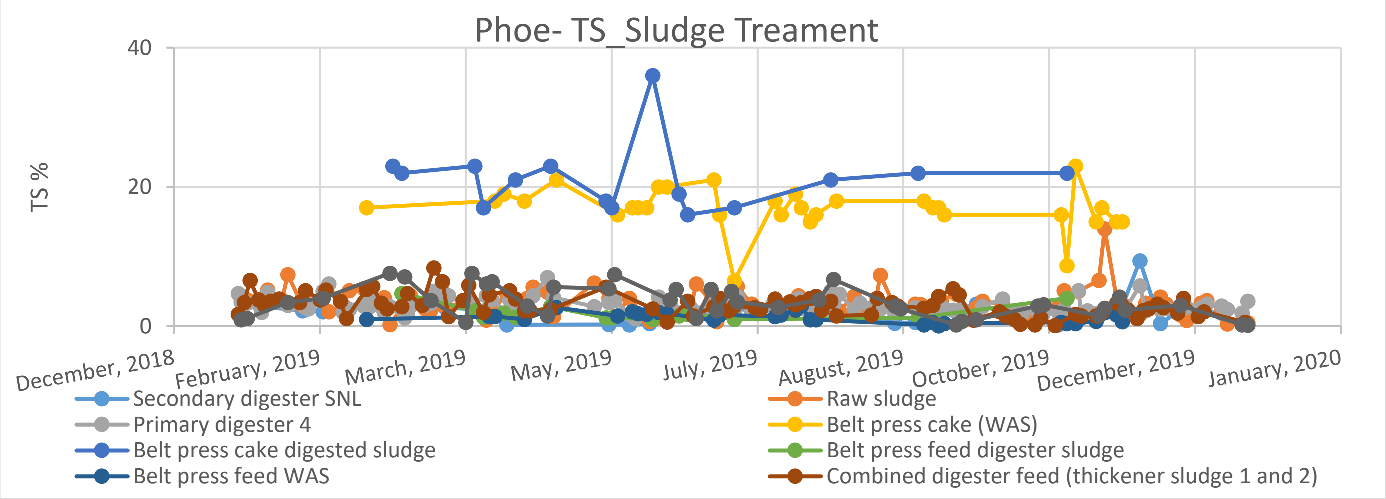


Figure 4.7 Total Solids in Sludge treatment processes a) TS concentrations of Verulam (Veru) b) TS concentrations of Phoenix (Phoe) c) TS concentrations of Kwa-Mashu (Mash)

The TS concentrations of the sludges from the 3 WWTPs vary a lot throughout the different stages of sludge treatment. These include during the thickening by gravity (belt presses) and by air flotation (dissolved air flotation, DAF), the anaerobic digestion and dewatering using the Huber technology. The Phoenix raw sludge TS % ranged from 3.3 % to 4.8% while the gravity-thickened sludge (combined feeder to the digesters) TS ranged from 1.1 to 4.5 %. The digested sludge is 0.2 to 6.4 % and the dewatered sludge (belt press cake) was from 15 to 19% and the belt press digested cake was 17.3 to 22.7%.

In Verulam, the range in raw sludge TS is from 3.8 to 7.3% and the thickened sludge (primary digester) ranges from 2.0 to 5.7%. The digested sludge TS % is from 3.1 to 8.3% while the dewatered sludge is 11.2 to 14.5%. In Kwa-Mashu, the TS % in the raw sludge ranges from 3.6 % to 6.7% whilst the thickened sludge from the DAF and gravity-thickened sludge (primary digester feed) ranged from 2.9 to 5.2% and 2.3 to 4.7%, respectively. The TS in the digested sludge in Mash is from 2.5 to 6.5 % whilst the dewatered (huber cake 7) sludge is from 14.5 to 17.9% (Table 4.6).

Table 4.6: A summary of the TS characterisation in the 3 WWTPs in this study

Type of sludge	WWTPs		
	Veru	Mash	Phoe
Raw sludge %	3.8 – 7.3	3.6 – 6.7	3.3 – 4.3
Thickened sludge (DAF) %	-	2.9 – 5.2	
Primary digester (feed) %	2.0 - 5.7	2.3 – 4.7	1.1 – 4.5
Digested %	3.1 – 8.3	2.5 – 6.5	0.2 – 6.4
Dewatered sludge %	11.2 – 14.5	14.5 – 17.9	17.3 – 22.7

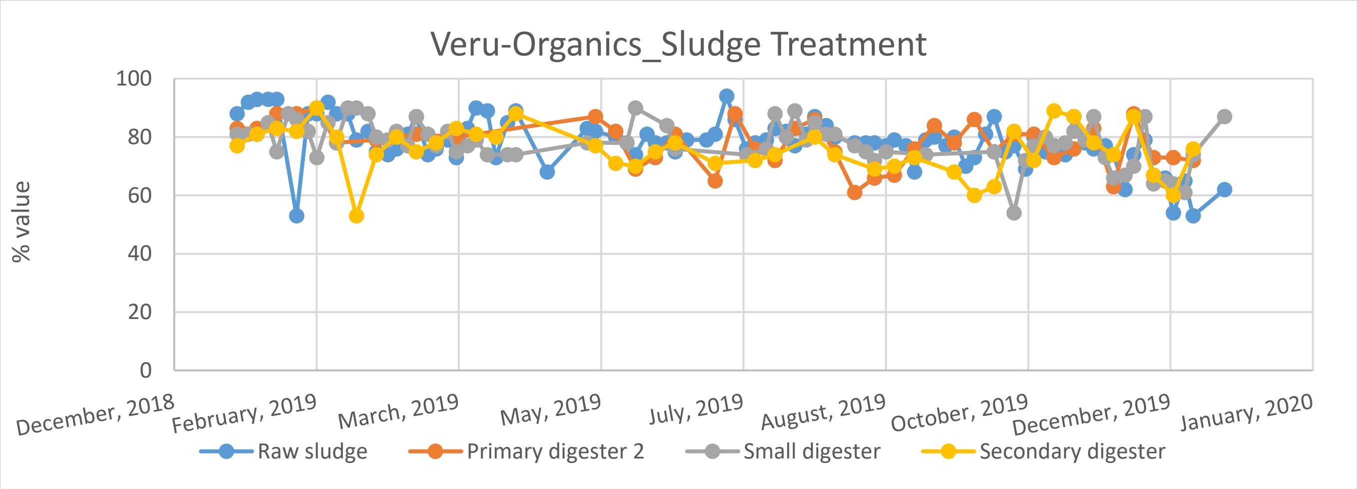
The raw sludge often contains 5 to 6 % solid material by weight. Higher dry solids (DS) concentration can be achieved by various technologies of sludge. Up to 20% DS can be achieved whereas 3 – 10 % sludge thickened by air flotation which includes the addition of polymer can be achieved (Metcalf & Eddy Inc. et al., 2003). A sludge increase from 0.8% Dry sludge (DS) to 4% DS and a moisture removal efficiency of 90 – 95 %, have been reported in a study using the thickening methods (Uggetti et al., 2010).

The TS% in the raw sludge of the 3 WWTPs assessed, in the Table above were varied, with Phoenix TS % ranking the lowest at 3.3 – 4.3 %. When sludge with lower solids concentration is used, the high moisture content decreases the efficiency of the digesters (Metcalf & Eddy Inc. et al., 2003). A minimum of 4 % solids is required in the sludge for effective dewatering however, the TS concentration may not go beyond 20% (Metcalf & Eddy Inc. et al., 2003). Thus, the 3 WWTPs, though they showed some improvements, the solids content in the raw sludge assessed was still generally low. There was some significant improvement in the solids content after the thickening and dewatering of the sludge though. Filter presses are very effective, having achieved as high as 30 to 45 % moisture reduction (McFarland, 2001).

4.6.2 Volatile Solids (Organics) Analysis

The Volatile Solids (VS) represents the organic content of the feedstock and it is expressed as a percentage of TS. It is one of the critical indicators to measure the progress of digestion. Figure 4.8 a-c, below are plotted to show the VS reductions in the 3 WWTPs:

a.



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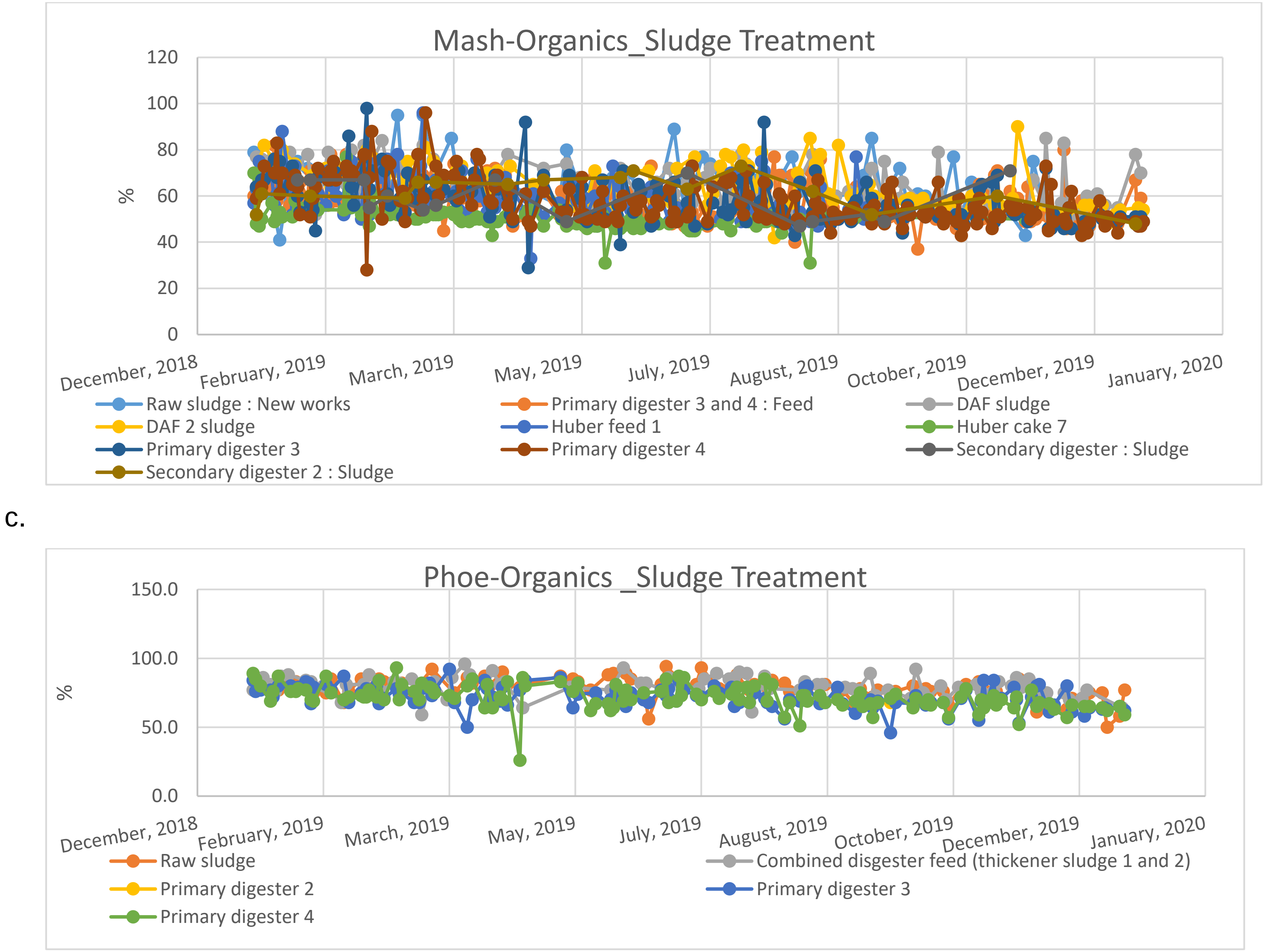


Figure 4.8: Organics concentrations in a) Verulam (Veru) WWTP b) Kwa-Mashu (Mash) WWTP c) Phoenix (Phoe) WWTP

Table 4.7 below is a summary of VS reduction in the different sludge treatment process units of the 3 WWTPs assessed using different types of sludge.

Table 4.7: A summary of the organics characterisation in the 3 WWTPs in the study

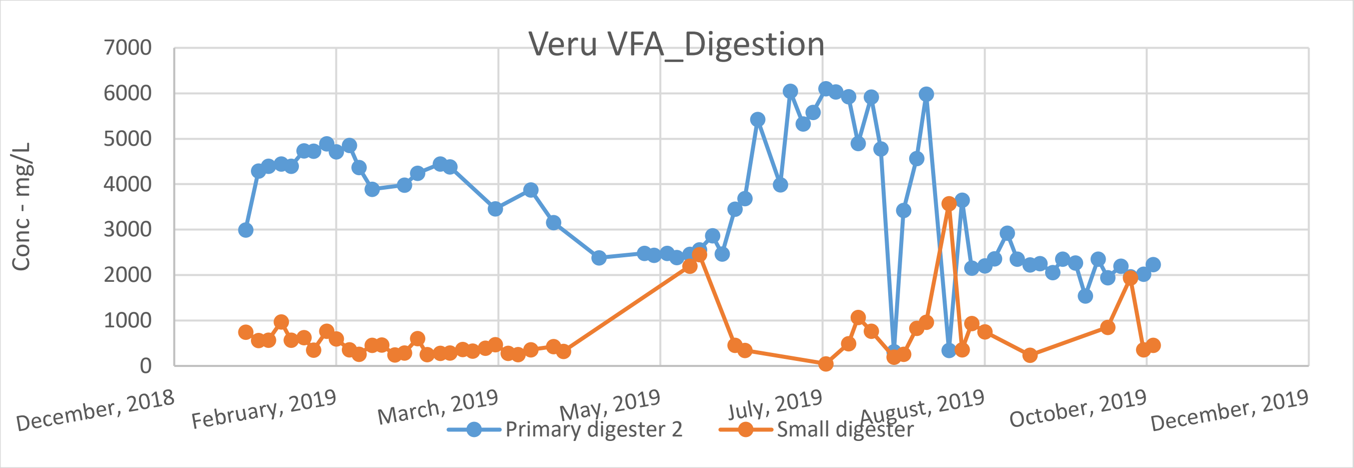
Type of sludge	eThekwini WWTPs		
	Veru	Mash	Phoe
Feed (Raw sludge) (Total VS) %	58.5– 85.3 (78.5%)	41–95 (68%)	46 - 94 (70%)
Thickened sludge (DAF) %	-	59.2 – 74.4	59 - 96
Primary digester (feed) %	67.3 – 85.5	52.3 – 67.3	46 - 92
Digested %	66.0–82.5 (74.25%)	28–96 (62%)	26 93 (60%)
Dewatered sludge (Huber cake) %		31 - 77	

According to Table 4.6, the raw feed sludge VS % in the 3 WWTPs was relatively low but no strong seasonal variations were seen. It is recommended that the feed (Raw sludge) (Total VS) % is > 80% in the digester in order to produce more biogas with a 40 - 60% VS reduction in a properly operating digester. Kwa-Mashu for instance had a daily VS % ranging from 41 % on 17th January. In March, it reached a maximum daily average of 95 %. Meanwhile, Verulam and Phoenix WWTPs contained a minimum of 58.5 and 46% in the feed, respectively. The VS % in the digested sludge was reduced though not significantly. The VS % reduction confirms the progression of digestion and importantly the breakdown of solids in the sludge by acid forming bacteria. Thus, it can be concluded that digestion did take place in the 3 WWTPs. The VS reduction comparison could not be properly done since Kwa-Mashu is the only one that was sending the digested sludge for analyses for the thickened and dewatered sludge during the sampling period. It is clear though as was seen previously that the TS concentration was low, thus, the VS % of the sample is likely to be low and so will be the VS % reduction. The low VS % in the 3 WWTPs could then be attributed to the characteristics of the feed sludge. Furthermore, the municipal ADs are operated at mesophilic temperatures, thus the low temperatures are likely to inhibit the effective destruction of organic matter. Diluting sludge with high moisture content is likely to cause a decrease in both the solid retention time and the operating temperature in the digester (Long et al., 2012). A typical AD stabilising municipal wastewater should be able to achieve at least 50% VS destruction of volatile matter and daily produce 6 $ft.^3$ per Lbs (96 kg/m^3) of biogas (Metcalf & Eddy Inc. et al., 2003).

4.6.3 Volatile Fatty Acids (VFA)

The VFAs are produced by acidogenic (or fermentative) bacteria along with ammonia, carbon dioxide and hydrogen sulphide amongst others. The four AD biochemical reactions are pH dependent (de Mes et al., 2003). As such a drop in pH levels which results in the accumulation of VFAs impacts the conversion of long-chain fatty acids (LCFA) into methane (Felchner-Zwirello, 2014). The fermentation products produced include amongst others acetic and propionic acid. An optimum pH level of 6.0 is seen as suitable for enhanced production of VFAs from a variety of organic wastes (Zhou et al., 2018).

a.



b.

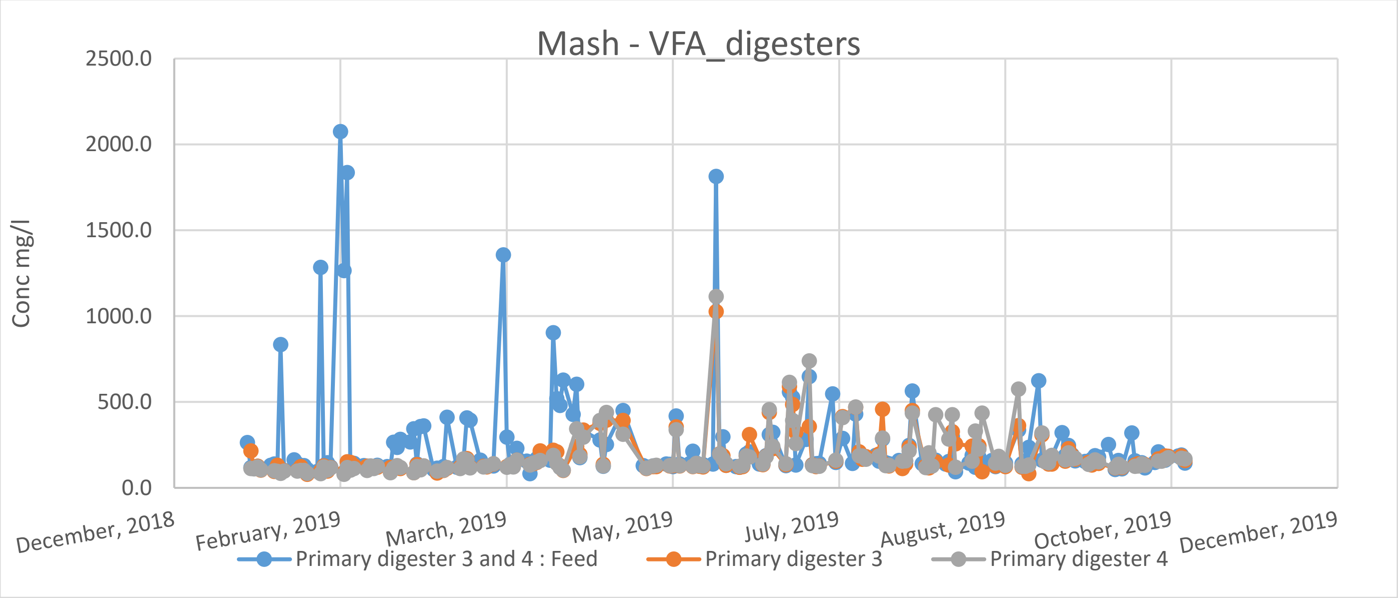


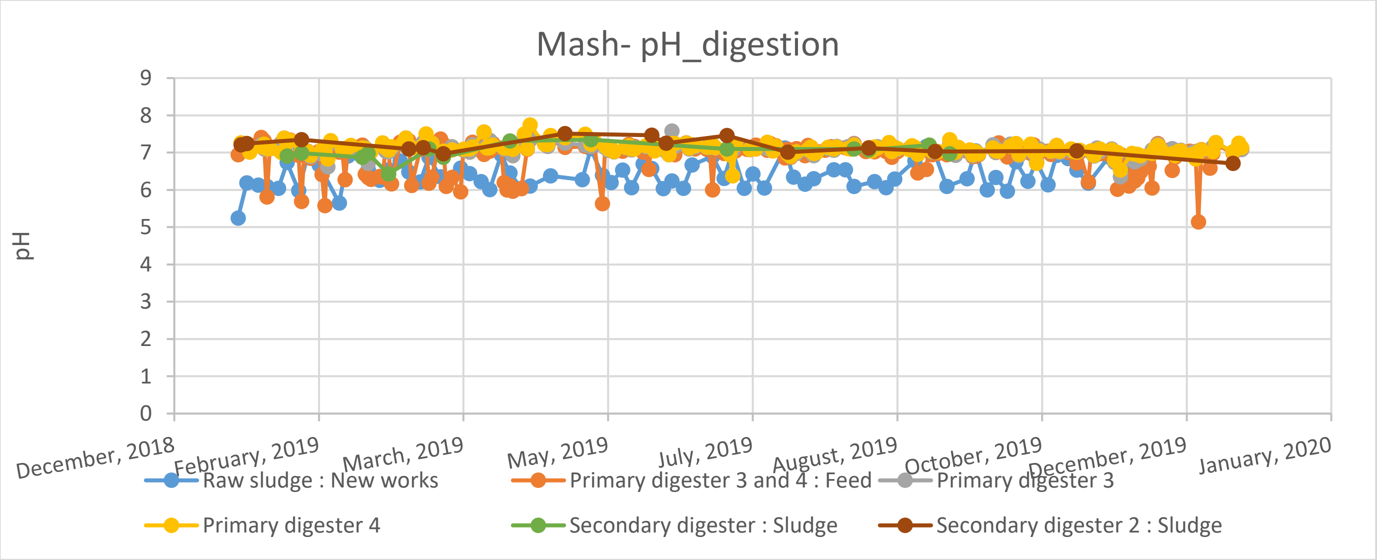
Figure 4.9: Volatile Fatty Acids vs time in sludge treatment in a) Verulam (Veru) WWTP b) Kwa-Mashu (Mash) WWTP

Volatile Fatty Acids concentration in the digester is typically in the range of 50 - 300 mg/l and a sudden increase signals a system failure (Felchner-Zwirello, 2014). Hence it is advisable that the VFAs are monitored daily in the WWTPs. A VFA:Alkalinity ratio of < 0.3 is recommended (Long et al., 2012). VFAs in Verulam WWTP were extremely high at 2 075 and 3 575 mg/l, respectively. In Kwa-Mashu WWTP though, the monthly averages were within the acceptable levels, however, the daily accumulation levels in the feed to the digester were high at 2 075 mg/l maximum recorded in February 2019. The daily averages in the acids in the digesters, 3 and 4 in Kwa-Mashu were also within the threshold however, on the 4, 5 and 6 February, extremely high daily VFAs of 2 075, 1 265 and 1 837 mg/l in the feed were recorded for 3 consecutive days. On the 28th May 2019, an unusual pattern was observed with a daily average of 1 813 mg/l in the feed whilst the digester's daily levels were 1 027 and 1 115 mg/l, in primary digesters 3 and 4, respectively. These anomalies could be attributed to the high organic loading rates in the digesters in the 3 WWTPs. Thus, decreasing the feed ensures that there is a good balance of microbial population for different stages of AD $CaCO_3$ (Long et al., 2012).

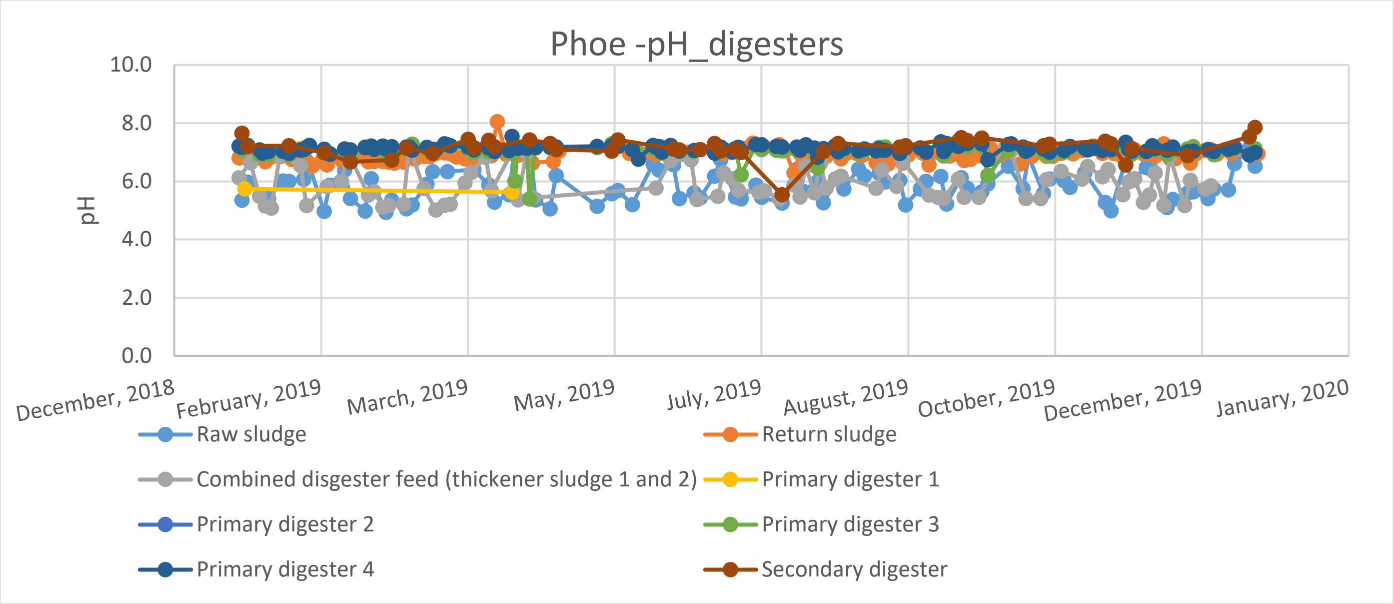
4.6.5 Acidity/pH

The pH levels, when they vary, affect microbial activity and impact biogas production. A drop in pH values is associated with the consumption and production of VFAs and ammonia, respectively. Methanogenic bacteria are extremely sensitive and prefer pH in the range of 6.5 and 7.2 and acidogens operate between pH levels of 5.5 and 6.5 (Appels et al., 2008; Conant et al., 2008). Fermentative microorganisms, however, are less sensitive and can function in a wider range of pH between 4.0 and 8.5 (Kougias et al., 2014).

a.



b.



c.

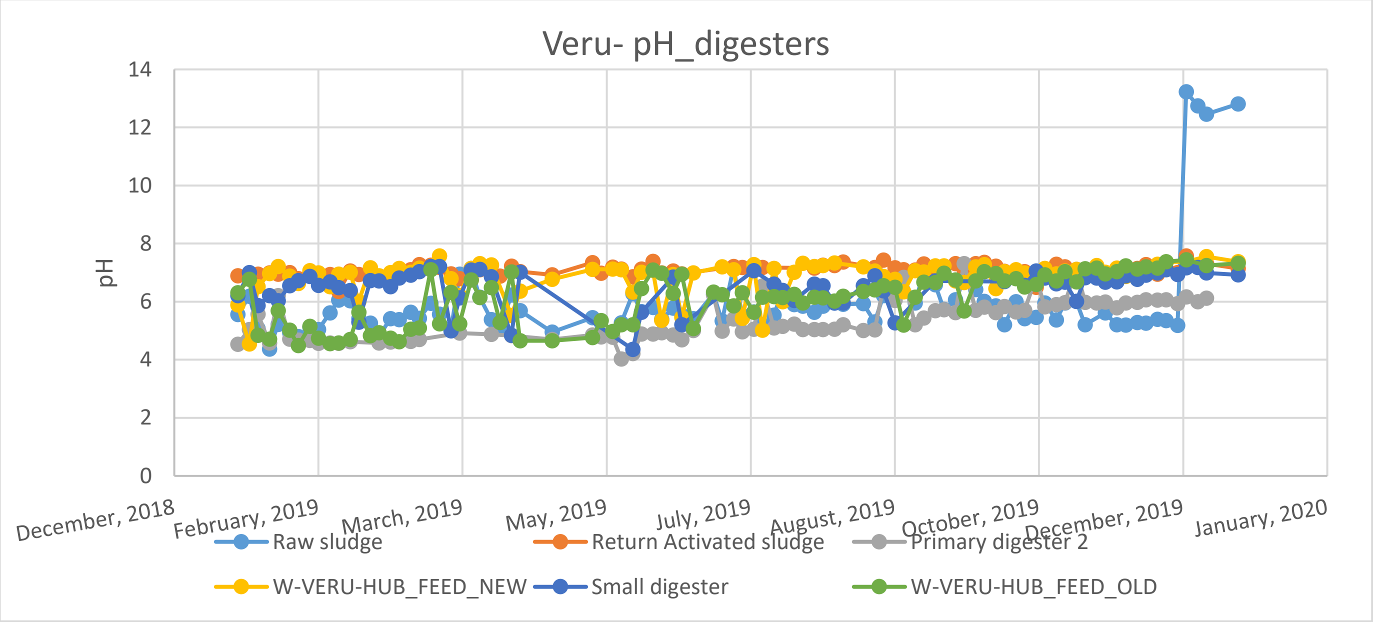


Figure 4.10: pH vs time during sludge treatment in a) Mash b) Phoe c) Veru WWTPs

In Kwa-Mashu WWTP the raw sludge monthly pH levels were low for example, pH of 5,2 and 5.7 was recorded on the 7th January and 11 February, respectively. These could be due to the pH levels in the influent wastewater as well as the nitrification processes in the reactor. The monthly pH levels in the digester feed (primary digester 3 and 4: feed) ranged between 5.14 to 7.24 whilst in the digesters (primary digester 3 and 4), were 6.35 to 7.27 and 6.53 to 7.27, respectively, which were good for methanogenesis to take place.

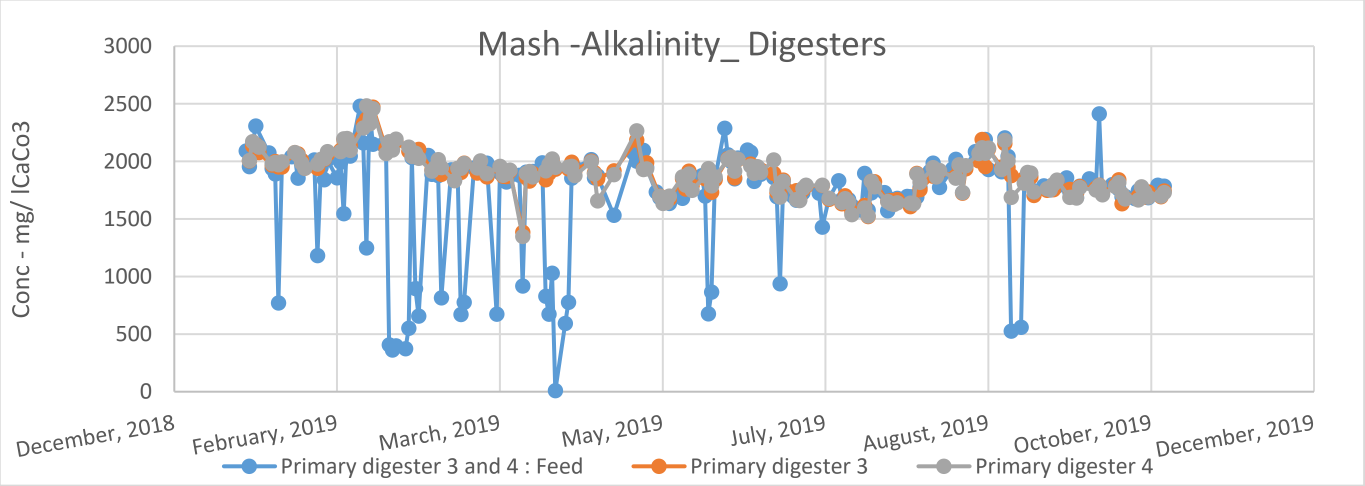
In Verulam, the raw sludge's average monthly pH values ranged from 5.2 to 12.8 whilst pH values of 4.4 were recorded on the 17th January with two outliers ranging from 12.5 to 13.2 in December. Verulam WWTP is the smallest of the 3 WWTPs and showed extremely low pH values (4.6) in the primary digester 2. Daily pH values of 4.0 recorded were recorded on 20 May and the maximum monthly pH value was 6.1. The monthly pH values in the secondary digester ranged from 5.0 to 7.1 and 4.4 on 24 May.

The raw sludge monthly averages in Phoenix ranged from 5.5 to 6.2 and a daily pH of 5.2 was recorded. In the digester feed (the combined feed) pH ranged from 5.7 to 6.0 with a daily value of 5.1 recorded. Phoenix has 4 primary digesters, however, only primary digesters 3 - 4, are used for digestion. The pH values monthly averages in primary digester 3 ranged from 6.9 to 7.2 but on the 16th April a daily pH value of 5.4 was recorded. The pH values in primary digester 4, ranged between 6.7 and 7.47 whilst in the secondary digester pH value of 5.5 were recorded on the 11th July 2019, all good for methanogenesis. The low pH values in the digesters could be due to the loss of alkalinity and high concentration of VFAs.

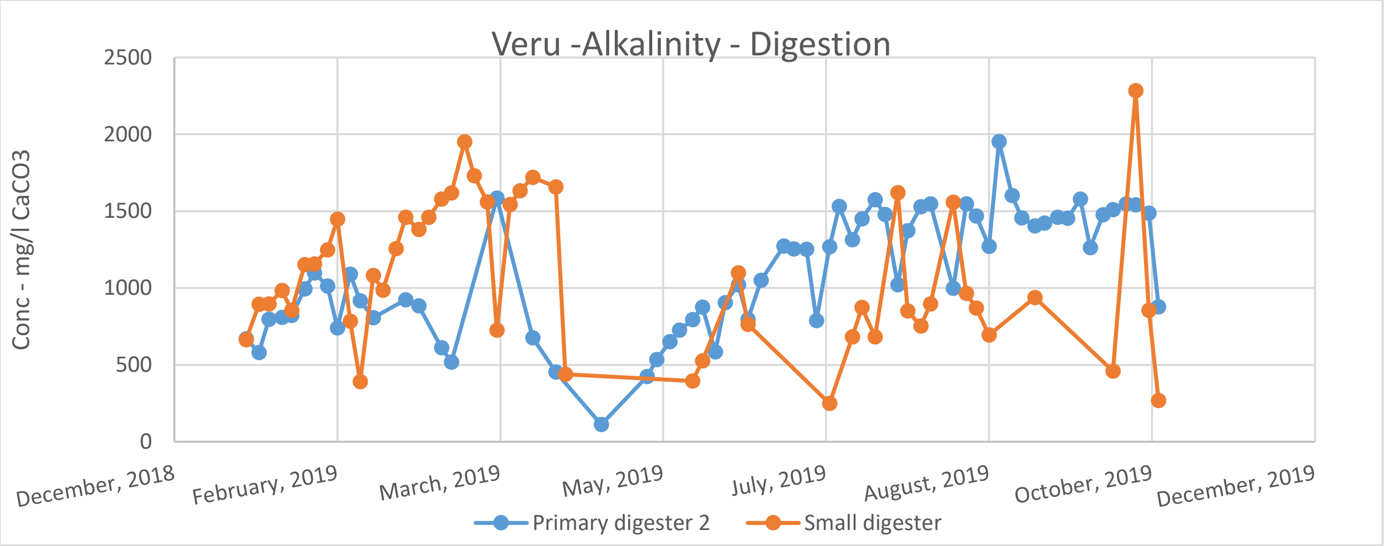
4.6.6 Alkalinity

Alkalinity is a result of the breakdown of proteins which reacts with CO_2 to form NH^{4+} and HCO_3. In digestion, the stability of the digester contents depends on the buffering capacity. Hence higher alkalinity indicates the increased capacity of the process for resisting pH changes. When alkalinity is reported, it is expressed as calcium carbonate or $CaCO_3$. The Alkaline (ALK) value in an anaerobic digester that is healthy can range between 1500 and 5000 mg/L (Long et al., 2012).

a.



b.



c.

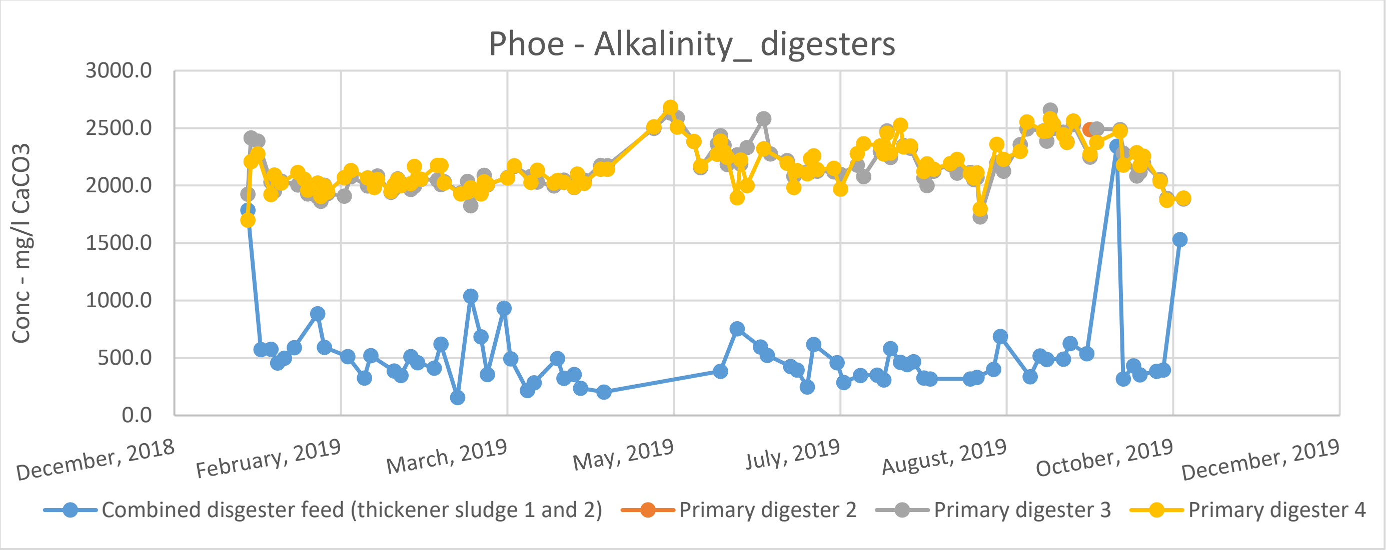


Figure 4.11: Alkalinity concentration vs time during sludge treatment, a) Mash WWTP b) Veru WWTP c) Phoe WWTP

The digester feeds had very low alkalinity values, especially in the digester feeds of Phoenix (157 mg/l) and Kwa-Mashu (7.3 mg/l) WWTPs (Verulam did not measure the mg/l $CaCO_3$ in the digester feed). Alkalinity values in the digesters of the 2 WWTPs were above 1 500 mg/l $CaCO_3$. Phoenix WWTP in May 2019 recorded an alkalinity of 2 684 mg/l $CaCO_3$ and in Verulam, both primary digesters were 112 mg/l $CaCO_3$ on the 26th April 2019 and 1 968 mg/l $CaCO_3$ in August 2019. The alkalinity in Verulam was fluctuating and in October 2019 2 283 mg/l $CaCO_3$ was registered in the small digester.

High levels of VFAs were recorded in the 3 WWTPs, in excess of 300 mg/l. This in turn caused a drop in pH levels. Thus, a good balance between the pH levels, VFAs and alkalinity is important.

Alkalinity values of less than 1 000 mg/l in the digester are not desirable and neither are values > 8 000 mg/l. The former leads to a drastic reduction of pH, causing acidification resulting in system failure. In order to avert this, the alkalinity can be enhanced by adding buffers such as sodium carbonate (Na_2CO_3) which will increase alkalinity to 1 500 mg/l (Soto et al., 1993). For higher alkalinity studies recommend the use of sodium sulphide or sodium bicarbonate, which increases alkalinity to 2 500 mg/l and 9 100 mg/l, respectively (Owen et al., 1979; Raposo et al., 2006). Lime can also be added however; excessive addition of sodium hydroxide can have a detrimental effect. According to Ngian & Pearce, (1979) who worked on the digestion of pig faeces, the addition of sodium hydroxide resulted in a higher volume and faster rate of gas at 7 and 9 gNaOH/100g Dry Matter (DM), respectively. Upon adjusting the pH, however, both the volume and the rate of gas production decreased significantly at 9 and 12 gNaOH/100g DM treated with sodium hydroxide.

4.7 Biochemical Methane Potential (BMP)

4.7.1 Feedstock compositional characteristics

The Biochemical Methane Potential (BMP) test assists to assess the biodegradability of the samples used for digestion. The seven (7) wastewater substrate and inoculum samples that were collected from the 3 WWTPs comprised of sludge samples (Kwa-Mashu) Mash-S1 a–c (thickened), Mash-S2 a–c (DAF sludge also feeding the primary digester) and Mash-In taken from the digester in Kwa-Mashu WWTP and was used as the inoculum. Gravity thickening often contains 5 to 6 % solid material by weight. The (Phoenix) Ph-S1a – c were the combined raw sludge samples and Ph-In an inoculum digested sludge sample from Phoenix WWTP. Samples from (Verulam) Veru WWTP comprised of primary sludge Ver-S1 a – c and Ver-In an inoculum digested sludge sample (Table 4.8). The samples were characterised in terms of the total solids (TS) and volatile solids (VS), as per Table 4.6 below:

Table 4.8: Sample labelling used in the 3 WWTPs

Sample label	Description
Mash-S1a-c	Thickened sludge from DAF feeding the primary digesters
Mash-S2a-c	Primary sludge feeding the thickener

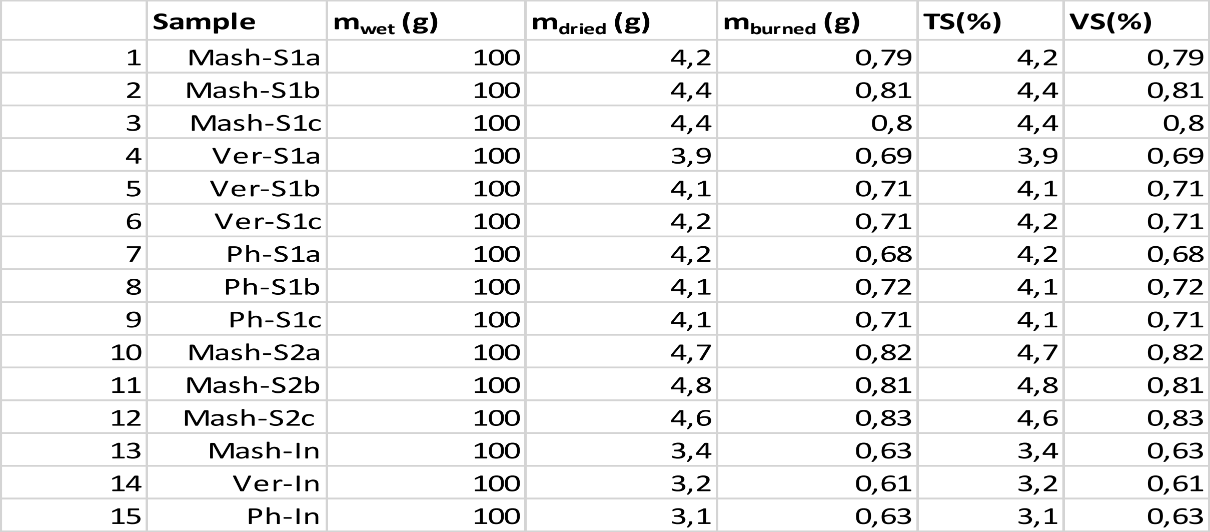
Mash-In	Inoculum from Kwa-Mashu digester
Ph-S1a-c	Primary sludge feeding the primary digesters
Ph-In	Inoculum from Phoenix digester
Ver-S1a-c	Primary sludge to primary digesters
Ver-In	Inoculum from Verulum digester

*Digesters are used as storage tanks and gas is flued into the atmosphere.

The total solids content of the substrate together with its associated volatile solids content are the important parameters that determine the biogas potential of a specific feedstock. The TS can be further categorized into degradable fractions (organic) and non-degradable fractions (ash) (Meegoda et al., 2018; Sayara & Sánchez, 2019). The organic contents can be quantified either as volatile solids (VS) or chemical oxygen demand (COD) (al Seadi et al., 2008).

The total solids concentration in conventional wastewater treatment processes usually produces primary sludge that ranges between 3% and 6%, whilst the stabilisation process may produce up to 20% TS (Kalderis et al., 2010). All the substrates samples from the 3 WWTPs indicated relatively low concentrations with the maximum TS at 4.8%, the Mash-S2b, which was thickened by air flotation, DAF (see Table 4.8). Historical records from the same process unit indicate that in 2019, the daily TS concentrations were as low as 1.1%. When solids with lower concentrations are used, the excess water decreases the efficiency of the digesters (Metcalf & Eddy Inc. et al., 2003). Thus, sludge with a decrease in moisture content and an increase in the TS concentration is recommended. In a study, however, that involved AD of sewage, it is reported that a decrease in feedstock moisture content from 97 % to 89 % (w/w) resulted in a significant decrease in methane yields (Fujishima et al., 2000).

Table 4.9: AMPTS feedstock characterisation for Mash, Phoe and Veru WWTPs



	Sample	m_{wet} (g)	m_{dried} (g)	m_{burned} (g)	TS(%)	VS(%)
1	Mash-S1a	100	4,2	0,79	4,2	0,79
2	Mash-S1b	100	4,4	0,81	4,4	0,81
3	Mash-S1c	100	4,4	0,8	4,4	0,8
4	Ver-S1a	100	3,9	0,69	3,9	0,69
5	Ver-S1b	100	4,1	0,71	4,1	0,71
6	Ver-S1c	100	4,2	0,71	4,2	0,71
7	Ph-S1a	100	4,2	0,68	4,2	0,68
8	Ph-S1b	100	4,1	0,72	4,1	0,72
9	Ph-S1c	100	4,1	0,71	4,1	0,71
10	Mash-S2a	100	4,7	0,82	4,7	0,82
11	Mash-S2b	100	4,8	0,81	4,8	0,81
12	Mash-S2c	100	4,6	0,83	4,6	0,83
13	Mash-In	100	3,4	0,63	3,4	0,63
14	Ver-In	100	3,2	0,61	3,2	0,61
15	Ph-In	100	3,1	0,63	3,1	0,63

The 3 inoculum samples Mash-In, Ver-In and Ph-In, after being dried at 103 °C, contained concentrations, ranging from TS 3.1 to 3.4 %. A study by Schievano et al., (2011), at the three full-scale co-digestion plants, showed the TS content ranged from 3.7% to 5.8 % (w/w) for digestate samples (inoculum).

The VS in a solid sample or COD of a liquid sample reduction provides an indication of how much material is being converted to biogas and can also assist to predict any potential organic overloading in the system (Meegoda et al., 2018). The VS refers to the weight of organic matter in the substrate and it is expressed as a percentage of TS. The 3 WWTPs samples indicate variable VS % concentrations, ranging from 68 to 83%, though VS % of > 80% in the digester and 40 – 60 % VS reduction is recommended. The VS content however only provides a quantitative analysis of organic content and does not describe the nature of organic molecules in an AD system (Schievano et al., 2011). The determination of TS and VS in acidic wastes can be challenging due to a possible loss of volatile organic matter during drying (Buffiere et al., 2008).

Wastewater sludge that contained 5 %TS had the potential to produce 300 m^3/ton comprising 65% CH_4 Raposo et al., (2012). Substrates have different total solids content hence they show different biogas yields.

4.7.2 Automatic Methane Potential Test System

The Automatic Methane Potential Test System II (AMPTS) system was used in this study over a period of 31 days, upon observing the drastic reduction in daily biogas and methane yields from the 28th day in all 15 reactors. The cumulative biogas yield (mL·g VS $_{\text{substrate}-1}$) and the daily biogas production rate (mL·g VS $_{\text{substrate}-1}$·/day) were calculated. The Specific Gas Yield (SGY), which is the amount of gas produced per gram of VS added and the Specific Methane Yield (SMY), are expressed as the normalized produced volume of biogas/methane per mass of organic material fed to the anaerobic digester. According to Qamaruz Zaman, (2010), once the daily methane production of <1 over three consecutive days is experienced it is recommended that the reaction should be stopped. The SRT should be long enough to ensure efficient conversion of organic matter, however, incubation times from 30 to over 100 days have been reported (Raposo et al., 2012).

4.7.2.1.1 Daily biogas and methane yields

The result of a BMP test reflects the biogas or methane produced from the experiments conducted (see Appendix E and F). The daily biodegradability rates of the substrate per gram of VS are used to calculate the biogas and methane potential and a comparison is made of various substrates used. These total BMP are determined by using the daily biodegradability rates and getting a mean value of the three blanks while subtracting the gas production from the inoculum. The average daily graphs of the biogas and methane yields were plotted vs the total digestion of 31 days below in Figures 4.12 and 4.13:

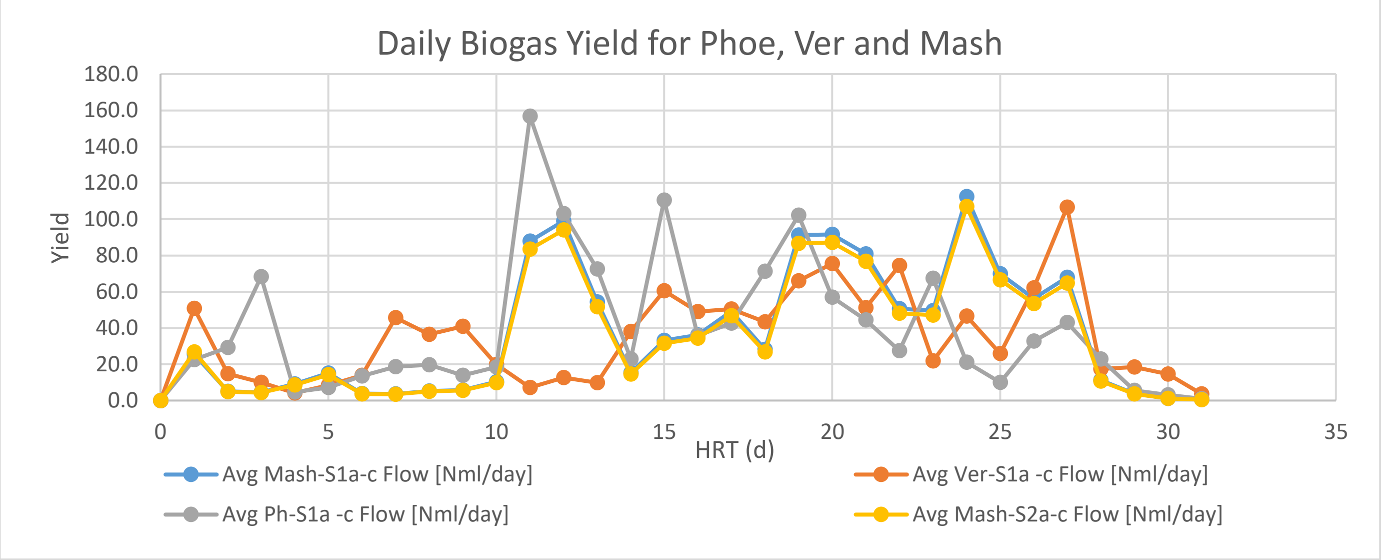


Figure 4.12: Plots of the daily biogas as a function of the digestion period of 31 days at 37 ^{0}C: Avg Mash-S1a – c DAF is thickened sludge from Kwa-Mashu WWTP, Avg Ver-S1a – c is raw sludge from Verulam WWTP, Avg Ph-S1 a – c is the thickened sludge from Phoenix WWTP, Avg Mash S2 a – c thickened sludge from Kwa-Mashu WWTP.

According to Figure 4.12, the daily biogas production of Ph-S1 a–c from Phoenix WWTP reached its maximum daily biogas yield at 156,8 Nml/d on the 11th day of its 31 digestion. The total biogas produced after 31 days in Phoenix is 264,18 Nml/g VS (26,42 m^3/kg VS). Kwa-Mashu's Mash-S1a – c and Mash-S2a – c, representing the DAF and gravity-thickened sludge, respectively produced their highest daily average on the 24th day with 112,4 Nml/d and 106,9 Nml/d, respectively. The total biogas yields from the Mash-S1a - c and Mash-S2 a–c, were 170,50 (17,05 m^3/kg VS) and 147,96 Nml/g VS (14,8 m^3/kg VS), respectively. Ver-S1-a c, which on day 1 produced the highest daily average at 50,8 Nml/d only achieved its highest daily average on the 27th at 106,6 Nml/d. The total biogas production in Verulam after 31 days was 181,79 Nml/g VS (18,18 m^3/kg VS).

Whilst the above results are the aggregated scores, however, Appendix E showed that individually Ph-S1a again produced the highest daily biogas of 165.1 Nml/d on the 11th day whilst substrate Ver-S1-a individually produced 50,2 Nml/d on the 1st day.

In a study involving sewage sludge at 6% TS digestion at mesophilic temperature, at HRT of 25 days, the results showed a biogas yield of 0.52 m^3/kg VS whilst the methane component was 68%

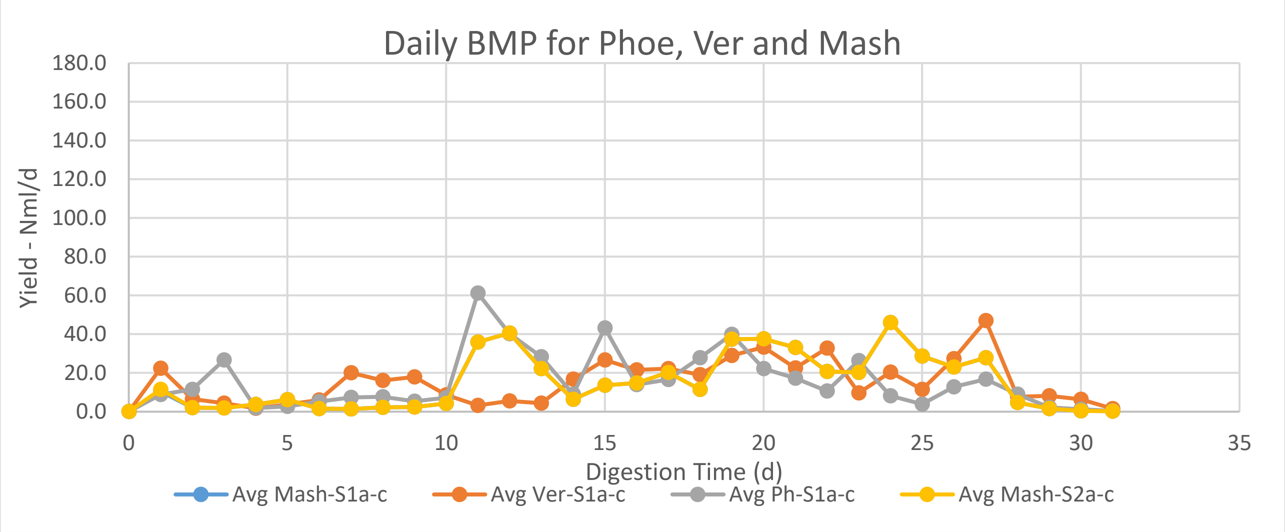


Figure 4.13: Methane daily yield plots as a function of total digestion of 31 days where: Avg Mash-S1a – c DAF is thickened sludge from Kwa-Mashu WWTP, Avg Ver-S1a – c is raw sludge from Verulam WWTP, Avg Ph-S1 a – c is the thickened sludge from Phoenix WWTP, Avg Mash S2 a – c thickened sludge from Kwa-Mashu WWTP.

Similarly, the daily methane yield results followed similar trends as shown in Figure 4.13. Ph-S1a - c on day 11 achieved the highest daily methane yield of 61.2 Nml CH_4/g VS per day. Again Mash-S1a – c and Mash-S2a – c, followed the same pattern and both achieved the highest daily average with 46.1 Nml CH_4/g VS per day recorded on the 24th day. Ver-S1-a-c, on the other hand, achieved its maximum daily average on the 27th at 47.0 Nml CH_4/g VS per day.

4.7.2.2 Cumulative volumes of biogas and methane

The cumulative biogas and methane curves show the total production over the incubation period. Using the data in Appendix E and F, Figures 4.14 and 4.15 below where cumulative volume was plotted as a function of the total digestion time of 31 days.

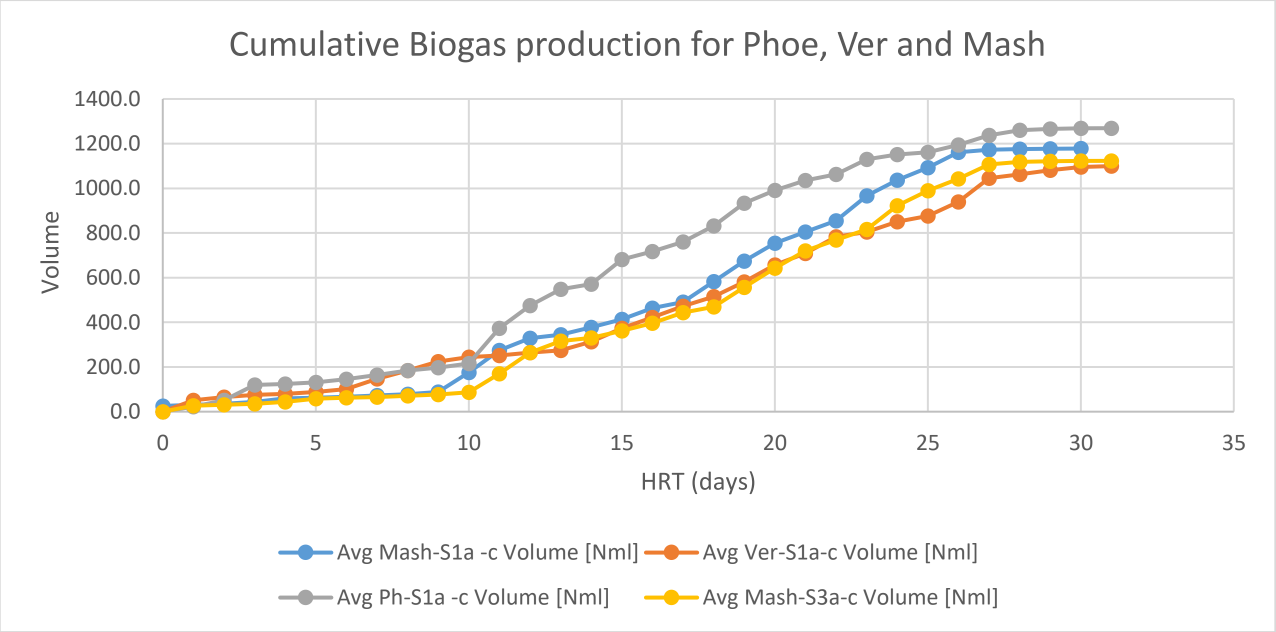


Figure 4.14: Cumulative biogas production (Nml) as a function of total digestion of 31 days at 37 ^{0}C where: Avg Mash-S1a – c DAF is thickened sludge from Kwa-Mashu WWTP, Avg Ver-S1a – c is raw sludge from Verulam WWTP, Avg Ph-S1 a – c is the thickened sludge from Phoenix WWTP, Avg Mash S2 a – c thickened sludge from Kwa-Mashu WWTP.

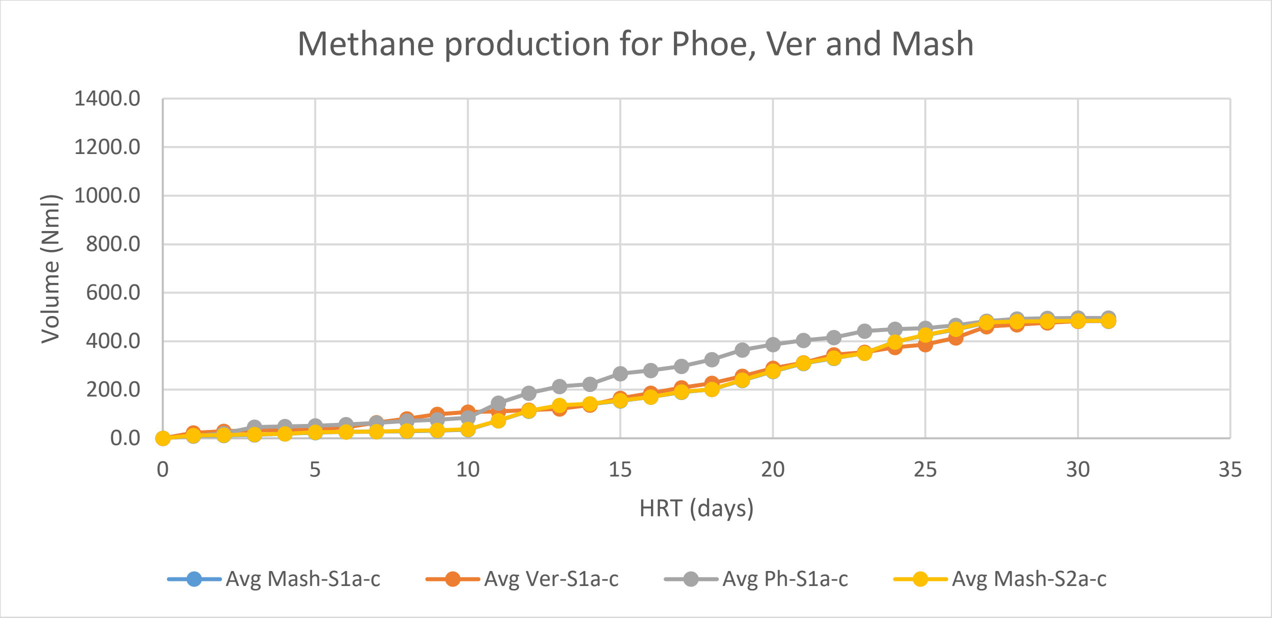


Figure 4.15: Cumulative methane (Nml) as a function of total digestion of 31 days at 37 0C where: Avg Mash-S1a – c DAF is thickened sludge from Kwa-Mashu WWTP, Avg Ver-S1a – c is raw sludge from Verulam WWTP, Avg Ph-S1 a – c is the thickened sludge from Phoenix WWTP, Avg Mash S2 a – c thickened sludge from Kwa-Mashu WWTP.

The cumulative methane curves in Figures 4.14 and 4.15 show that in all the mixtures, both the biogas and methane started peaking after the 10th day. Similar to its daily biogas production, sample Ph-S1a – c digestion cumulative total biogas and methane is the highest at 1 269,2 Nml and 495,8 Nml, respectively on day 31. Similarly, on day 31 Mash-S1a-c, and Mash-S2a-c, biogas cumulatively achieved 1178 and 1122 Nml, respectively. The cumulative methane volumes on day 31 of Mash-S1a-c, and Mash-S2a-c, were 483 and 484 Nml, respectively. After 31 days, Ver-S1a-c cumulative biogas and methane volumes were 1 099,5 Nml and 484,4 Nml, respectively.

A notable lag phase of 10 days was observed in all the experiments. This could indicate hydrolysis as the rate-limiting step in the anaerobic digestion process whilst its absence means that the test material is readily biodegradable. A long lag phase also implies that the test material may have inhibitors in the initial phase of incubation, such toxic substances inhibit the microorganisms. In the latter case, the situation would result in the test material producing lower methane.

4.7.3.1 Electrical Energy Potential

In order to estimate the electrical energy potential that can be produced in the 3 WWTPs assessed in this study, it was assumed that 1 m^3 of biogas contains about 6 - 9 kWh/m^3 which is an equivalent of 21 MJ/m3. An electrical efficiency value (η_{elec}) of 35% which was thought reasonable, was assumed. Using equation 4.2 below, the potential electrical energy contained in Table 4.9 below was calculated for the 3 WWTPs assessed.

$$e_{biogas}\ (kWh) = E_{biogas}\ (Btu) \times 0{,}000293\ (kWh/Btu) \times \eta_{elec} \qquad \text{Equation 4.2}$$

where:

e_{biogas} is the total electricity that can be generated from biogas, in kWh,

E_{biogas} x is the unconverted raw energy in the biogas (in BTUs),

η_{elec} is overall conversion efficiency.

Table 4.10: Electricity produced estimates in the 3 WWTPs, based on the biogas yields results from the AMPTS.

Name	Mash-S1a - c	Ver-S1a - c	Ph-S1a - c	Mash-S2a - c
m^3 biogas/kg VS	0,17	0,18	0,26	0,15
Assuming Calorific value (HHV) of 21 MJ/m^3	3,58	3,82	5,55	3,11
Electricity produced (kWh) = Ebiogas/3,6MJ per kWh	12,89	13,74	19,97	11,19
At η = 35%	4,51	4,81	6,99	3,91

The estimated electricity potential produced in the 3 WWTPs ranged from 4 to 7 kWh. Phoenix WWTP produced the highest electricity with a total biogas yield of 264,18 Nml/g VS over the 31 days with an electrical energy potential of 7 kWh. The total biogas yields from the Mash-S1a-c and Mash-S2a–c were 170,50 Nml/g VS and 147,96 Nml/g VS, respectively, whilst the electrical potential is 4,51 and 3,91 kWh, respectively. The total biogas production in Verulam was 181,79 Nml/g VS with an energy potential of 4,81 kWh. The energy outputs in the 3 WWTPs were relatively low which could be attributed to the low strength of the municipal sewage in general. The characterisation of the feedstock used in the AD ranged between 61 – 83 % for VS and 3,1 – 4,8 for TS whilst in a study involving soda drink wastewater, maximum electricity was 18.9 kWh after 24 days, where the substrates used contained TS and COD at 27.4% and 2 200 mg/l, respectively. The carbon content (W%) is directly proportional to the calorific value hence the maximum biogas yield of 2 800 ml in the soda study (Admasu et al., 2022).

CHAPTER 5

This chapter presents the summary of results, the conclusions as well as the recommendations for future studies.

5.1 Summary

The study set out to assess the eco-efficiency of the case WWTPs in EThekwini municipality, by looking at the treatment efficiency and potential for biogas recovery. In this regard, one of the tasks involved characterise the influent by evaluating the impact of the operational flows and rainfall. Below is the summary of the results:

Table 5.4: Summary of the operating flows and the rainfall data

WWTP	**Kwa-Mashu**	**Phoenix**	**Verulam**
Parameter	**Plant Flows**		
Operating Capacity (m^3/d)	65000	29000	8000
Avg. Daily Flows (m^3/d)	63135	23011	7080
Min.	47389	12022	4500
Max.	96305	35284	10675
Total Monthly Flows (m^3/m)	1916742	697924	215121
Min.	1421655	372669	137200
Max.	2985441	1093808	310608
Rainfall			
Avg. Rainfall (mm)	8	3	4
Min.	0	0	0
Max.	51	8	16
Total Monthly Rainfall (mm)	246	99	118
Min.	0	0	0
Max.	1584	382	406

Using the IBM SPSS statistical package, moderate to strong correlations were observed between rainfall intensity (I) and flowrate (Q) for all 3 WWTPs as can be seen below:

- Verulam showed a weak/small correlation (-0.42)
- Phoenix also had a weak/small correlation (0.164).
- Kwa-Mashu showed a strong/ large correlation (0.756).

The influent wastewater characteristics analysis included: Chemical Oxygen Demand (COD) concentrations, ammonia (NH_3) concentrations and total solids (TS) concentrations. Below is the summary of the results of key parameters:

Table 5.5: Summary of characteristics of the influent parameters

Parameter		**Kwa-Mashu**	**Phoenix**	**Verulam**
COD (mg/l)	Avg.	819	500	638
	Min.	0	0	0
	Max.	1513	615	848
SS (mg/l)	Avg.	575	337	351
	Min.	0	0	0
	Max.	1095	476	493
NH_3 (mg/l)	Avg.	21	27	25
	Min.	0	0	0
	Max.	33	41	44

The treatment efficiency was evaluated by using the desired design target of 95% based on the key parameters in the final effluent streams. Below is the summary of the results:

Table 5.6: Summary of removal efficiencies

Parameter	**Kwa-Mashu**	**Phoenix**	**Verulam**
	Removal efficiency (%)		
COD (mg/l)	85	70	83
SS (mg/l)	88	77	86
NH_3 (mg/l)	60	27	62
PV4 (mgO2/l)	81	0	78

The biogas potential from the AD of the 3 WWTPs in Table 4.8, showed the TS % of the sludge ranged from 3.1 to 4.8% whilst the VS % ranged from 61% to 83%. Meanwhile, Table 4.9 showed the electricity potential ranges from 3,91 kWh to 7 kWh.

5.2 Conclusions

The major conclusions drawn from the study are the following:

- The infiltration/inflow and storm water run-off contribution including seasonal variations to the operational flows were observed;
- The quality (physicochemical characteristics) of the influent were above the domestic wastewater concentrations thus confirming the industrial wastewater contributions;
- The treatment efficiencies of the 3 WWTPs were generally high, though for some parameters the removal efficiency was below the threshold;
- There were biogas yields observed in the 3 WWTPs even though it was substantially low.

5.3 Recommendations and future work

1) The contributions of the infiltration and the rainfall is difficult to quantify. Thus, more work needs to be done in this respect;
2) Whilst the treatment removal of some parameters was achieved in this work, large volumes of microbiology pollutants were still found in the effluent. It is important to investigate the efficacy of the treatment processes for different pollutants and customize the treatment technologies accordingly;
3) The digestion of wastewater sludge has a long history however, the low biodegradability, as well as the inhibitory factors of the wastewater sludge are still a challenge. Thus more research is needed in order to identify any potential inhibition and optimise the potential energy recoverable.
4) Biogas generation integrates waste management and energy technologies and as such, impacts all three pillars of sustainability: environmental, social and economic. South Africa, in 2008, adopted the National Framework for Sustainable Development (NFSD) which expresses the country’s vision for sustainable development. Wastewater treatment in South Africa remains focused on the removal of main pollutants.
5) In South Africa the first municipal digesters were built in the 1940s and recently the community pilot projects that were implemented around the early 2000s ceased to operate within ten years after their installations. To date, most municipalities incorporate the ADs into their sludge management processes, however, South Africa still lags behind in the use of biogas for large-scale as well as for off-grid applications in the rural areas.

6. References

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Appendix A: Wastewater flows and Rainfall data

Mash				
	Sewage Flows		Rainfall	
Dates	Total Monthly Inflows (m3/m)	Avg. Daily Inflows (m3/d)	Total Rainfall (mm)	Avg. Daily Rainfall (mm)
Jan-19	1569602	50632	40	1,3
Feb-19	1513242	54044	284	10,1
Mar-19	1685864	54383	266	8,6
Apr-19	2151966	71732	160	5,3
May-19	1488730	49624	0	#DIV/0!
Jun-19	1421655	47389	0	#DIV/0!
Jul-19	1545792	49864	0	0,0
Aug-19	1670050	53873	25	0,8
Sep-19	2158070	71936	20	0,7
Oct-19	2333581	75277	81	2,6
Nov-19	2476910	82564	495	16,5
Dec-19	2985441	96305	1584	51,1

Phoe				
	Sewage Flows		Rainfall	
Dates	Total Monthly flows (m3/d)	Avg. Daily Inflows (m3/d)	Total Rainfall (mm)	Avg. Rainfall (mm)
Jan-19	810597	26148	170,0	5,5
Feb-19	857654	30630	84,0	3,0
Mar-19	822507	26532	112,0	3,6
Apr-19	678389	22613	382,0	3,6
May-19	548306	17687	2,0	0,1
Jun-19	555430	18514	6,0	3,6
Jul-19	372669	12022	0,0	0,0
Aug-19	493500	15919	3,0	0,1
Sep-19	537391	17913	35,0	1,2
Oct-19	584817	18865	28,0	0,9
Nov-19	1020024	34001	240,0	8,0
Dec-19	1093808	35284	130,0	4,2

Veru				
	Sewage Flows		Rainfall	
Dates	Total Monthly Inflows (m3/m)	Avg. Daily Inflows (m3/d)	Total Rainfall (mm)	Avg. Daily Rainfall (mm)
Jan-19	289353	9334	98,0	3,2
Feb-19	298896	10675	171,5	6,1
Mar-19	310608	10020	219,0	7,1
Apr-19	277474	9249	86,0	3,6
May-19	217407	7013	0,0	0,0
Jun-19	194646	6488	0,0	0,0
Jul-19	163121	5262	406,0	16,2
Aug-19	188541	6082	20,0	0,6
Sep-19	186311	6010	0,0	0,0
Oct-19	178401	5755	50,0	1,6
Nov-19	137200	4573	226,0	7,5
Dec-19	139492	4500	137,0	4,4

Appendix B: Mass Loadings

Veru					
Raw Sewage Loadings					
	Flows		COD (kg/d)	NH3 (kg/d)	SS (kg/d)
Dates	Total Monthly Inflows (m3/m)	Avg. Plant Daily Inflows (m3/d)	Qa*(CODraw/ 1000)	Qa*(NH3raw/ 1000)	Qa*(SSraw/ 1000)
Jan-19	289353	9334	6510	313	3888
Feb-19	298896	10675	6709	0	4206
Mar-19	310608	10020	6438	261	3629
Apr-19	277474	9249	0	0	2462
May-19	217407	7013	3902	0	2133
Jun-19	194646	6488	4041	287	2696
Jul-19	163121	5262	4464	166	1948
Aug-19	188541	6082	4687	192	2151
Sep-19	186311	6010	4788	189	2960
Oct-19	178401	5755	4279	199	2618
Nov-19	137200	4573	2780	138	0
Dec-19	139492	4500	3325	162	1728

Mash					
Raw Sewage Loadings					
	Flows		COD (kg/d)	NH3 (kg/d)	SS (kg/d)
Dates	Total Monthly Inflows (m3/m)	Avg. Plant Daily Inflows (m3/d)	Qa*(CODraw /1000)	Qa*(NH3raw/ 1000)	Qa*(SSraw/ 1000)
Jan-19	1569602	50632	43434	1384	25733
Feb-19	1513242	54044	39355	0	28226
Mar-19	1685864	54383	34671	933	27798
Apr-19	2151966	71732	0	0	23729
May-19	1488730	49624	35262	0	25595
Jun-19	1421655	47389	41349	1422	29073
Jul-19	1545792	49864	54822	1538	39574
Aug-19	1670050	53873	48771	1702	35410
Sep-19	2158070	71936	70773	2044	59263
Oct-19	2333581	75277	113856	2310	82447
Nov-19	2476910	82564	53685	1682	0
Dec-19	2985441	96305	83592	3178	51427

Phoe					
Raw Sewage Loadings					
	Flows		COD (kg/d)	NH3 (kg/d)	SS (kg/d)
Dates	Total Monthly flows (m3/d)	Avg. Plant Daily Inflows (m3/d)	Qa*(COD$_{raw}$/ 1000)	Qa*(NH3$_{raw}$/ 1000)	Qa*(SS$_{raw}$/ 1000)
Jan-19	810597	26148	14643	863	10656
Feb-19	857654	30630	13976	0	9963
Mar-19	822507	26532	14660	816	9203
Apr-19	678389	22613	0	0	7625
May-19	548306	17687	9165	0	6381
Jun-19	555430	18514	10939	741	6369
Jul-19	372669	12022	7397	493	5724
Aug-19	493500	15919	9216	588	5834
Sep-19	537391	17913	10027	663	6284
Oct-19	584817	18865	11597	692	8088
Nov-19	1020024	34001	15842	1048	0
Dec-19	1093808	35284	17133	1376	10397

Appendix C: Influent and effluent data

WWTP	Kwa-Mashu						Phoenix						Verulam					
Quality Parameters	COD$_{in}$ (mg/l)	COD$_{fe}$ (mg/l)	NH$_{3in}$ (mg/l)	NH$_{3fe}$ (mg/l)	SS$_{in}$ (mg/l)	SS$_{fe}$ (mg/l)	COD$_{in}$ (mg/l)	COD$_{fe}$ (mg/l)	NH$_{3in}$ (mg/l)	NH$_{3fe}$ (mg/l)	SS$_{in}$ (mg/l)	SS$_{fe}$ (mg/l)	COD$_{in}$ (mg/l)	COD$_{fe}$ (mg/l)	NH$_{3in}$ (mg/l)	NH$_{3fe}$ (mg/l)	SS$_{in}$ (mg/l)	SS$_{fe}$ (mg/l)
Jan-19	857,8	55,9	27,3	2,6	508,2	17,1	560,0	131,7	33,0	17,3	407,5	123,2	697,5	0,0	33,5	3,1	416,5	20,3
Feb-19	946,9	42,5	🟦	0,0	522,3	6,8	456,3	0,0	🟦	🟦	325,3	34,5	628,5	0,0	🟦	🟦	394,0	19,4
Mar-19	939,0	44,0	17,2	1,8	511,2	6,1	552,5	0,0	30,8	14,8	346,8	73,0	642,6	0,0	26,0		362,2	6,3
Apr-19	921,3	0,0	🟦	0,0	330,8	8,3	🟦	0,0	🟦	🟦	337,2	67,1	762,3	0,0	🟦	🟦	266,2	4,0
May-19	860,9	60,3	🟦	0,0	515,8	18,9	518,1	201,7	🟦	🟦	360,8	31,2	701,2	65,4	🟦	🟦	320,7	36,7
Jun-19	825,8	50,9	30,0	0,6	613,5	11,7	590,9	391,2	40,0	38,0	344,0	69,8	727,0	58,2	44,3	8,5	415,5	21,0
Jul-19	775,5	197,1	30,8	2,8	793,6	140,7	615,3	186,3	41,0	27,5	476,2	111,1	727,5	66,2	31,5	7,7	370,2	38,0
Aug-19	734,2	50,2	31,6	6,5	657,3	17,8	578,9	115,0	36,9	9,6	366,5	68,5	730,5	56,2	31,5	3,6	353,6	12,3

Sept-19	728,6	51,0	28,4	0,9	823,8	13,3	559,8	125,9	37,0	13,3	350,8	48,3	748,6	59,2	29,1	3,2	492,5	26,4
Oct-19	721,9	87,3	30,7	3,3	1095,3	18,7	614,8	91,5	36,7	23,6	428,8	21,1	697,4	71,7	34,5	6,6	455,0	61,2
Nov-19	724,7	43,0	20,4	3,6			465,9	97,6	30,8	21,2		0,0	731,4	50,4	30,3	3,3		
Dec-19	719,4	35,4	33,0	0,2	534,0	7,3	485,6	96,9	39,0	40,5	294,7	11,7	705,1	87,9	36,0	18,0	384,0	5,0

APPENDIX D - Plant overall performance efficiency

Phoe					
Overall Plant Reductions					
Monitoring Dates	**Parameter** **Design Target %**	**COD %** **(CODraw-CODfe)/CODraw ×100**	**NH3 %** **(NH3raw-NH3fe)/NH3raw×100**	**SS %** **((SSraw - SSfe)/SSraw)×100**	**PV4 %** **(PV4raw-PV4fe)/PV4raw×100**
Jan-19	95%	76%	47%	70%	#DIV/0!
Feb-19	95%	100%	#DIV/0!	89%	#DIV/0!
Mar-19	95%	100%	52%	79%	#DIV/0!
Apr-19	95%	#DIV/0!	#DIV/0!	80%	#DIV/0!
May-19	95%	61%	#DIV/0!	91%	#DIV/0!
Jun-19	95%	34%	5%	80%	#DIV/0!
Jul-19	95%	70%	33%	77%	#DIV/0!
Aug-19	95%	80%	74%	81%	#DIV/0!
Sep-19	95%	78%	64%	86%	#DIV/0!
Oct-19	95%	85%	36%	95%	#DIV/0!
Nov-19	95%	79%	31%	#DIV/0!	#DIV/0!
Dec-19	95%	80%	-4%	96%	#DIV/0!

Veru					
Overall Plant Efficiencies					
Monitoring Dates	**Parameter** **Design Target**	**COD %** **(CODraw-CODfe)/CODraw×100**	**NH3 %** **(NH3raw-NH3fe)/NH3raw×100**	**SS %** **((SSraw - SSfe)/SSraw)×100**	**PV4 %** **(PV4raw-PV4e)/PV4raw×100**
Jan-19	95%	93%	91%	95%	90%
Feb-19	95%	92%	#DIV/0!	95%	88%
Mar-19	95%	93%	100%	98%	87%
Apr-19	95%	#DIV/0!	#DIV/0!	98%	88%
May-19	95%	90%	#DIV/0!	88%	80%
Jun-19	95%	89%	81%	95%	81%
Jul-19	95%	90%	76%	90%	80%
Aug-19	95%	93%	89%	97%	88%
Sep-19	95%	92%	89%	95%	84%
Oct-19	95%	81%	81%	87%	78%
Nov-19	95%	91%	89%	#DIV/0!	#DIV/0!
Dec-19	95%	85%	50%	99%	88%

Mash					
Overall Plant Reductions					
	Parameter	COD %	NH3 %	SS %	PV4 %
Monitoring Dates	Design Target %	(CODraw-CODfe)/CODraw ×100	(NH3raw-NH3fe)/NH3raw×100	((SSraw - SSfe)/SSraw) ×100	(PV4raw-PV4e)/PV4raw×100
Jan-19	95%	93%	90%	97%	88%
Feb-19	95%	94%	#DIV/0!	99%	89%
Mar-19	95%	93%	90%	99%	87%
Apr-19	95%	#DIV/0!	#DIV/0!	98%	87%
May-19	95%	92%	#DIV/0!	96%	83%
Jun-19	95%	94%	98%	98%	86%
Jul-19	95%	82%	91%	82%	80%
Aug-19	95%	94%	79%	97%	92%
Sep-19	95%	95%	97%	98%	92%
Oct-19	95%	94%	89%	98%	92%
Nov-19	95%	93%	82%	#DIV/0!	#DIV/0!
Dec-19	95%	96%	99%	99%	92%

Appendix E: Biogas Production data

Day	Mash-S1a Volume [Nml]	Mash-S1b Volume [Nml]	Mash-S1c Volume [Nml]	Ver-S1a Volume [Nml]	Ver-S1b Volume [Nml]	Ver-S1c Volume [Nml]	Ph-S1a Volume [Nml]	Ph-S1b Volume [Nml]	Ph-S1c Volume [Nml]	Mash-S2a Volume [Nml]	Mash-S2b Volume [Nml]	Mash-S3c Volume [Nml]	Mash-In Volume [Nml]	Ver-In Volume [Nml]	Ph-In Volume [Nml]
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	25,1	26,6	25,1	50,2	48,6	53,6	21,8	24,1	21,5	26,2	27,6	26,2	6,4	12,2	9,5
2	30,2	31,0	30,7	64,8	69,2	62,7	50,2	55,6	49,2	31,1	31,8	31,6	10,0	15,6	12,8
3	35,4	34,6	35,6	69,7	78,1	78,8	122,9	116,2	120,8	36,0	35,3	36,2	11,4	17,0	14,1
4	44,1	44,1	44,6	75,8	82,6	80,4	126,5	122,9	124,7	44,3	44,3	44,8	16,1	21,5	18,4
5	59,5	59,5	59,0	82,4	91,5	89,9	130,0	130,3	135,2	58,9	58,9	58,5	17,7	23,1	20,0
6	65,6	62,4	61,2	101,0	98,1	106,2	150,3	142,1	143,6	64,7	61,7	60,6	19,9	25,2	22,0
7	66,3	66,6	67,1	149,1	141,9	151,2	161,8	170,5	159,7	65,4	65,7	66,1	29,9	34,7	31,2
8	72,7	71,2	72,0	185,5	181,1	185,2	181,8	187,1	182,0	71,5	70,1	70,8	34,9	39,5	35,8
9	78,5	75,6	79,0	226,3	228,1	220,0	190,7	202,5	199,2	77,0	74,2	77,5	48,2	52,2	48,1
10	88,3	87,6	88,5	243,8	245,4	244,7	207,6	220,9	219,4	86,3	85,6	86,5	50,7	54,6	50,4
11	157,3	192,2	178,3	248,8	250,8	255,8	372,7	374,5	370,9	152,0	185,1	171,9	63,7	67,0	62,5
12	251,0	293,9	279,8	265,4	265,4	262,9	470,8	481,8	474,6	241,0	281,9	268,4	67,0	70,2	65,5
13	321,5	336,3	330,0	273,1	270,1	279,9	543,5	554,8	546,6	308,1	322,2	316,2	89,2	91,4	86,0
14	340,7	350,7	342,4	313,9	310,5	313,0	567,0	573,7	572,9	326,4	335,9	328,0	92,2	94,3	88,8
15	373,2	382,4	377,8	374,1	382,9	362,1	677,4	684,3	683,3	357,3	366,1	361,7	106,1	107,6	101,6
16	402,7	425,1	413,9	423,6	425,6	417,0	713,2	719,9	719,1	385,4	406,7	396,0	129,6	130,1	123,4
17	459,3	467,3	462,7	474,0	474,9	468,5	756,0	760,8	763,4	439,2	446,8	442,4	132,7	133,0	126,2
18	485,8	491,7	496,1	514,2	521,2	511,9	827,9	829,7	836,4	464,5	470,0	474,2	133,2	133,6	126,7
19	583,7	581,5	581,9	582,7	581,8	580,4	938,0	932,6	930,0	557,5	555,4	555,9	145,1	145,0	137,7
20	677,6	670,2	673,9	655,6	661,3	654,7	992,8	991,7	987,1	646,8	639,9	643,3	156,8	156,1	148,5
21	749,7	759,3	754,9	709,8	712,1	703,0	1038,3	1035,0	1031,4	715,5	724,5	720,4	164,0	163,0	155,1
22	795,8	814,1	805,6	782,7	783,6	781,8	1058,3	1062,9	1065,7	759,3	776,7	768,6	165,9	164,8	156,9
23	850,5	859,0	854,6	807,4	804,9	801,1	1129,5	1131,8	1127,9	811,3	819,4	815,2	175,9	174,4	166,1
24	954,4	979,7	967,1	852,4	853,5	846,9	1148,2	1153,5	1150,7	910,1	934,3	922,2	188,4	186,3	177,7
25	1020,2	1053,2	1037,6	878,0	881,7	870,8	1160,4	1157,9	1164,3	972,8	1004,1	989,2	189,2	187,1	178,4
26	1084,4	1102,2	1093,2	941,8	934,3	940,5	1196,0	1180,4	1204,7	1033,8	1050,7	1042,1	192,8	190,5	181,8
27	1153,4	1168,5	1161,7	1047,8	1043,1	1045,6	1241,1	1224,7	1244,4	1099,4	1113,8	1107,3	206,9	204,1	194,8
28	1178,8	1173,2	1165,6	1062,8	1067,6	1058,3	1257,0	1263,1	1258,8	1123,6	1118,2	1111,0	219,7	216,2	206,6
29	1181,5	1178,5	1169,0	1081,4	1092,3	1070,5	1262,8	1271,0	1261,8	1126,1	1123,3	1114,3	231,0	227,1	217,1
30	1182,9	1179,0	1170,5	1100,5	1106,9	1080,5	1263,9	1278,0	1263,1	1127,5	1123,8	1115,7	232,1	228,2	218,1
31	1183,6	1179,5	1171,0	1101,4	1111,8	1085,3	1264,1	1278,7	1264,9	1128,2	1124,3	1116,2	233,0	229,0	218,9
	498,55	**506,15**	**501,57**	**491,88**	**493,78**	**489,47**	**663,20**	**666,03**	**664,92**	**476,48**	**483,71**	**479,35**	**111,24**	**112,33**	**106,28**
	502,09			**491,71**			**664,72**			**479,84**			**109,95**		
$BMP = \frac{Vs - Vi}{mVs,ss}$	169,94			181,18			265,92			147,44					
Max.													400,00	1,25	
$BMP = Vs - Vb\frac{mIS}{mMB}$		170,50			181,79			264,18			147,96		0,02	500,00	
													7,08		

	DAILY BIOGAS RATES														
Day	Mash-S1a Daily Biogas Production [Nml/day]	Mash-S1b Daily Biogas Production [Nml/day]	Mash-S1c Daily Biogas Production [Nml/day]	Ver-S1a Flow [Nml/day]	Ver-S1b Flow [Nml/day]	Ver-S1c Flow [Nml/day]	Ph-S1a Flow [Nml/day]	Ph-S1b Flow [Nml/day]	Ph-S1c Flow [Nml/day]	Mash-S2a Flow [Nml/day]	Mash-S2b Flow [Nml/day]	Mash-S2c Flow [Nml/day]	Mash-In Flow [Nml/day]	Ver-In Flow [Nml/day]	Ph-In Flow [Nml/day]
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	25,1	26,6	25,1	50,2	48,6	53,6	21,8	24,1	21,5	26,2	27,6	26,2	6,4	12,2	9,5
2	5,1	4,4	5,6	14,6	20,7	9,1	28,4	31,5	27,6	4,9	4,2	5,3	3,6	3,4	3,3
3	5,1	3,7	4,9	4,9	8,9	16,1	72,7	60,7	71,7	4,9	3,5	4,6	1,4	1,3	1,3
4	8,8	9,5	9,0	6,1	4,5	1,6	3,6	6,7	3,8	8,4	9,0	8,6	4,7	4,5	4,4
5	15,4	15,4	14,4	6,6	8,9	9,5	3,6	7,4	10,5	14,6	14,6	13,7	1,7	1,6	1,5
6	6,1	2,9	2,2	18,6	6,6	16,3	20,2	11,8	8,4	5,8	2,8	2,1	2,2	2,1	2,0
7	0,7	4,1	5,9	48,1	43,8	44,9	11,5	28,4	16,1	0,7	3,9	5,6	10,0	9,5	9,2
8	6,3	4,6	4,9	36,3	39,3	34,1	20,0	16,6	22,3	6,0	4,4	4,6	5,0	4,8	4,6
9	5,9	4,4	7,1	40,9	47,0	34,7	9,0	15,4	17,2	5,6	4,2	6,7	13,3	12,7	12,3
10	9,8	12,0	9,5	17,5	17,3	24,7	16,9	18,4	20,2	9,3	11,4	9,0	2,5	2,4	2,3
11	69,0	104,6	89,8	5,0	5,4	11,1	165,1	153,6	151,6	65,7	99,5	85,4	13,0	12,5	12,0
12	93,7	101,7	101,5	16,6	14,5	7,0	98,0	107,3	103,7	89,1	96,7	96,5	3,3	3,2	3,1
13	70,5	42,4	50,2	7,7	4,8	17,0	72,7	73,0	71,9	67,0	40,4	47,8	22,2	21,2	20,5
14	19,3	14,4	12,4	40,9	40,4	33,1	23,6	18,9	26,4	18,3	13,7	11,8	3,0	2,9	2,8
15	32,4	31,7	35,4	60,2	72,4	49,0	110,3	110,6	110,3	30,9	30,2	33,6	13,9	13,3	12,8
16	29,5	42,7	36,1	49,5	42,7	54,9	35,8	35,6	35,8	28,1	40,6	34,3	23,5	22,5	21,8
17	56,6	42,2	48,8	50,4	49,3	51,5	42,8	41,0	44,3	53,8	40,1	46,4	3,0	2,9	2,8
18	26,6	24,4	33,4	40,2	46,3	43,4	71,9	68,9	73,0	25,3	23,2	31,8	0,6	0,5	0,5
19	97,8	89,8	85,9	68,6	60,6	68,6	110,1	102,9	93,7	93,0	85,4	81,7	11,9	11,4	11,0
20	93,9	88,8	92,0	72,9	79,4	74,2	54,8	59,1	57,1	89,3	84,4	87,5	11,6	11,1	10,8
21	72,2	89,0	81,0	54,3	50,8	48,4	45,6	43,3	44,3	68,7	84,7	77,0	7,2	6,9	6,7
22	46,1	54,9	50,7	72,9	71,5	78,8	20,0	27,9	34,3	43,8	52,2	48,3	1,9	1,9	1,8
23	54,6	44,9	49,0	24,7	21,3	19,3	71,2	68,9	62,2	52,0	42,7	46,6	10,0	9,5	9,2
24	103,9	120,7	112,4	44,9	48,6	45,9	18,7	21,8	22,8	98,8	114,8	107,0	12,5	11,9	11,5
25	65,9	73,4	70,5	25,7	28,1	23,8	12,3	4,4	13,6	62,6	69,8	67,0	0,8	0,8	0,8
26	64,1	49,0	55,6	63,8	52,7	69,7	35,6	22,5	40,4	61,0	46,6	52,9	3,6	3,4	3,3
27	69,0	66,3	68,5	106,0	108,7	105,1	45,1	44,3	39,7	65,7	63,1	65,2	14,1	13,5	13,1
28	25,4	4,6	3,9	15,0	24,5	12,7	15,9	38,4	14,3	24,1	4,4	3,7	12,7	12,2	11,8
29	2,7	5,4	3,4	18,6	24,7	12,3	5,9	7,9	3,1	2,6	5,1	3,2	11,4	10,9	10,5
30	1,5	0,5	1,5	19,1	14,5	10,0	1,0	6,9	1,3	1,4	0,5	1,4	1,1	1,1	1,0
31	0,7	0,5	0,5	0,9	5,0	4,8	0,3	0,8	1,8	0,7	0,5	0,5	0,8	0,8	0,8

Appendix F: Methane potential yield

Day	Mash-S1a	Mash-S1b	Mash-S1c	Ver-S1a	Ver-S1b	Ver-S1c	Ph-S1a	Ph-S1b	Ph-S1c	Mash-S2a	Mash-S2b	Mash-S2c	Mash-In	Ver-In	Ph-In
0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
1	10,3	10,9	10,3	22,1	21,4	23,6	8,5	9,4	8,4	11,3	11,9	11,3	2,3	4,6	3,7
2	12,4	12,7	12,6	28,6	30,5	27,6	19,6	21,7	19,2	13,4	13,7	13,6	3,6	5,9	5,0
3	14,5	14,2	14,6	30,7	34,4	34,7	48,0	45,4	47,2	15,5	15,2	15,6	4,1	6,4	5,5
4	18,1	18,1	18,3	33,4	36,4	35,4	49,4	48,0	48,7	19,1	19,1	19,3	5,8	8,1	7,2
5	24,4	24,4	24,2	36,3	40,3	39,6	50,8	50,9	52,8	25,4	25,4	25,2	6,4	8,7	7,8
6	26,9	25,6	25,1	44,5	43,2	46,8	58,7	55,5	56,1	27,9	26,6	26,1	7,2	9,5	8,6
7	27,2	27,3	27,5	65,7	62,5	66,6	63,2	66,6	62,4	28,2	28,3	28,5	10,8	13,1	12,2
8	29,8	29,2	29,5	81,7	79,8	81,6	71,0	73,1	71,1	30,8	30,2	30,5	12,6	14,9	14,0
9	32,2	31,0	32,4	99,7	100,5	96,9	74,5	79,1	77,8	33,2	32,0	33,4	17,4	19,7	18,8
10	36,2	35,9	36,3	107,4	108,1	107,8	81,1	86,3	85,7	37,2	36,9	37,3	18,3	20,6	19,7
11	64,5	78,8	73,1	109,6	110,5	112,7	145,6	146,3	144,9	65,5	79,8	74,1	23,0	25,3	24,4
12	102,9	120,5	114,7	116,9	116,9	115,8	183,9	188,2	185,4	103,9	121,5	115,7	24,2	26,5	25,6
13	131,8	137,9	135,3	120,3	119,0	123,3	212,3	216,7	213,5	132,8	138,9	136,3	32,2	34,5	33,6
14	139,7	143,8	140,4	138,3	136,8	137,9	221,5	224,1	223,8	140,7	144,8	141,4	33,3	35,6	34,7
15	153,0	156,8	154,9	164,8	168,7	159,5	264,6	267,3	266,9	154,0	157,8	155,9	38,3	40,6	39,7
16	165,1	174,3	169,7	186,6	187,5	183,7	278,6	281,2	280,9	166,1	175,3	170,7	46,8	49,1	48,2
17	188,3	191,6	189,7	208,8	209,2	206,4	295,3	297,2	298,2	189,3	192,6	190,7	47,9	50,2	49,3
18	199,2	201,6	203,4	226,5	229,6	225,5	323,4	324,1	326,7	200,2	202,6	204,4	48,1	50,4	49,5
19	239,3	238,4	238,6	256,7	256,3	255,7	366,4	364,3	363,3	240,3	239,4	239,6	52,4	54,7	53,8
20	277,8	274,8	276,3	288,8	291,3	288,4	387,8	387,4	385,6	278,8	275,8	277,3	56,6	58,9	58,0
21	307,4	311,3	309,5	312,7	313,7	309,7	405,6	404,3	402,9	308,4	312,3	310,5	59,2	61,5	60,6
22	326,3	333,8	330,3	344,8	345,2	344,4	413,4	415,2	416,3	327,3	334,8	331,3	59,9	62,2	61,3
23	348,7	352,2	350,4	355,7	354,6	352,9	441,2	442,1	440,6	349,7	353,2	351,4	63,5	65,8	64,9
24	391,3	401,7	396,5	375,5	376,0	373,1	448,5	450,6	449,5	392,3	402,7	397,5	68,0	70,3	69,4
25	418,3	431,8	425,4	386,8	388,4	383,6	453,3	452,3	454,8	419,3	432,8	426,4	68,3	70,6	69,7
26	444,6	451,9	448,2	414,9	411,6	414,3	467,2	461,1	470,6	445,6	452,9	449,2	69,6	71,9	71,0
27	472,9	479,1	476,3	461,6	459,5	460,6	484,8	478,4	486,1	473,9	480,1	477,3	74,7	77,0	76,1
28	483,3	481,0	477,9	468,2	470,3	466,2	491,0	493,4	491,7	484,3	482,0	478,9	79,3	81,6	80,7
29	484,4	483,2	479,3	476,4	481,2	471,6	493,3	496,5	492,9	485,4	484,2	480,3	83,4	85,7	84,8
30	485,0	483,4	479,9	484,8	487,6	476,0	493,7	499,2	493,4	486,0	484,4	480,9	83,8	86,1	85,2
31	485,3	483,6	480,1	485,2	489,8	478,1	493,8	499,5	494,1	486,3	484,6	481,1	84,1	86,4	85,5
	204,4	**207,5**	**205,6**	**216,7**	**217,5**	**215,6**	**259,1**	**260,2**	**259,7**	**205,4**	**208,5**	**206,6**	**40,2**	**42,4**	**41,5**
Averages	**205,9**			**216,6**			**259,7**			**206,8**					
Gas Production		**Vs**			**Vs**			**Vs**			**Vs**				
$BMP = \frac{Vs - Vi}{mVs,ss}$	**72,0**			**83,0**			**103,9**			**66,7**			VB		
	NmL/gVS			NmL/gVS			NmL/gVS			NmL/gVS					
Max															
$BMP = \frac{Vs - Vb\frac{mIS}{mMB}}{mVs,ss}$	**72,0**			**83,0**			**103,9**			**66,7**					

DAILY METHANE RATES

Day	Mash-S1a	Mash-S1b	Mash-S1c	Ver-S1a	Ver-S1b	Ver-S1c	Ph-S1a	Ph-S1b	Ph-S1c	Mash-S2a	Mash-S2b	Mash-S2c	Mash-In	Ver-In	Ph-In
0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
1	10,3	10,9	10,3	22,1	21,4	23,6	8,5	9,4	8,4	11,3	11,9	11,3	2,3	4,6	3,7
2	2,1	1,8	2,3	6,5	9,1	4,0	11,1	12,3	10,8	2,1	1,8	2,3	1,3	1,3	1,3
3	2,1	1,5	2,0	2,2	3,9	7,1	28,4	23,7	28,0	2,1	1,5	2,0	0,5	0,5	0,5
4	3,6	3,9	3,7	2,7	2,0	0,7	1,4	2,6	1,5	3,6	3,9	3,7	1,7	1,7	1,7
5	6,3	6,3	5,9	2,9	3,9	4,2	1,4	2,9	4,1	6,3	6,3	5,9	0,6	0,6	0,6
6	2,5	1,2	0,9	8,2	2,9	7,2	7,9	4,6	3,3	2,5	1,2	0,9	0,8	0,8	0,8
7	0,3	1,7	2,4	21,2	19,3	19,8	4,5	11,1	6,3	0,3	1,7	2,4	3,6	3,6	3,6
8	2,6	1,9	2,0	16,0	17,3	15,0	7,8	6,5	8,7	2,6	1,9	2,0	1,8	1,8	1,8
9	2,4	1,8	2,9	18,0	20,7	15,3	3,5	6,0	6,7	2,4	1,8	2,9	4,8	4,8	4,8
10	4,0	4,9	3,9	7,7	7,6	10,9	6,6	7,2	7,9	4,0	4,9	3,9	0,9	0,9	0,9
11	28,3	42,9	36,8	2,2	2,4	4,9	64,5	60,0	59,2	28,3	42,9	36,8	4,7	4,7	4,7
12	38,4	41,7	41,6	7,3	6,4	3,1	38,3	41,9	40,5	38,4	41,7	41,6	1,2	1,2	1,2
13	28,9	17,4	20,6	3,4	2,1	7,5	28,4	28,5	28,1	28,9	17,4	20,6	8,0	8,0	8,0
14	7,9	5,9	5,1	18,0	17,8	14,6	9,2	7,4	10,3	7,9	5,9	5,1	1,1	1,1	1,1
15	13,3	13,0	14,5	26,5	31,9	21,6	43,1	43,2	43,1	13,3	13,0	14,5	5,0	5,0	5,0
16	12,1	17,5	14,8	21,8	18,8	24,2	14,0	13,9	14,0	12,1	17,5	14,8	8,5	8,5	8,5
17	23,2	17,3	20,0	22,2	21,7	22,7	16,7	16,0	17,3	23,2	17,3	20,0	1,1	1,1	1,1
18	10,9	10,0	13,7	17,7	20,4	19,1	28,1	26,9	28,5	10,9	10,0	13,7	0,2	0,2	0,2
19	40,1	36,8	35,2	30,2	26,7	30,2	43,0	40,2	36,6	40,1	36,8	35,2	4,3	4,3	4,3
20	38,5	36,4	37,7	32,1	35,0	32,7	21,4	23,1	22,3	38,5	36,4	37,7	4,2	4,2	4,2
21	29,6	36,5	33,2	23,9	22,4	21,3	17,8	16,9	17,3	29,6	36,5	33,2	2,6	2,6	2,6
22	18,9	22,5	20,8	32,1	31,5	34,7	7,8	10,9	13,4	18,9	22,5	20,8	0,7	0,7	0,7
23	22,4	18,4	20,1	10,9	9,4	8,5	27,8	26,9	24,3	22,4	18,4	20,1	3,6	3,6	3,6
24	42,6	49,5	46,1	19,8	21,4	20,2	7,3	8,5	8,9	42,6	49,5	46,1	4,5	4,5	4,5
25	27,0	30,1	28,9	11,3	12,4	10,5	4,8	1,7	5,3	27,0	30,1	28,9	0,3	0,3	0,3
26	26,3	20,1	22,8	28,1	23,2	30,7	13,9	8,8	15,8	26,3	20,1	22,8	1,3	1,3	1,3
27	28,3	27,2	28,1	46,7	47,9	46,3	17,6	17,3	15,5	28,3	27,2	28,1	5,1	5,1	5,1
28	10,4	1,9	1,6	6,6	10,8	5,6	6,2	15,0	5,6	10,4	1,9	1,6	4,6	4,6	4,6
29	1,1	2,2	1,4	8,2	10,9	5,4	2,3	3,1	1,2	1,1	2,2	1,4	4,1	4,1	4,1
30	0,6	0,2	0,6	8,4	6,4	4,4	0,4	2,7	0,5	0,6	0,2	0,6	0,4	0,4	0,4
31	0,3	0,2	0,2	0,4	2,2	2,1	0,1	0,3	0,7	0,3	0,2	0,2	0,3	0,3	0,3