OPTIMISATION OF BIOGAS PRODUCTION FROM CO-DIGESTION OF WATER HYACINTH, MUNICIPAL SOLID WASTE AND COW DUNG

by

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Submitted in partial fulfillment of the requirements for the degree
Philosophiae Doctor (Electrical Engineering)

in the

Department of Electrical, Electronic and Computer Engineering
Faculty of Engineering, Built Environment and Information Technology

UNIVERSITY OF PRETORIA

November 2021

SUMMARY

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Keywords:	Anaerobic digestion, Bioenergy, Biogas, Co-digestion, Cow dung, Hybrid energy system, Liquid petroleum gas, Modelling, Munucipal solid waste, Optimisation, Renewable energy, Substrate mix ratios, Water hyacinth

The acceleration and integration of renewable energy technologies (RETs) is at the core of research and development in a bid to deal with climate change issues as well as to ensure sufficient energy access to all. The incorporation of RETs requires thorough investigations to ensure that energy generation via these routes is maximised to obtain optimal yields and that their assimilation into the existing energy demand and supply mix is smooth and competitive. Anaerobic digestion is one such renewable energy technology avenue, which produces bioenergy in the form of biogas, a biofuel. Anaerobic co-digestion of different substrates is reported to increase biogas output volumes owing to the optimistic interactions created in the digestion medium, microbial variations in diverse substrates as well as provision of missing nutrients by the co-substrates. This will help to deal with the issues of environmental sustainability since wastes will be converted to energy as well as help to strike a balance between energy demand and supply.

In order to maximise the overall biogas yield from co-digestions, modelling and optimisation using

specific substrates such as water hyacinth, cow dung and municipal solid waste is necessary. This necessitates the need for mathematical modelling and application of optimisation tools in biogas production to accurately arrive at optimal parameters such as the co-digestion substrate mixing ratios as opposed to just the experimental approaches which are more of a trial and error way of getting these optimal feed ratios. The overall optimal yields are affected by the time of the year and the environment from which the substrates are derived from since these dictate the amount and quality of the same. Biogas production and optimisation models developed to date do not account for the accuracy of co-digestion blending ratios, the improvement of the quality of biogas, geographical/environmental and seasonal variation of substrates. The integration of biogas in hybrid systems to cater for energy demand has not been dealt with in an in-depth way targeting energy cost reductions and minimisations of fossil fuel usages. This study aims to enhance biogas production from the co-digestion of varied substrates (water hyacinth, municipal solid waste and cow dung are used in this research work) by way of exploring simulation, modelling and optimisation approaches in combination with mathematical analytical tools.

Firstly, a survey of previous works on the subject matter is conducted to investigate the status, current trends and future perspectives of anaerobic co-digestion, modelling and optimisation with focus on enhancing biogas yields. A model for biogas production is built based on Boyle's modified Buswell and Mueller equation (3.2) in which carbon, hydrogen, oxygen, nitrogen and sulphur make up the elemental constuents of the biomaterial composition and methane, carbon dioxide, ammonia and hydrogen sulphide constitute the biogas product. Baseline biogas potential yields of 747.4 Nml/gVS, 790.83 Nml/gVS and 884.24 Nml/gVS were obtained from water hyacinth, municipal solid waste and cow dung respectively in a case study. The formulated model is further developed and optimised to give optimal co-digestion substrate blending ratios for varied co-digestion mixtures of which water hyacinth, municipal solid waste and cow dung are used for the purposes of this study. The optimisation problem is solved using a linear programming mathematical approach in MATLAB. Optimal co-digestion results in co-digestion percentage substrate blending ratios of 53.27 : 24.64 : 22.09 for water hyacinth, municipal solid waste and cow dung respectively in a case study. 1 kg of substrate mixture yields 124.56 m^3 of biogas which translates to 124 560 Nml/gVS. Co-digestion and optimisation of substrate blend mix proportions increased the biogas output by 157.11 %.

Seasonal variations in the availability of co-digestion substrates are incorporated in an advanced formulation and development of a co-digestion model in which the methane component of biogas is maximised whilst the other components (carbon dioxide, ammonia and hydrogen sulphide) are minimised so as to improve the quality of the biogas. The formulated problem was solved using the Optimisation Interface tool (OptiTool) in combination with the Solving Constraint Integer Programs (SCIP) toolbox in MATLAB. Finally the methane-optimised biogas is hybridised with liquid petroleum gas in a bid to cut down import costs as well as to lower pollutant emissions from the liquid petroleum gas fossil fuel which is conventionally used (by a community in a case study) for heating and cooking purposes. Consideration of seasonality changes in the availability of substrates in the modelling and optimisation led to an increase of 174.58 % in annual biogas output. A 6.97 % annual lowest cost savings was realised in winter and 18.24 % annual highest cost savings was realised in summer from the methane-optimised biogas-liquid petroleum gas hybrid system. Physical laboratory experimental approaches towards biogas production enhancement and optimisation are out of scope of this study. However, their integration with this particular kind of work together with multi-stage co-digestion is recommended for future studies.

DEDICATION

This thesis is dedicated to my children Nyasha Kunatsa and Makanaka Kunatsa. I hope this will be an inspiration to you in life. Endeavour to acquire as much education as you can not just to have knowledge but also to be think tanks and innovators in whatever disciplines you will venture into. To my beloved wife Yvonne Kunatsa, the sky is the limit, excellence is yours in your academic and other pursuits in life, just keep on foccussed and determined.

To my parents Mr Raphael Kunatsa and Mrs Judith Kunatsa, you sacrificed a lot and strived to see me through my entire educational journey. The foundation and grounding you gave helped me to reach this far. To my brothers Luke, Tonderai, Alec and sister Beauty, I am grateful to have you as siblings. In loving memory of our late beloved brother Farai, may his dear soul rest in eternal peace. Each of you had their significant contribution in one way or the other in my life. Your support and confidence in me has helped me to reach this far.

ACKNOWLEDGEMENT

Acknowledgements goes to the National Hub for the Postgraduate Programme in Energy Efficiency and Demand Side management (EEDSM) and the University of Pretoria, Centre of New Energy Systems (CNES) for financial support rendered.

Chinhoyi University of Technology is hereby acknowledged for granting me a study leave and for supporting me financially through the Staff Development Fund (SDF) scheme. Thank you for the opportunity you gave to me to further my studies.

Heartfelt gratitude goes to my supervisor; Professor Xiahoua Xia and my co-supervisor Professor Lijun Zhang for their supervision, guidance and assistance throughout the entire research, may you continue to impart your wisdom to those in need of it.

Acknowledgements go to the Zimbabwe Environmental Management Agency (EMA), Zimbabwe Parks & Wildlife Management, Zimbabwe National Water Authority (ZINWA) and The Department of Livestock and Verterinary Services under the Ministry of Lands, Agriculture, Water, Climate and Rural Resettlement for granting permission and access to their premises and provision of research data.

Appreciation goes to Dr Downmore Musademba, Dr Chido Hermes Chihobo and the entire Chinhoyi University of Technology Fuels & Energy department for encouragement, advice and support.

Thanks also to my research colleagues at the Centre for New Energy Systems hub, Dr. C. Kagiri, Mr. F. Wamalwa, Dr. A. Ikuzwe, Mr. T. Nyamayoka, Mr. J. Tshikaya, Mr. D. Bajany, Mr. S. Masaki, Mr. D. Mulongoti, Mr. D. Lin, Dr. J. Mei, Mrs. M. Michaels Ntsula, Mrs. D. Siyakimu, Dr. F. Badzegar and Mr. A. Njepu. You were quite an inspirational team and I got great motivation from all of you. Lots of appreciation to Professor. X. Ye for organising and spearheading research meetings.

My wife Yvonne Kunatsa, my son Nyasha Kunatsa, my daughter Makanaka Kunatsa, my parents Mr. and Mrs. Kunatsa and my inlaws Mr. and Mrs. Shonhe, I appreciate your tremendous love, inspiration and support. We have been through it all together, you stood by me when I needed you the most. Thank you for being my pillars and being there for me.

To the almighty God, the father of our Lord and saviour Jesus Christ who promised to be with me right from the inception of this PhD journey, and to this end He has been faithfull. Glory be unto Him forever and ever. Amen!

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November 2021

LIST OF ABBREVIATIONS

ACO	Ant colony optimization
AD	Anaerobic digestion
ADM1	Anaerobic digestion model No. 1
ANN	Artificial neural networks
CD	Cow dung
CNES	Centre of new energy systems
EEDSM	Energy efficiency and demand side management
EMA	Environmental management agency
GHG	Green house gases
MSW	Municipal solid waste
RETs	Renewable energy technologies
SCIP	Solving constraint integer programs
SDF	Staff development fund
TS	Total solids
VFAs	Volatile fatty acids
VS	Volatile Solids
WH	Water hyacinth
ZINWA	Zimbabwe national water authority

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CHAPTER 1 INTRODUCTION

1.1 PROBLEM STATEMENT

1.1.1 Context of the problem

The energy sectors world over are faced with a task to come up with alternative sources of energy to substitute fossil derived fuels. There is urgent need for boosting energy generation to fill in the shortfalls in supply to the ever increasing energy demand. Generating energy from alternative sources will help in climate change mitigation and minimisation of alarms posed to the environment [1]. There has been a high uptake of renewable energy technologies (RETs) world over in a bid to deal with the detrimental effects paused by fossil related energy generation technologies. In a bid of increasing energy accessibility whilst simultaneously restricting worldwide temperature increament to 2 °C, adoption of RETs and energy efficiency must be encouraged and raised significantly [2]. This growing impetus for renewable energy alternative avenues demands the consideration of different feedstocks, development of novel techniques, as well as improvements to existing technologies.

Bio-energy can be regarded as the most substantial renewable energy source due to its cost-effective advantages and its great potential to substitute non-renewable fuel sources. Bioenergy comes from biomass materials: any biological organic matter obtained from plants or animals. Biomass energy sources include but are not limited to terrestrial plants, aquatic plants, timber processing residues, municipal solid wastes, animal dung, sewage sludge, agricultural crop residues and forestry residues. It is one of the most versatile among the renewable energies since it can be made available in solid, liquid and/or gaseous forms. Different avenues can be explored to haverst energy from biomass materials.

Biogas originates from anaerobic digestion (AD) of biodegradable biological materials. Biogas generation via AD has advantages of better compatibility with the environment. The process makes use of continuously generated accumulating quantities of bio-wastes, value adding them into some form of energy [3]. This technology reduces the discharges of greenhouse gases leading to a sustainable form of energy and a cleaner environment [4].

Anaerobic digestion is the breaking down of biomaterials by bacteria in an environment without oxygen. It is the most favourable substitute to discarding of biodegradable organic municipal solid waste, agricultural residues and animal wastes because of its efficient energy recovery nature. The bio-conversion is catalysed by a huge consortia of microorganisms complementing each other, catalysing the diverse biochemical reactions, therefore the metabolic pathways accompanying anaerobic digestion are quite complex. In anaerobic digestion, co-digestion entails simultaneous digestion of varied wastes having harmonising features. In the AD process biomass materials are broken down by bacterial action in an oxygen free environment producing a gaseous blend comprising mainly of methane [5]. This gaseous blend/mixture is known as biogas and it consists of methane, carbon dioxide, hydrogen sulphide, ammonia, hydrogen and water vapour. A mineral rich digestate which is usually referred to as spent slurry or sludge, a bio-fertiliser is also obtained as a secondary product of the biogas generation process.

In contrast with other biofuels, biogas production is flexible to different substrates on condition that they are biodegradable. The waste streams which are the raw materials for biogas production vary significantly due to seasonal and geographical location causing a dissimilarity in biogas yields reported by various authors [6]. The substrate must have the dietary rations for the microorganisms for it to be biodegraded optimally. Therefore, structure and constituent components of feed is exceedingly crucial in AD to optimally produce biogas.

Water hyacinth is an invasive species invading water bodies, out-competing other species and decreasing biodiversity [7, 8]. Municipal solid waste is dumped in landfills resulting in the formation of a more intoxicating greenhouse gas. Municipal solid waste and cow dung have been implicated in poor aesthetic quality of the environment and pollution of surface and ground water sources. Agricultural wastes (plant and animal), *Eichhornia crassipes* (water hyacinth) and municipal solid waste are hugely available sources to be tapped into for the attainment of biogas [8, 9]. Anaerobic co-digestion of different feedstocks integrated with subsequent optimisations can bring about enhanced yields of biogas. With respect to substrates for anaerobic digestion, use of wastes is prioritised over other options since it addresses the environmental pollution issues while simultaneously generating energy

[10].

According to [11], co-digestion increases biogas outputs, however, it has a disadvantage of largely still remaining unstudied for many varying substrates. Biogas production is enhanced by co-digestion of different substrates rather than individual substrates but there is difficulty in getting to the exact blend ratio for optimality since it depends on the type of substrates together with actual reaction conditions availed [3]. Co-digestion technology needs scrutinised supervision and controlling since no single customary set of working parameters could be practical to all organic biodegradable wastes. Given this scenario, and that the availability of raw materials is of broad nature, this study researches on co-digestion, modelling and optimisation of biogas generation.

1.1.2 Research gap

Biogas potential determination for a wide range of bio-degradable feedstocks are yet to be ascertained. A number of ways ranging from experimental to theoretical tools are available for use to determine biogas potential of bio-materials [12]. Varied researchers [13, 14] used the physical experimental biomethane potential prediction approach for different biomass materials. However, no previous works investigated on the optimal co-digestion substrate blending ratios using accurate well informed simulation and modelling analytical mathematical approaches and little is reported on biogas and/or biomethane potential of co-digestion mixtures. Dynamic, steady state and computational models based on individual substrates such as sludge, manures, organic waste and municipal solid waste are the key existing anaerobic digestion models [15, 16, 17, 18], nevertheless without accompanying optimisations and thus optimisation and modelling of biogas production from different substrate mixtures in co-digestion still remains an area requiring further investigtions. Modelling and optimisation of biogas production from different substrate mixtures incorporating seasonal variations in availability of the substrates is lagging behind in research and development. Current biogas production processes are not fully exploiting co-digestion of multifaceted bio-materials with manures and other biowastes to optimise the overal biogas yields.

1.2 RESEARCH OBJECTIVE AND QUESTIONS

The main objectives of this research are:

- to investigate the current status, recent trends and future perspectives in biogas production, modelling and optimisation of anaerobic co-digestion

- to determine the mono-digestion biogas potentials of water hyacinth, municipal solid waste and cow dung substrates
- to develop a model for the modelling and subsequent optimisation of anaerobic co-digestion of water hyacinth, municipal solid waste and cow dung
- to find substrate blend ratios in the co-digestion mixture that maximises biogas production from water hyacinth, municipal solid waste and cow dung
- to develop a model which facilitates the attainment of high quality biogas constituted of a high proportion of methane while at the same time taking into consideration the seasonality changes of the substrates.
- to hybridise the high quality methane-optimised biogas with Liquid Petroleum Gas (LPG) and channel it towards the gas requirements of a community where LPG meets the rest of the demand not met by the biogas

The following are the research questions of this study:

- What are the current, recent trends and future perspectives of anaerobic digestion when it comes to co-digestion, modelling and optimisation?
- How can anaerobic co-digestion be modelled and optimised to obtain enhanced biogas yields?
- How can the biogas potential of different (individual and mixed) substrates such as water hyacinth, municipal solid waste and cow dung be ascertained using mathematical analytical tools other than just the conventional experimental route which others can't access or afford?
- How to determine optimal co-digestion substrate blend ratios using the simulation, modelling and optimisation route?
- How can the quality of biogas be improved to have more of the methane component in the ultimate yield?
- What is the effect of seasonal changes on the availability of substrates and how does this affect anaerobic co-digestion?
- What is the effect of hybridisation of biogas with other conventional fuels such as liquid petroleum gas?

1.3 APPROACH

Firstly, a survey of previous works on the subject matter is conducted to investigate the status, current trends and future perspectives of anaerobic co-digestion, modelling and optimisation with focus on enhancing biogas yields. A model for the determination of biogas potential is formulated based on simulation and modelling mathematical analytical tools. The formulated model is further developed and optimised to give optimal co-digestion substrate blending ratios for varied co-digestion mixtures of which water hyacinth, municipal solid waste and cow dung are used for the purposes of this study. The optimisation problem is solved using a linear programming mathematical approach in MATLAB. Then seasonal variations in the availability of co-digestion substrates are incorporated in an advanced formulation and development of a co-digestion model in which the methane component of biogas is maximised whilst the other components (carbon dioxide, ammonia and hydrogen sulphide) are minimised so as to improve the quality of the biogas. Finally the methane-optimised biogas is hybridised with with liquid petroleum gas in a bid to cut down import costs as well as to lower pollutant emissions from the liquid petroleum gas fossil fuel which is conventionally used. Physical laboratory experimental investigations are out of scope of this study, due to time and financial constraints for this study.

1.4 RESEARCH GOALS

The goals of this research are to determine biogas potentials of water hyacinth, municipal solid waste and cow dung as well as to model and optimise the anaerobic co-digestion of these substrates inorder to attain optimal substrate blend ratios and ultimately enhanced biogas yields. Poor perfomances of energy sources and inadequacy of current energy supplies to meet demand is of great concern world over. As such it is the goal of this research to improve the efficiency and/or quality of the generated biogas by developing an optimisation model which maximises the methane component and minimises the other constituents of the biogas. The other goal is to improve access to environmentally friendly and affordable energy by developing a hybrid system of methane-optimised biogas and other conventional fuels such as liquid petroleum gas.

1.5 RESEARCH CONTRIBUTION

The contributions of this research are as follows:

- the development of an anaerobic digestion model which determines biogas potentials for both mono-digestion and co-digestion substrates.

- The development of an optimal anaerobic co-digestion model that foretells substrate blending ratios.
- The development of a model and optimisation formulations which take seasonal changes of co-digestion substrates availability into account.
- The development of a model and its subsequent optimisations which cater for improvement of biogas quality by maximisation of methane and minimisation other biogas constituent components
- This work value adds to the existing knowledge in academia and provides more opportunities for new and further investigations in the biogas arena. Small to medium enterprises as well as commercial biogas players will benefit from the results of this work in ventures to invest in biogas technology.
- This work gives an important contribution to the current world shift towards renewable energy technologies and energy efficient approaches when it comes to energy generation and use as it feeds in immensely to the mitigation of climate change by promoting generation of biogas, a renewable biofuel.
- This work fosters the efficient use of energy systems by advancing hybrid energy systems. A methane-optimised biogas-liquid petroleum gas hybrid system approach developed in this in study has the potential to bring about a huge difference to energy transformation in developing countries like Zimbabwe where energy access is still a huge challenge for many. Dependence on imported fossil fuels such as liquid petroleum gas will be reduced and monetery savings on imports will be realised as more biogas in the hybrid system will be tapped in to meet part of the energy demand.

1.6 RESEARCH OUTPUTS

1.6.1 Journal papers

T. Kunatsa, L. Zhang, and X. Xia, "Biogas potential determination and production optimisation through optimal substrate ratio feeding in co-digestion of water hyacinth, municipal solid waste and cow dung," Biofuels, pp. 1–11, 2020.

T. Kunatsa and X. Xia, "Co-digestion of water hyacinth, municipal solid waste and cow dung: A methane optimised biogas-liquid petroleum gas hybrid system," Applied Energy, vol. 304, p. 117716, 2021.

T. Kunatsa and X. Xia, "A review on anaerobic digestion with focus on the role of biomass co-digestion, modelling and optimisation on biogas production and enhancement," Bioresource Technology, p. 126311, 2021.

1.7 OVERVIEW OF STUDY

The layout of the rest of this thesis is as follows:

Chapter 2, describes the review of the literature for this study. Topics covered in the review include biochemical processes in anaerobic digestion, anaerobic digestion technologies and feeding modes, factors that affect biogas production, anaerobic codigestion, modelling and optimisation of anaerobic digestion, techno-economic analysis of anaerobic digestion as well as research gaps and future perspectives.

In Chapter 3, a model for the determination of biogas potential from individual substrates as well as from co-digestion substrates is formulated and developed. The model is further developed and subsequent optimisations are done to give optimal co-digestion substrate blending ratios for water hyacinth, municipal solid waste and cow dung in a case study. The developed model and the accompanying optimisation formulations are applicable to any other anaerobic digestion co-substrates and can be used in any part of the world.

In Chapter 4, a unique methane-optimized biogas-liquid petroleum gas hybrid system model which incorporate seasonal variations of co-digestion substrates is formulated and developed. The model is applied in a case study with anaerobic co-digestion of water hyacinth, municipal solid waste, and cow manure. In the developed model, biogas production is enhanced as the model simultaneously determines optimal mixing ratios and improves the biogas quality by integrating formulations (in its objective function and constraints) which maximise methane and minimises carbon dioxide, ammonia and hydrogen sulphide. The methane optimised biogas is fed to a demand in a hybrid system with liquid petroleum gas in a case study application. The Optimisation Interface tool (OptiTool) was used in conjunction with the Solving Constraint Integer Programs (SCIP) toolbox in MATLAB to solve the formulated optimisation problem which also took into account seasonal fluctuations in biomass feedstocks.

In Chapter 5, conclusions drawn from the study are given and recommendations for future research works are provided.

CHAPTER 2 LITERATURE REVIEW

2.1 CHAPTER OVERVIEW

This chapter gives the literature study of this thesis and is based on our published work [19] entitled "A review on anaerobic digestion with focus on the role of biomass co-digestion, modelling and optimisation on biogas production and enhancement". The status, recent trends and future perspectives in anaerobic digestion, modelling and optimisation of anaerobic co-digestion are reviewed in herein this chapter. Areas that can be focused on and those which need further research towards enhancing biogas production are pointed out. Co-digestion, modelling and optimisation of anaerobic digestion as well as techno-economic aspects are reviewed in this chapter.

Section 2.2 discusses biochemical processes in anaerobic digestion. In Section 2.3 anaerobic digestion technologies and modes of feeding are reviewed. The factors that affect biogas production are discussed in Section 2.4, In Section 2.5, anaerobic co-digestion is discussed and reviewed. Literature on modelling and optimisation of anaerobic digestion is reviewed in Section 2.6, Section 2.7 discusses the techno-economic analysis of anaerobic digestion. In Section 2.8 some research gaps and future perspectives of anaerobic digestion are given. Section 2.9 concludes the literature review chapter.

2.2 BIOCHEMICAL PROCESSES IN ANAEROBIC DIGESTION

The AD process constitutes of hydrolysis, acidogenesis, acetogenesis as well as methanogenesis [20]. During enzymatic hydrolysis complex bio-matter embedded in lignocellulosic substrates is converted to simpler uncomplicated structures [20]. This stage is reported to have the most influence on the speed of the AD progression reaction [21]. Monomers produced by hydrolysis develop to be feed material for the microbes in the second stage [22].

In acidogenesis microbes of anaerobic and facultative type, jointly named the acid formers, hydrolyse and ferment composites into volatile solids and acids [23]. This acidification stage generates hydrogen, which is catalyzed by facultative or strict anaerobes, as well as some aerobes. Clostridium butyricum, Clostridium pasteurianum, Clostridium saccharobutylicum, and Enterobacter aerogenes produce hydrogen under mesophilic conditions, while Caldicellulosiruptor saccharolyticus and Thermoanaerobacterium thermosaccharolyticum produce hydrogen in thermophilic conditions [24, 25]. Compound organic materials are changed to simple chemical organic acids. The acidic medium is brought about by the production of NH_3, H_2, CO_2, H_2S and volatile fatty acids amongst others [26]. Sometimes, these acids can be released in huge quantities thereby lowering the pH level consequently arresting all biological activity. According to [20], acidogenesis can go for two weeks and huge amounts of CO_2 are emitted during this time. The simple molecules which emanate from the acidogenesis phase are further worked upon in acetogenesis by microbes to a complete conversion producing mainly acetic acid, H_2 and CO_2 [26]. Acetogens link the four biochemical stages of biogas production [20]. Acetogenesis provide hydrogen and acetate which are the two major inputs for transforming biodegradable materials.

In the final methanogenesis step, organic acids formed in the preceding reactions are converted into CH_4 and CO_2 by strictly anaerobic microbes known as the methane fermenters [4]. During this stage, methanogenic bacteria produce methane by fermenting acetic acid and finally reducing CO_2. A specific type of bacteria known as the methanogenic archaea dominates this last stage of anaerobic digestion. These are characterised by the existence of the co-factor F_{420}, which works as a hydrogen carrier in the presence of hydrogenase and is found only in methanogenic bacteria [25]. In the acidogenic stage, active methanogens arise, but the quantity of methanogenic archaea grows in the methanogenic stage. It was reported by [27] that acetoclastic methanogenic genus Methanosaeta and hydrogenoclastic methanogenic genera such as Methanolinea, Methanospirillum, Methanobrevibacter, Candidatus Methanofastidiosa, and Methanosarcina dominate the methanogenesis stage of biogas production.

2.3 ANAEROBIC DIGESTION TECHNOLOGIES AND MODES OF FEEDING

Biogas is produced using either the wet anaerobic digestion technology or the dry anaerobic digestion technology [28]. In the wet technology the substrates are mixed with water to make a bio-slurry which constitutes about 90 % water. Examples of digesters used in the wet digestion technology include fixed dome, floating drum, polyethylene tube digesters and balloon digesters. In dry digestion technology the substrates are not mixed with water but slurry with cultured microbes can be added. Dry digestion is usually done on raw materials with a lot of fibre. The digestion chambers can look more like composting facilities. AD maybe classified as "single" or "multi" stage. In multi-stage digestion there are two or more reaction chambers separating the bioprocesses whilst in single stage there is only one reaction chamber in which all the bioprocesses occur. The digester feeding mechanisms can be categorised into batch feeding and continuous feeding. In batch feeding substrates are fed once and left till they are completely digested before a new set of substrates is fed. In continuous digestion a certain constant quantity of feed is administered to the reactor at regular intervals.

2.4 FACTORS THAT AFFECT BIOGAS PRODUCTION

The purpose of this subsection is to explore the aspects that can be dealt with in a bid to enhance the biogas production process. The following factors are very important when looking at prospects of enhancing biogas production. Improved ultimate biogas yields can be achieved if careful consideration of these factors is adhered to.

2.4.1 Temperature

Temperature variations lead to significant changes in AD process due to alterations in bacterial population. In comparison to other microbes, methanogenic bacteria are extremely quick to respond to temperature alterations [29]. Anaerobic fermentation is in principle possible within the temperature range of 3 - 70 °C. Psychrophilic digestion occurs at temperatures of 20 °C and below, mesophilic digestion occurs within the range of 20 - 40 °C and thermophilic digestion occurs at temperatures of 40 °C and above. Nevertheless, anaerobic microorganisms are effective within the mesophilic and thermophilic categories [30]. According to [31], the duration of hydrolysis and acidogenesis is temperature dependent.

Psychrophilic digestion needs longer retention times as microbial growth and conversion progressions are sluggish under low temperature environments consequently necessitating bigger digester capacities. Smaller digester capacities are required in mesophilic digestion. Thermophilic digestion is more preferred when pathogen removal is a critical issue. For the thermophilic temperature AD process, stability is disturbed by temperature variations [32]. Increased feeding rates are possible during thermophilic digestion. Anaerobic digestion is possible even at 0 °C, however, biogas generation scales up with increased temperature up to the critical point. [33] studied the effect of mesophilic and thermophilic temperature phase variations using horse manure and a biogas increase of 58.1 % and 59.8 % was noted respectively. [34] reported a double increase in methane production rate on a research using buffalo excretement in the thermophilic category. [35] reported mesophilic optimal of 30 - 35 °C in addition to 55 - 60 °C for the thermophilic AD category. Generally, reaction kinetics double with each 10 °C increament up to an optimal around 60 °C.

2.4.2 Innoculation

Inoculation is the process of starting an anaerobic system with a high concentration of anaerobic organisms (for instance, digester effluent). During the startup of an anaerobic digester, the quality and quantity of inoculums are crucial to the performance, time required, and stability of bio-methanogenesis [36]. The microorganisms required for digestion would already be existing in pretty small proportions in manures and some wastes, albeit in sufficient proportions to act as inoculums, and will proliferate into completely operational microbial populations if the correct conditions are availed.

2.4.3 pH

The pH inside an anaerobic digester constantly varies as the process proceeds. In the early acid forming phase, in the fermentation progression, the pH is about 6 and a lot of CO_2 is released. The pH rises corresponding to the rise in acid and nitrogen compounds are assimilated and methane is formed. pH has to be monitored and maintained in the digester so as to keep having a perpetual gas supply. Buffering is needed so as to keep the pH in the range of 6.5 to 7.5 [37]. Anaerobic bacteria will be very lively in this pH range and biomass degradation will be very optimal. Hydrogen ion potential above or below this will impede fermentation. Introducing a lot of substrate causes acid concentration to be higher than required ultimately rendering micro-organisms ineffective. Ammonia is added to increase and restore the pH quickly. When the acid is insufficient the pH value grows high and the degradation process becomes sluggish up to the extent when the fermentation progression creates adequate acidic CO_2 to re-establish stability [20].

2.4.4 Substrate carbon to nitrogen proportion

The substrate embedded carbon and nitrogen are crucial in biogas generation. Research on anaerobic co-digestion highlights that overall obtainable biogas has leeway of being upgraded by regulating substrate carbon to nitrogen ratio (C/N) [38]. [39] noted that animal dungs normally have more carbon while crop wastes and aquatic weeds have high nitrogen values. Co-digesting these different substances expedites increased biogas production having high methane content which enhances the combustion characteristics of the biogas [39]. Main foods for the anaerobic microorganisms are carbohydrates which contain carbon, and protein as well as ammonium nitrates which contain nitrogen. Carbon sustains energy while nitrogen aids cell structure building. Microbes consume carbon nearly 30 times quicker than they expend nitrogen [40]. A proportion of 30:1 for C:N ratio is a suitable amount for an optimal reaction supposing that other parameters are favourable [20]. If the proportion is greater, nitrogen will be used up whilst there will be carbon available. A number of microbes will be made to die, liberating nitrogen in them and ultimately re-establishing the balance needed. Digestion continues sluggishly as this transpires [20]. When nitrogen is in higher amounts, the fermentation process comes to a halt since carbon will be used up. Excess nitrogen is not assimilated and sludge mineral composition will be inappropriate to meet expected organic fertiliser standards [41].

2.4.5 Total solids and uniform feeding

A key precondition of effective digestion is unvarying feeding of substrates to the digestion chambers. By so doing, the microbes are retained in a reasonably steady solid concentration all the time. It is necessary to feed the digester at similar periods daily with substrate of similar nature and amount [20]. For an optimal gas generation via anaerobic digestion, generally, 8-10 % total solids (TS) is essential [42]. Additional water is needed for the feed material to reach the required TS concentration. If excess water is added, solid constituents of the mixture will accumulate at the bottom of the digester and if not enough quantity of water is added the flow of gas is hampered. Biogas generation will not be at its optimum in both scenarios.

2.4.6 Hydraulic retention time

The average amount of time biomaterials remain in a digester is referred to as hydraulic retention time (HRT). As a result, from a realistic view, it is an essential factor since it determines the daily flow rate into the reactor. It should be long enough to allow for the solubilization of complex organic matter, allowing for subsequent acidogenic hydrolysate fermentation [43].

Changes in hydraulic retention time (HRT) frequently disrupt the functioning of methanogenic bacteria and this affects methane generation. In theory, a lower HRT equals a higher organic loading rate (OLR). Increased HRT improves the elimination efficiency of soluble chemical oxygen demand (COD), resulting in increased methane generation [44]. Variations in volatile fatty acids (VFAs) concentration occur as a result of HRT, OLR, and temperature changes. Reduced HRT induces methanogenesis instabilities and a reduction in biogas and methane production, owing to increased VFA levels.

Substrate retaining duration is determined by the raw material type as well as the temperature. Typical retaining period is in the range of 30 to 45 days but can go up to 60 days for certain cases [20]. Among other factors which affect biogas production the substrate retention time is very key. Small retention time leads to inefficient extraction of biogas. Extended retention time leads to spending a lot on additional capacity and inadequate feed is supplied to realise the most of proceeds [45].

2.4.7 Volatile fatty acid level

Syntrophic acetogens and methanogenic microbes can subsequently convert volatile fatty acids (VFAs) generated by bacteria during acidogenesis into CH_4 and CO_2. Heavy organic loading causes VFA accumulation, which causes a drop in pH far below the methanogenic range, potentially leading to the collapse of methanogenesis. Methanogens are pH-sensitive organisms that thrive best between pH 6 and 8.5, with a narrower range of 6.5 - 7.2 being preferable [44]. Acetic acid is the most common VFA for biogas generation among the VFAs that are formed: acetate, propionate, butyrate, valerate, and caproic acid. Propionic acid is generally hazardous when compared to other VFAs. The proportion of propionate to acetate level is a reliable predictor of methanogenic imbalance. A value greater than 1.4 indicates failure of methanogenesis [46].

2.4.8 Pretreatment

There are many hydrogen rich cellulosic and lignocellulosic materials, for instance, water hyacinth, which can be used for biogas production. Their application in biogas production is limited due to their recalcitrance nature to the process of hydrolysis. The lignocellulosic biomass' intricate biochemical and molecular structure necessitates pretreatment to unravel its compact complex configuration [47]. The enzymatic breakdown of polymeric biomass materials is made easier by pretreatment, and readily biodegradable compounds are generated [48].

A wide range of biomass pretreatment techniques have been attempted and examined to assess the overall effect on resultant biogas yield and/or other biofuels under investigation. Pretreatment methods for biomass materials are mainly categorised into physical, physico-chemical, chemical, and biological [49]. The methodologies adopted, as well as their intensity, are linked to the nature of the biomaterial's complexity. Chipping, crushing, milling, and irradiation are some of the physical pretreatment approaches which have been studied in literature [50, 51]. Physco-chemical methodologies include steam explosion, microwave radiation, liquid hot water pretreatment and pasteurisation [52]. [53] pretreated waste paper with rumen fluid. Preservations were done at 4 °C, 20 °C, and 35 °C for 7 days. The quantity of protozoa and fibrolytic enzymes was found to be higher in rumen preserved at 4 °C compared to the other two temperatures. Pretreatment with rumen preserved at 4 °C was the most suitable for methane fermentation. Chemical pretreatment techniques including alkali pretreatment, acid pretreatment, and wet oxidation have been investigated [54, 55]. Biological pretreatment involves the action of microbes and/or enzymes amongst other pretreatment approaches in the hydrolysis phase of anaerobic digestion [56]. Microaerobic pretreatment where a limited oxygen is supplied to the digestion process and microbiological treatment invoving growing of bacteria on biomass through solid-state fermentation are typical biological pretreatment methodologies that have been explored [57, 58].

In addition to the major factors discussed in this section, some other factors are presented in Figure. 2.1 which shows a summary of the various factors that affect biogas production and these also have a considerable bearing on the enhancement of biogas generation. Among them is the utilisation of high methane potential substrates, enzyme and microbial addition, optimisation of process conditions and parameters, co-digestion of various substrates and separating the digestion process into phases *(multi-stage digestion)* [59]. Sreekrishnan et al. [30] highlighted using additives, sludge recycling, reducing feed partcle size *(increasing surface area)* as well as using biofilters as some of the techniques for enhancing biogas production.

2.5 ANAEROBIC CO-DIGESTION

Anaerobic digestion of biomass wastes can be done on individual materials (mono-digestion) or mixtures of numerous materials (mixed-digestion or co-digestion). Mono-digestion is commonly employed for digesting animal manure in smaller biogas production facilities, but co-digestion is frequently employed in bigger facilities which process bio-wastes from various origins (farms, residential areas and industry). Co-digestion occurs when different feed materials are concurrently digested in the same reactor. Customarily, AD technology was meant for one feed material but lately, it has been recognised that anaerobic digestion turns out to be more stable when a diversity of substrates are co-digested simultaneously. Co-digesting varied substrates improved biogas production potentials in contrast to single substrates [60, 61, 62].

Generally all biomaterials and organic wastes are augmented with numerous nutrients necessary for growth of micro-organisms. The differing nutrient quantities are interconnected with age, geographical origins and species of the organic material. A great proportion of the agricultural residues and aquatic plants are enriched with high nutrients, however, their lignocellulosic recalcitrant nature renders them resistive to micro-bacterial degradation hence reduced gas outputs. Co-digesting these multifaceted biomaterials with animal manures and other biodegradable organic substances gives enough access and potential to micro-organisms to foster optimised degradation [63].

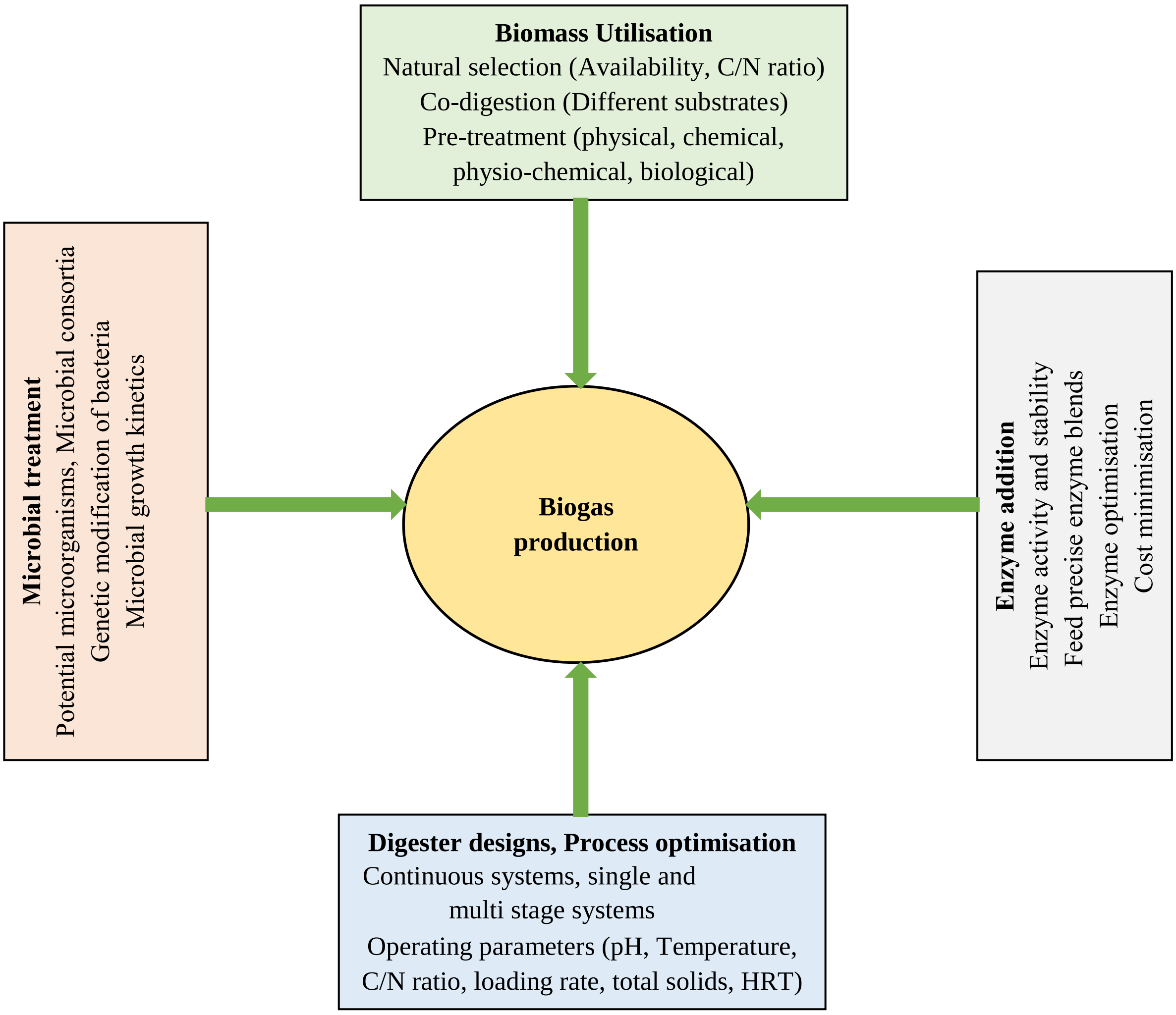

Figure 2.1. Overview of factors that affect biogas production. Adapted from [59], (c)2015, Elsevier.

In an investigation, [64] found out that more biogas was produced from co-digestion of *Eichhornia crassipes*, poultry waste and cow manure. Co-digestion presents immaculate digestibility, supreme mineral manure, odour and germs management together with costs reduction in addition to being environmentally friendly among other benefits [65]. Table 2.1 shows a review of a few mono-digestion and co-digestion studies some improved methane yields through co-digestion.

Table 2.1 shows that there is a vast potential of biogas generation from the co-digestion of a wide range of biomass wastes. The recalcitrant nature of most of the lignocellulosic substrates can be overcome by co-digesting them with animal manures which already has bacteria for anaerobic digestion and this in turn enhances biogas yield from them. It can also be deduced that a different combination of substrates as well as different mixing ratios consequently lead to different biogas production volumes and hence

Table 2.1. Effect of co-digestion on biogas yield

Feedstocks	Comparison of mono-digestion and co-digestion biogas yields	Source
Wastewater sludge and olive pomace	mono-digestion yielded 0.18 and 0.16 L CH_4/gVS_{added} for olive pomace and wastewater sludge respectively. Co-digestion yielded 0.21 L CH_4/gVS_{added}. Co-digestion increased methane production by 17 - 31 %	[66]
Wastewater sludge (WAS) and fish waste (FW) or garden-grass (GG)	gradual increase of fish concentration increased methane generation up to 1.9 when 75 % was added. With grass methane production only improved after adding 25 %, adding more than 50 % grass increased the production rate and final product by 1.5 and 1.7 times, respectively.	[67]
Sugarcane press mud (P) and vinasse (V)	The combination V_{75}/P_{25} had the best methane generation rate of 69.6 NmL CH_4 g^{-1} COD_{fed}^{-1} d^{-1}. In co-digestion, methane outputs of 365 L CH_4 kg^{-1} VS and biogas production output of 1.6 L L^{-1} were achieved, which was 64 % greater than mono-digestion.	[68]
Microalgae and primary sludge	Co-digestion of microalgae and primary sludge (25/75 % on a volatile solids basis) was compared to microalgae mono-digestion. co-digestion improve methane generation by 65 %.	[69]
Poultry droppings (PD) and lignocellulosic co-substrates (LCSs) (wheat straw (WS) and meadow grass (MG))	In co-digestion, maximum methane concentrations were found to be 330.1 and 340.1 Nl kg^{-1} VS at a blending ratio of 70:30 (PD:WS) and 50:50 (PD:MG) respectively. This was an increase of 1.14 and 1.13 times higher than the LCSs individually.	[38]

different methane concentrations. This section concludes that further research has to be conducted on a wide range of co-digestion feedstock combinations and their respective blend ratios.

2.6 MODELLING AND OPTIMISATION OF ANAEROBIC DIGESTION

Co-digestion logically and concurrently manages biological organic matter thereby obtaining an alternative form of energy. It is more vulnerable to process instability due to substantial dissimilarity in feed stock composition. Mechanistic models emanating from the anaerobic digestion model no.1 (ADM1) framework are more well-known in anaerobic co-digestion modelling. Nevertheless, major aspects in present-day anaerobic co-digestion, particularly interactions between system performance and co-substrate ratios and properties for optimal biogas yields still remain underdeveloped.

There is a necessity of the development of models of different levels for the respective different categories of users. The small to medium enterprises (SMEs) only need a general understanding and as such require low level-less complicated models. Commercial entities and all big revenue focused companies require general to medium level models for the purposes of just informing on the expected biogas yields in relation to time, rate of return on investment, and profits. Lastly senior technical managers, engineers and researchers have the capacity and ability to understand deeper technical models with higher level of sophistication and complexity. It is necessary to take into consideration different research interests in the development of models of different levels. Table 2.2 shows the 2 major model categories and the respective research interests together with the aspects to be considered in model development.

Optimisation of anaerobic digestion can be improved through proper modelling [70]. Process monitoring and control have been noted as further improvements needed for the biogas production process [71]. Research and investigations on modelling, together with optimisation, inclusive of control and regulation of the AD reactions are critical to the biogas fraternity. In comparison to other well established fields, the modelling and optimisation of biochemical reactions such as the ones in biogas generation are still a challenge mainly attributed to by the peculiarity and unsimilar nature of the reaction progressions [72]. The bacteria involved in the biogas generation process drastically respond to environmental alterations hence making it a challenge to predict and control the process [73]. [73] concluded that for anaerobic digestion processes, the available detailed models are too complex for practical use and recommended the use of a combination of empirical and physical and/or biological models as a possible approach.

Table 2.2. Research interests and model level categories

Model Category	Aspects to be considered
Production level	medium to high level modelling
	Process control and regulation *(temperature and pH monitoring)*
	Substrate blend ratios *(in case of co-digestion)*
	Reaction kinetics
Utilisation and management level	low to medium level modelling
	Optimising CH_4 proportion in biogas
	biogas production vs demand side management
	Impurity removal and quality improvement for advanced uses
	Slurry and other by-products management
	biogas yields in relation to time, rate of return on investment and profits

2.6.1 Modelling

2.6.1.1 The Buswell biogas prediction equation

[74] developed a mechanism for methane fermentation which describes biogas constituent composition after anaerobic digestion as per the chemical composition of the initial substrates entering into the digestion process. The elemental composition of the majority of substrates employed in biogas production comprises of C, H, O, N and S in a complex molecular structure. The complex structure is subjected to the biochemical reactions and biogas is obtained as the main product together with slurry

as a by-product. If it is assumed that a total coversion of biomass to biogas occurs after the complex interdependant bio-chemical reactions, then the elemental composition approach developed by [75], is arrived at; that biogas is constituted mainly of CH_4, CO_2, NH_3 and H_2S and that other trace elements and gases are negligible. This is typical high level steady state modelling which takes material balances into account. Since some of the biomass is not completely converted to biogas but goes to slurry, a conversion factor of 0.8 is assumed and applied to the resultant biogas quantity to arrive at a more accurate representation of the entire process. The Buswell equation for predicting biogas output is as shown in Equation (2.1).

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right) H_2O \Rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right) CH_4 \\ + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right) CO_2 + dNH_3 + eH_2S. \tag{2.1}$$

where a, b, c, d and e are given by percentage composition by mass of each of the elements devided by the relative atomic mass (Ar) of each of the elements as depicted below:

$$a = \frac{\text{Carbon ultimate mass}}{Ar_C}, \tag{2.2}$$

$$b = \frac{\text{Hydrogen ultimate mass}}{Ar_H}, \tag{2.3}$$

$$c = \frac{\text{Oxygen ultimate mass}}{Ar_O}, \tag{2.4}$$

$$d = \frac{\text{Nitrogen ultimate mass}}{Ar_N}, \tag{2.5}$$

$$e = \frac{\text{Sulphur ultimate mass}}{Ar_S}. \tag{2.6}$$

Equation (2.1) helps to build a material balance model. Reference is made to [63], when there are three different substrates. In this previous work, a biogas generation model for the determination of optimal substrate blend ratios is formulated and optimised. Equation (2.1) can be expressed in the form of Equations (2.7), (2.8) and (2.9) for substrates 1, 2 and 3 respectively.

$$C_{a_1}H_{b_1}O_{c_1}N_{d_1}S_{e_1} + \left(a_1 - \frac{b_1}{4} - \frac{c_1}{2} + \frac{3d_1}{4} + \frac{e_1}{2}\right) H_2O \Rightarrow \left(\frac{a_1}{2} + \frac{b_1}{8} - \frac{c_1}{4} - \frac{3d_1}{8} - \frac{e_1}{4}\right) CH_4 + \left(\frac{a_1}{2} - \frac{b_1}{8} + \frac{c_1}{4} + \frac{3d_1}{8} + \frac{e_1}{4}\right) CO_2 + d_1NH_3 + e_1H_2S, \tag{2.7}$$

$$C_{a_2}H_{b_2}O_{c_2}N_{d_2}S_{e_2} + \left(a_2 - \frac{b_2}{4} - \frac{c_2}{2} + \frac{3d_2}{4} + \frac{e_2}{2}\right) H_2O \Rightarrow \left(\frac{a_2}{2} + \frac{b_2}{8} - \frac{c_2}{4} - \frac{3d_2}{8} - \frac{e_2}{4}\right) CH_4 + \left(\frac{a_2}{2} - \frac{b_2}{8} + \frac{c_2}{4} + \frac{3d_2}{8} + \frac{e_2}{4}\right) CO_2 + d_2NH_3 + e_2H_2S, \tag{2.8}$$

$$C_{a_3}H_{b_3}O_{c_3}N_{d_3}S_{e_3} + \left(a_3 - \frac{b_3}{4} - \frac{c_3}{2} + \frac{3d_3}{4} + \frac{e_3}{2}\right) H_2O \Rightarrow \left(\frac{a_3}{2} + \frac{b_3}{8} - \frac{c_3}{4} - \frac{3d_3}{8} - \frac{e_3}{4}\right) CH_4 + \left(\frac{a_3}{2} - \frac{b_3}{8} + \frac{c_3}{4} + \frac{3d_3}{8} + \frac{e_3}{4}\right) CO_2 + d_3NH_3 + e_3H_2S. \tag{2.9}$$

The aggregate biogas yield obtainable from these 3 substrates was modeled as:

$$B_{cod} = 0.8 \times \sum_{i=1}^{3} V_i, \tag{2.10}$$

where B_{cod} is the summative biogas that is realised from the co-digestion of the 3 substrates and 0.8 is the substrates' biomass to biogas conversion factor. V_1, V_2 and V_3 are the biogas volumes from substrates 1, 2 and 3 respectively and are determined as shown below:

$$V_1\ (\mathrm{m}^3) = \frac{(22.4 \times 10^{-3}) \times (CO_{2_1} + NH_{3_1} + H_2S_1 + CH_{4_1})}{Mr_{WH}}, \tag{2.11}$$

$$V_2\ (\mathrm{m}^3) = \frac{(22.4 \times 10^{-3}) \times (CO_{2_2} + NH_{3_2} + H_2S_2 + CH_{4_2})}{Mr_{MSW}}, \tag{2.12}$$

$$V_3\ (\mathrm{m}^3) = \frac{(22.4 \times 10^{-3}) \times (CO_{2_3} + NH_{3_3} + H_2S_3 + CH_{4_3})}{Mr_{CD}}, \tag{2.13}$$

where $CO2_{1,2,\&3}$, $NH3_{1,2,\&3}$, $H_2S_{1,2,\&3}$ and $CH4_{1,2,\&3}$ are the number of moles of carbon dioxide, ammonia, hydrogen sulphide and methane for water hyacinth (WH), municipal solid waste (MSW) and cow dumg (CD) respectively and are determined as shown below.

$$
\begin{aligned}
CH_{4_1} &= \frac{a_1}{2} + \frac{b_1}{8} - \frac{c_1}{4} - \frac{3d_1}{8} - \frac{e_1}{4};\\
CO_{2_1} &= \frac{a_1}{2} - \frac{b_1}{8} + \frac{c_1}{4} + \frac{3d_1}{8} + \frac{e_1}{4};\\
NH_{3_1} &= d_1 \text{ and}\\
H_2S_1 &= e_1;
\end{aligned}
$$

$$
\begin{aligned}
CH_{4_2} &= \frac{a_2}{2} + \frac{b_2}{8} - \frac{c_2}{4} - \frac{3d_2}{8} - \frac{e_2}{4};\\
CO_{2_2} &= \frac{a_2}{2} - \frac{b_2}{8} + \frac{c_2}{4} + \frac{3d_2}{8} + \frac{e_2}{4};\\
NH_{3_2} &= d_2 \text{ and}\\
H_2S_2 &= e_2;
\end{aligned}
$$

$$
\begin{aligned}
CH_{4_3} &= \frac{a_3}{2} + \frac{b_3}{8} - \frac{c_3}{4} - \frac{3d_3}{8} - \frac{e_3}{4};\\
CO_{2_3} &= \frac{a_3}{2} - \frac{b_3}{8} + \frac{c_3}{4} + \frac{3d_3}{8} + \frac{e_3}{4};\\
NH_{3_3} &= d_3 \text{ and}\\
H_2S_3 &= e_3.
\end{aligned}
$$

Mr_{WH} is the relative molecular mass of water hyacinth, Mr_{MSW} is the relative molecular mass of municipal solid waste and Mr_{CD} is the relative molecular mass of cow dung. These relative molecular masses are as denoted in Equations (2.14), (2.15) and (2.16) respectively.

$$Mr_{WH}\ (\text{kgmol}^{-1}) = a_1 * Ar_C + b_1 * Ar_H + c_1 * Ar_O + d_1 * Ar_N + e_1 * Ar_S, \tag{2.14}$$

$$Mr_{MSW}\ (\text{kgmol}^{-1}) = a_2 * Ar_C + b_2 * Ar_H + c_2 * Ar_O + d_2 * Ar_N + e_2 * Ar_S, \tag{2.15}$$

$$Mr_{CD}\ (\text{kgmol}^{-1}) = a_3 * Ar_C + b_3 * Ar_H + c_3 * Ar_O + d_3 * Ar_N + e_3 * Ar_S, \tag{2.16}$$

where Ar is the relative atomic mass of each respective element in the substrate molecule.

2.6.1.2 First order dynamic model

The first order dynamic model is a high level-production level, dynamic modelling approach that looks at the overall production response. [76] described and evaluated a dynamic model to generate biogas from co-substrates, it was concluded that applying the modified first order dynamic model produced higher biogas yield when compared to experiments in which it was not applied. Raw material digestability was analysed through computational formulation of first order nature for batch systems as was highlighted by [77] as shown in Equation (2.17):

$$\frac{y_m}{y_m - y_t} = \frac{C_o}{C_t}, \tag{2.17}$$

and

$$\ln \frac{C_o}{C_t} = kt, \tag{2.18}$$

where: "C_o is the initial volatile solid, C_t is the volatile solid concentration at any given time (t), y_t is the volume of biogas produced per unit mass of VS fed at any time (t) and y_m is the volume of biogas per unit of mass of VS converted at maximum time" [77].

Therefore:

$$\frac{y_m}{y_m - y_t} = e^{kt}. \tag{2.19}$$

Equation 2.19 can be writtens as:

$$y_t = y_m(1 - e^{-kt}). \tag{2.20}$$

To determine the change in the amount of biogas with time we find the first order derivative of Equation (2.20)

$$y_t' = ky_m e^{-kt}. \tag{2.21}$$

Equation (2.20) can now be written as:

$$y_t = y_m - \frac{y_t'}{k}. \tag{2.22}$$

Equation (2.22) can now be written as:

$$y_t' = ky_m - ky_t. \tag{2.23}$$

Equation (2.23) gives the dynamic version of Equation(2.20) that is potentially useful in future biogas production modelling using the first order dynamic model. The dynamic model offers easy foretelling of the response of the system and its output to mass and energy variations over time, easy parameter identification, easy control and optimisation variable introduction as well as easy evaluation and comparison of process control strategies [78]. Biogas generation kinetics are key in aiding the assessment of organic matter digestibility characteristics [79].

2.6.1.3 The modified Gompertz model

Unlike the first order dynamic model which gives supplementary data on hydrolysis rate, the modified Gompertz model gives time delay to biogas generation together with the highest methane generation rate [80]. The modified Gompertz was verified to be an outstanding emperical non-linear regression model informing of gas generation time delay in addition to describing bacterial growth as exponential

[81, 80]. Many researchers reported that biogas formation rate is assumed to relate proportionally to the increase of methanogens in the bio-digester and as such biogas prediction follows the modified Gompertz equation as in Equation (2.24) [82, 83].

$$P = A.exp\left(-exp\left[\frac{Ue}{A}(\lambda - t) + 1\right]\right), \tag{2.24}$$

where P is the cummulative biogas production at a given time t, Nml/gVS; A is biogas production potential, ml; U is highest biogas generation rate (Nml/gVS.day); e is a mathematical constant, 2.718; λ is the biogas formation delay time *(minimum time to produce biogas)*, day; and t is the aggregate time for biogas formation, day. A, λ, and U are ascertained by non-linear regression. The higher U exhibits, the higher the biogas production rate. Biogas generation increases with increased values of U.

2.6.1.4 Artificial Neural Networks (ANNs)

Neural networks comprise of nodes (similar to human brain neurons) classified in sequences of layers interlinked in different ways and they can regulate a reaction progression through immitating the functioning human of brain [84]. Figure.2.2 shows a schematic of ANNs. Artificial Neural Networks (ANNs) can be used to forecast output data for complex systems having numerous operational input variables [85]. ANNs work using initial data provided, trains on it and simulates the reaction progression by resembling the actual process. Many researchers used ANNs to predict, model and optimise biogas production from different substrates [86, 87, 88]. ANNs employ data-driven high level modelling, however, without physics, it is less useful in terms of optimising physical parameters. Another disadvantage of ANNs is that by its nature of being data driven, it disregards process kinetics.

2.6.1.5 The anaerobic digestion model no.1 (ADM1)

ADM1 simulates the biological transformation of intricate biodegradable matter to CH_4, CO_2 and other inert by-products [90]. The structured model has several phases that describe biological and physicochemical process reactions. The ADM1 is a complex model well suited for simulation but has significant limitations when it comes to optimisation and process control applications. The ADM1 model simulates constant volume, completely mixed systems which is not the case in many anaerobic digestion reactors especially when it comes to bigger systems.

ADM1 has physico-chemical steps integrated together with biological steps. 19 process reactions, 33 state variables in addition to 105 Stoichiometry based relations and kinetic parameters [90]. According to [91], the complexity of the ADM1 model necessitates requirement of several parameters, eventually

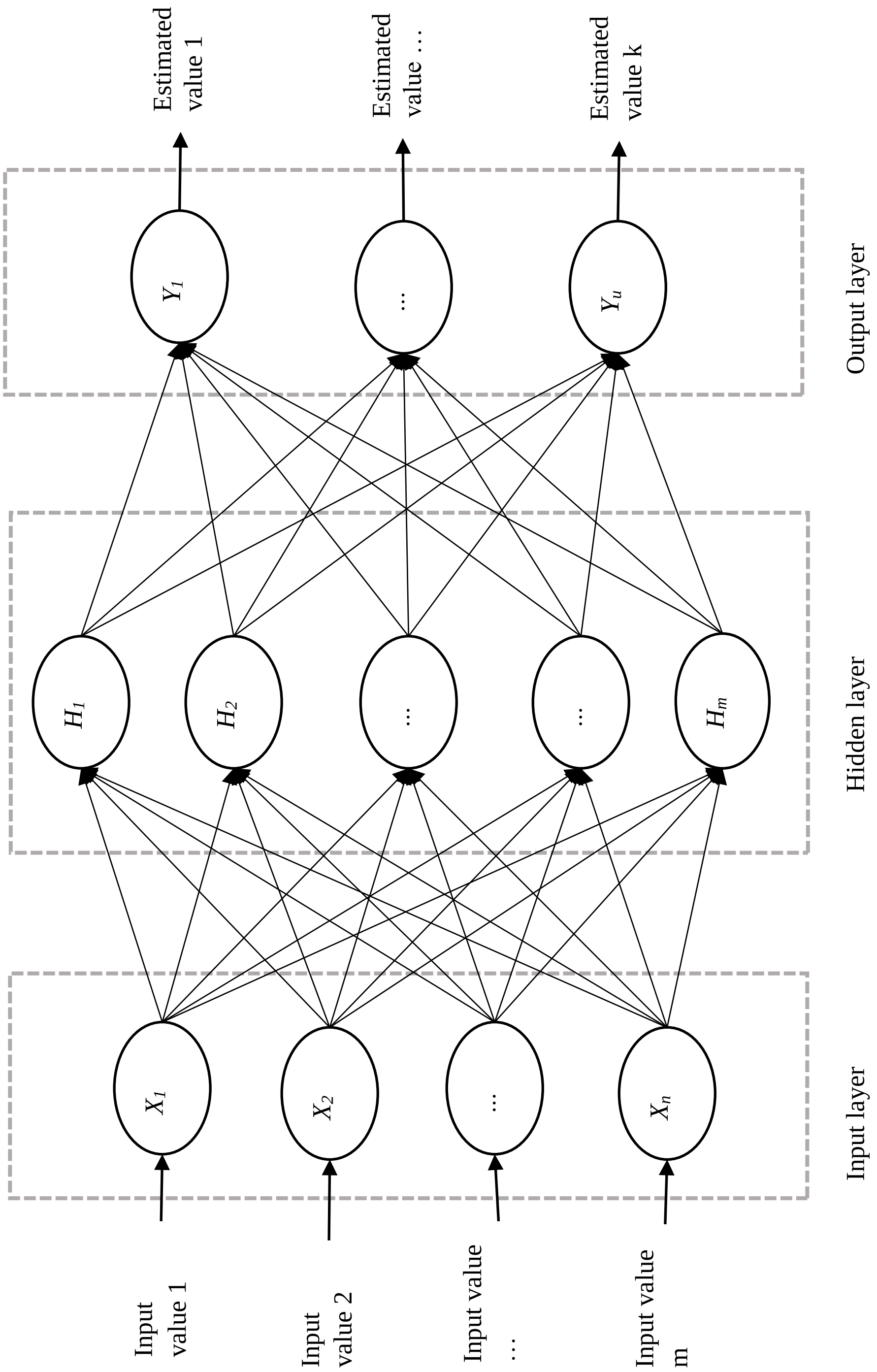

Figure 2.2. Artificial Neural Network schematic. Taken from [89], (c)2015, Authors.

leading to complicated reaction progression equations. Identification of parameters and handling of these several equations can be very difficult. [92] highlighted issues to do with Stoichiometric impreciseness, glitches in solids retention time, and absence of restraints on thermodynamic bounds. However, due to the variations in the substrates under digestion only a few parameters will considerably affect the output of the model. ADM1 modelling is complex and as such an improved practicality is required when it comes to co-digesting substrates anaerobically [93].

Modelling the biogas generation process will lead to improvement of the biogas yield by manoeuvring into enhanced options for controlling the digestion process. Table 2.3 gives the key existing anaerobic digestion models. It can be deduced from Table 2.3 that the dynamic model and the steady state model dominate in the existing anaerobic digestion models. The hydrolysis kinetics are mainly of first order. The Monod and the modified Monod are the prevailing growth kinetics. Another deduction that can be made from Table 2.3 is that a lot of modelling have been done on sludge but only a few articles present research on organic wastes, manures and aquatic biomass. Many diverse attributes and factors are able to inhibit biogas generation as shown in the table. Inhibition is primarily influenced by nature of substrate and reaction conditions and/or parameters to which the process is subjected to.

Table 2.3. Summary of key existing anaerobic digestion models

Model type	Substrate	Hydrolysis kinetics	Type of inhibition	Source
Stoichiometric	-	-	- [1]	[74]
dynamic; steady state	sludge	-	VFA[1], pH	[94]
dynamic; steady state	organic waste	-	VFA, pH and NH_3	[95]
dynamic	complex organic material	first order	H_2, pH, NH, H_2S, Propionate	[96]
dynamic; steady state	organic waste	first order	LCFA, acetic acid, NH_3	[97]
dynamic	swine manure	first order	-	[98]
dynamic; steady state	sludge	first order	H_2, pH, NH_3, acetic acid	[99]
dynamic; steady state	wide variety of substrates	first order	H_2, pH, NH_3, butyric acid	[90]
dynamic	cattle manure	first order	pH, VFA and NH_3	[100]

Table 2.3 Summary of key existing anaerobic digestion models (continued from previous page)

Model type	Substrate	Hydrolysis kinetics	Type of inhibition	Source
dynamic	wastewater	-	-	[101]
dynamic	sludge	Contois	H_2	[102]
steady state	sludge	first order, Monod, saturation	-	[103]
dynamic; steady state	sludge	first order	H_2, pH, NH_3, butyric acid	[104]
dynamic; steady state	agro-waste	first order	H_2, pH, iN[2] NH_3, H_2S	[105]
steady state	horse manure and cow dung	first order	-	[77]
computational	organic fraction of municipal solid waste (OFMSW)	first order	-	[76]

[1]Volatile Fatty Acids [2]inorganic Nitrogen

2.6.2 Optimisation

According to the dictionary [106], to optimise is "to determine the maximum or minimum values of (a specified function that is subject to certain constraints)". [107] highlighted that process optimisation and improvement of biogas production still needs more investigations to be done and that the use of simulation ways and means can lead to realisation of substantial enhancement of biogas yields. Diverse optimisation approaches are established in literature in a bid to obtain the best reaction conditions, best reaction parameters and best substrate ratios for different feed stocks so as to enhance and optimise the biogas production process.

The conventional method of optimisation of anaerobic digestion comprise of laboratory batch experiments with different ratios of co-digestion feedstocks to assess the extent of digestion of the substrates. Co-digestion of varied substrates has shown that an improved biogas production potential is achieved in comparison to mono-digestion of single substrates [108, 109, 110]. ANNs, genetic algorithms (GAs), ant colony optimisation (ACO) and particle swarm optimisation (PSO) are possible tools for simulating and optimising the anaerobic biogas generation process. ANNs and GAs are some of the modern optimisation approaches applied to deal with complex biogas maximisation problems. [111] employed the ACO optimisation approach to anaerobic co-digestion. According to their results, employment of the ACO algorithm proved to be a beneficial way for optimising anaerobic digestion blends, leading to the effective simulation of various co-digestion optimisation scenarios. [112] investigated the appropriateness and effectiveness of a gradient-based optimiser for multi-objective anaerobic digestion process optimisation. Various optimisation problems were designed and solved using this model to gain insights into the effectiveness of this strategy. The proposed optimisation method was found to be extremely effective.

Genetic algorithms employ a random search algorithm that is created in an attempt to mimic the principles of natural selection and genetics [113]. They work with string structures, similar to biological structures, that evolve over time and use a randomized but systematic exchanging of information to follow the theory of survival of the fittest. As a result, a fresh batch of strings is generated in every generation, using portions of the old batch's fittest members. GAs are able to cope with parallelism and complicated scenarios. They can be employed with an objective function that is static or dynamic, linear or nonlinear, continuous or discontinuous, or with random noise [114]. Since multiple offspring in a population function as autonomous agents, the population will concurrently navigate the search space in various multiple directions, and consequently, an optimal solution is arrived at. This function makes parallelising algorithms for implementation much easier.

Linear programming approaches, response surface methodologies as well as simplex-centroid mixture design and central composite design are also among the optimisation approaches which have been applied in anaerobic digestion [115, 116]. Prospects of enhancing biogas generation from varied substrates such as water hyacinth, cow dung and municipal solid waste via the avenues of co-digestion and use of optimisation tools and techniques are investigated herein. Table 2.4 shows a summary of some of the key biogas optimisations which were done.

Table 2.4. Summary of key biogas optimisations

Substrates	Model used	Optimisation approach	Highlights	Source
Cassava (manioc, tapioca) processing wastewater	-	experimental	effect of pH and temperature variations with biogas production were analysed, the control strategy was based mainly on pH control	[117]
Cob Corn Mix (CCM), Rye and pig manure	ADM1	GA and PSO	quantity and composition of substrates were varied, authors noted huge improvement capability by optimising substrate feed. It was noted that PSO was about 14 % quicker than GA in this instance	[118]
variety of lignocellusosic biomass	ADM1, Lignogas & Lignogas-SIM	experimental, nonlinear least squares, & simplex in AQUASIM	the Lignogas model gave a closer match of modelling and measurement results	[119]

Table 2.4 Summary of key biogas optimisations (continued from previous page)

Substrates	Model used	Optimisation approach	Highlights	Source
grass, wheat straw, silage wastewater	-	experimental	anaerobic digestion was devided into a two-phase process and higher methane yields were realised	[120]
organic fraction of MSW	first order kinetic	experimental	variations of organic loading rates were done, repercussions of varying total solids and retention time were analysed. A high CH_4 proportion was realised	[121]
Miscanthus Fuscus mixed with cow dung	-	RSM and Box-Behnken (BBD) design	Investigation was done to evaluate the effect of varying parameter settingson co-digestion was done. A pH of 6, a temperature of 30°C, HRT of 20 days and F/I ratio of 75% were idientified as the optimal process parameters. F/I ratio was observed to have a major impact on biogas production.	[122]

Table 2.4 Summary of key biogas optimisations (continued from previous page)

Substrates	Model used	Optimisation approach	Highlights	Source
glycerine, gelatine and pig manure	ADM1	adaptive linear programming, experimental	a linear programming to maximise chemical oxygen demand (COD) transformation which mantains reactor media as well as biogas quality was developed.	[123]
cow-manure and grass-silage	ADM1, ANNs	ant colony optimisation (ACO)	ADM1 model was used for simulations, ANNs to forecast biogas flow rate and ACO was used to depict important process parameters	[124]
maize silage, manure and the solid fraction of manure	ADM1	nonlinear model predictive control (NMPC)	an online NMPC algorithm was analysed. Authors highlighted that biogas production can be controlled and optimised	[125]
maize silage and liquid cow manure	ADM1	nonlinear model predictive control (NMPC)	a closed-loop substrate feed control was suggested. A multi-objective NMPC was used for feed constituents regulation	[126]

Table 2.4 Summary of key biogas optimisations (continued from previous page)

Substrates	Model used	Optimisation approach	Highlights	Source
rural household domestic waste	-	RSM	RSM was employed using central composite rotatable design. Biogas production was optinised through variation of PH, detention time and ratio of substrate to water. Highest biogas yield was obtained from a combination of detention time of 30 days, substrate to water ratio of 1:1 and pH of 7	[127]
Carica papaya peels, poultry droppings	-	RSM and ANN	C. papaya was shown to be an excellent substrate for biogas production when co-digested with poultry droppings. Both RSM and ANN models proved to be effective in predicting methane generation from C. papaya peels and poultry dropping, according to the results of the modeling and optimisation	[128]

Table 2.4 Summary of key biogas optimisations (continued from previous page)

Substrates	Model used	Optimisation approach	Highlights	Source
organic fraction of municipal solid wastes, cow manure, and municipal sewage sludge	GA	simplex-centroid mixture design (SCMD) and ANN	combination of the SCMD and ANN model and optimising with GA helped to predict biomethane generation	[129]
palm oil mill effluent (POME) and cattle manure (CM)	ANN	combined ANN-PSO framework	biogas production from POME was predicted and optimised using ANN and PSO in a co-digestion setup in a solar bioreactor. According to the results reported, the suggested method was successful and flexible in estimating biogas output from the co-digestion of POME and CM	[130]
cow dung and flower waste	ANN, RSM	statistical optimization	The ANN model predicted biogas output more precisely and effectively than the RSM model. Statistical optimisation and pretreatment approaches dramatically boosted biogas generation	[131]

Table 2.4 Summary of key biogas optimisations (continued from previous page)

Substrates	Model used	Optimisation approach	Highlights	Source
goose manure and wheat straw	experimental	statistical (regression)	methane was increased by upto 94.10 % due to C/N ratio optimisation	[132]
Siam weed (*Chromolaena odorata*) and poultry manure	experimental	RSM	increased quanties of of biogas were attained due to co-digestion. The biogas quality was also improved. RSM proved to predict biogas well	[133]
algal-bacteria biomass and cellulose	kinetic model	-	Biogas production time delay was decreased by 50 % and methane generation was improved by 35 %	[134]
cow manure and oat straw	modified Gompertz and non-linear regression	Box-Behnken test design	addition of cow manure at levels below 2/3 boosted methane yields and decreased biogas production startup time, however the methane generation rate was not affected	[135]

Table 2.4 Summary of key biogas optimisations (continued from previous page)

Substrates	Model used	Optimisation approach	Highlights	Source
carrot, cabbage, tomato, bread (French baguette), beef meat at 5 % fat and manure (a mix of cow dung and straw)	experimental, kinetic	-	the predicted results using the model with constant endogenous generation and kinetics determined at 80 % of total batch time matched the observed methane yields well under rising organic loading rates. Data obtained from batch reactors predicted semi-continuous biogas production in an effective manner	[136]
hemicelluloses hydrolysate, vinasse, yeast extract and sugarcane bagasse fly ashes	experimental, modified Gompertz model and the two-phase exponential model	experimental	biochemical methane potential tests were used to optimize anaerobic co-digestion of sugarcane biorefinery by-products. The sugarcane biorefinery wastes blend enhanced anaerobic co-digestion and boosted methane generation	[137]

Table 2.4 Summary of key biogas optimisations (continued from previous page)

Substrates	Model used	Optimisation approach	Highlights	Source
pig manure and corn straw	experimental	-	the beffect of organic loading rate, total solids and crbon to nitrogen ratio was investigated in co-digestion of pig manure and corn straw. Maximum biogas output was discovered to be attained at a C/N ratio of 25, whilst the optimum biogas slurry performance was found to be at a C/N ratio of 35. Increased organic loading rates and total solids also led to significant biogas generation and biogas slurry performance.	[138]
acorn slag waste, dairy manure and bio-based carbon	experimental	-	the use of bio-based carbon in the co-digestion of acorn slag and dairy manure was researched. The carbon-based accelerant was reported to have improved the biogas yield in co-digestions	[139]

Table 2.4 Summary of key biogas optimisations (continued from previous page)

Substrates	Model used	Optimisation approach	Highlights	Source
food waste and chicken manure	experimental, computational fluid dynamics (CFD)	-	Experimental and numerical studies of the impact of mixing time on anaerobic digestion performance were conducted. Extending the mixing time did not enhance biogas output, but did increased overall input.	[140]
Laminaria digitata and animal dung	dynamic bioconversion model (BioModel) and a hybrid MATLAB-Microsoft Excel software	-	biogas yield was boosted by co-digesting Laminaria digitata and animal dung. Laminaria digitata increased biogas output, whereas cattle manure assisted in buffering. BioModel simulation validated the results from the batch and continuous reactors.	[141]

Table 2.4 Summary of key biogas optimisations (continued from previous page)

Substrates	Model used	Optimisation approach	Highlights	Source
food waste and cow manure	experimental, modified Gompertz and first-order kinetic	-	start-up conditions were optimised. Optimal substrate mixing ratio, substrate to inoculum ratio, and initial pH were verified by experimentation. A steady anaerobic digestion was started with FW/CM = 2.5, S/I less than 0.07, and an initial uncontrolled pH. These conditions were verified in a dynamic membrane bioreactor	[142]
spent coffee grounds, spent tea waste, glycerin, and macroalgae	experimental, modified Gompertz, linear regression	-	Different wastes were co-digested with oil-extracted spent coffee grounds. With the oil extraction procedure, specific methane output rose by 10 %. The results of the modified Gompertz model were generally consistent with those of the experiments.	[143]

As noted earlier on, mathematical and analytical optimisation techniques that can be applied to biogas production include the linear programming approach, non-linear programming approaches, such as non-linear model predictive control (NMPC), artificial intelligence theory approaches, such as ANNs, fuzzy logic, GAs, PSO, ACO, simulated annealing and immunity algorithm. [126] applied the ADM1 model to biogas production. NMPC was used as the optimisation approach to control the constituency and quantity of the feed. [144] carried out an investigation to concurrently maximise chemical oxygen demand (COD_{eff}) and biogas flow rate (Q_{gas}). The authors reported that by using GA-ANN model, an increased biogas was attained when compared to ANNs alone. [123] used linear programming optimisation approach to maximise methane production by way of determining the feedings into the processes. The ADM1 model was used and the method was validated experimentally. Implimentation was done in MATLAB, *'linprog'* was used to determine substrate blends and *'fminbnd'* was used to ascertain HRT that optimises methane production. The objective function was expressed as in Equation (2.25)

$$max f_{objective} = \frac{\sum_{i=1}^{N} pMet_i \times CODt_i \times x_i}{HRT}. \tag{2.25}$$

According to the authors, the objective function was subjected to the following linear restrictions: "(i) organic loading rate (OLR); (ii) total Kjeldahl nitrogen (TKN); (iii) moisture or liquid fraction; (iv) lipid content; (v) total alkalinity or salinity (vi) Na^+ concentration and (vii) K^+ concentration; (viii) H_2S content in biogas; and (ix) effluent COD content".

[124] optimised biogas flow rate using the ACO approach, the ADM1 model was used to generate data and the ANNs model was used for simulations. The ACO algorithm was used for variable selection. The selection probability of a variable prob(n) was described as in Equation (2.26)

$$prob(n) = \frac{p(n)}{\sum_{i=1}^{N} p(n)}. \tag{2.26}$$

Most of the biogas production models presented and discussed in Subsection 2.6.1 were barely used in biogas optimisations. This can also be noted from Table 2.4. Of the models that were applied, the ADM1 was applied more often followed by ANNs and then the first order kinetic model. The majority of the reported researches on biogas optimisation were by way of laboratory experimental approaches. These laboratory experiments would be under specific conditions which might not be universal to all subatrates and geographic locations. This eventually results in gaps and lack of confidence and reliability in their data being used to commercialise biogas technologies. The authors of this current review work would like to stress out and comment that there is a disjoint or rather a discontinuity between the biogas production models developed to date and their respective application to optimise and control the the overall biogas generation process progression with a prior objective to maximise the ultimate biogas yield.

2.7 TECHNO-ECONOMIC ANALYSIS OF ANAEROBIC BIOGAS PRODUCTION

A techno-economic assessment enables the creation of an investment and operational cost framework for the estimation of biogas generation's possible present and future economic sustainability. Informed financial and technical decisions such as biogas plant size or scale of operation as well as commercialisation prospects amongst other key considerations can be made based on techno-economic analysis.

[145] produced biogas from a variety of food wastes and conducted a techno-economic analysis to determine the financial feasibility of establishing a small-scale biogas plant. Economic examination gave a break even at \$0.2944 / m^3, with all pricing beyond that yielding a positive net present value. The researchers noted that incorporation of waste management charge savings could have increased the total savings.

A techno-economic investigation by [146], on bio-methane generation from agricultural and food wastes indicated that pressure swing adsorption cycles gave 37 % lower capital costs and a 10 % lower average life-time cost when compared to solvent-based technologies. This indicates that biomass processing, pretreatment and feeding techniques have a great impact on the overall techno-economic results.

[147] carried out techno-economic studies on the installation of a biogas plant at an institution. Biogas production proved to be viable, with payback periods ranging from 0.61 to 1.65 years for cow dung based biogas plants and 0.38 to 1.47 years for kitchen waste based biogas plants. It can be deduced that the type of feedstock has a huge influence on the total biogas yield which will in turn implicate on the economic parameters such as payback period, net present value, internal rate of return, among others.

Several other researchers investigated techno-economic aspects of anaerobic biogas production [148, 149, 150]. However, the majority of the works were focussed towards ascertaining if the process was feasible or not. The previous works lack the merging of the technical and the economic aspects to come up with analytical models for the optimisation of the entire process. It is vital to examine the tradeoffs arising from the relationships between technical developments and financial aspects in order to come up with an effective biogas production system. Optimising feedstock availability, controlling and regulating process conditions, maximising biogas output through co-digestion, feeding in of optimal substrate blend proportions and process stabilisation are among the technological aspects which are lacking in previous research works and still need to be investigated in greater detail. Objectives of reducing investment and operational costs as much as possible while increasing economic benefits are among the economic considerations which need to be explored in depth.

Process designs should incorporate anticipated operational and maintenance cost evaluations as well as the investment requirements for the entire biogas production facility. This will provide a concrete foundation for techo-economic analysis. Dynamic linkages will be formed with regards to the variation of the different techno-economic aspects with time leading to the development of informed anaerobic digestion modelling and optimisation frameworks for biogas enhancement. Consequently, the techno-economic implications will not only aid technology investors and financiers in decision making but will also guide research and development in the anaerobic biogas production niche. As such, generation of multi-objective techno-economic functions are imperative to the modelling and optimisation of anaerobic digestion.

This section concludes by discussing the whole process of conducting techno-economic assessments of typical anaerobic digestion projects as well as highlighting on how the analysis of costs and benefits is done. Investment appraisal computations are carried out based on the technical parameters of the project in order to ascertain the overal techno-economic viability of the project. The following procedure is suggested by the authors:

1. The initial investment costs (I_0) are determined basing mainly on the capital requirements of the specific project. Capital requirements include the digester construction costs, biomass harvesting equipment for use in cases where agricultural residues and aquatic bio-materials such as water hyacinth are among the substrates. Pretreatment equipment such as dryers and choppers can be included to the capital requirements. Construction and erection costs of biogas plant infrastructure and other ancillary facilities such as substrate storage compartments are included to the capital requirements and are integral components of the initial investment costs.
2. Transport costs for ferrying feedstocks/substrates to the digesters are calculated and taken into

consideration. The siting of most anaerobic digestion plants is usually done within the vicinity of feedstocks and water. However, transport costs have to be factored in for cases whereby the resources have to be ferried from some other locations to the biogas generation plant.

3. The operation and maintenance (O&M) costs are ascertained. The O&M costs of anaerobic digestion are a bit difficult to arrive at as these fluctuate with time and availability of replacement and/or refurbishment parts and accessories. As a rule of thumb a certain percentage of the initial investment costs for instance 2 % is taken to be the value of O&M costs.

4. The price of biogas is prescribed. The price of fuel on the market has a huge bearing on the determination of the price of biogas. In many countries, the energy sectors have a regulatory board which stipulates and governs fuel prices. However, it is worthwhile to set the selling price of biogas below that of conventional fuels such as Natural Gas and Liquid Petroleum Gas (LPG) for the reason that the conventional fuels are more efficient and as such for biogas to be competitive on the market its price has to be relatively lower. Biogas generation costs generally range from USD 0.22 to USD 0.39 per cubic meter of methane for animal dung-based biogas, and from USD 0.11 to USD 0.50 per cubic meter of methane for industrial waste-based biogas [151].

5. Carbon dioxide emissions are determined and carbon credits are calculated. The Paris Climate Agreement intends to keep global warming below 2 °C and promote initiatives to keep it below 1.5 °C [152]. There are specific limits which companies cannot exceed when it comes to greenhouse gas emissions. Carbon taxes are in operation world-over whereby entities pay for the amount of carbon dioxide they produce and emission trading schemes are operational creating a carbon market where businesses buy and sell carbon credits. Entities that avoid carbon dioxide emissions sell their rights to those having higher emission reduction costs [153]. Proceeds from carbon credits are taken as benefits and they positively influence the revenue of a company.

6. The amount of bio-slurry/bio-fertilizer is determined. It is not all the biomass material fed into the biogas reactor that is digested completely. The residue sludge normally referred to as sludge or bio-slurry can be used as a bio-fertiliser as it is rich in nutrients. This bi-product of anaerobic digestion can be sold to farmers and other interested stakeholders after drying it or in its wet form. Revenue is realised from selling this bio-fertiliser.

7. The Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period (t_{PB}) among other project appraisal criterion parameters are employed to ascertain the financial viability of the project under study.

2.8 RESEARCH GAPS AND FUTURE PERSPECTIVES

Co-digesting different substrates is reported to increase biogas output volumes owing to the optimistic interactions created in the digestion medium, microbial variations in diverse substrates as well as provision of missing nutrients by the co-substrates. Anaerobic co-digestion still remains largely unstudied for many varying substrates. Application of the co-digestion technology therefore needs close management since no one customary laid out operating parameters and settings are practical for all organic biodegradable wastes. Considering the availability of many different organic materials which can be feedstocks for co-digestion, further research in enhancement and controlling of biogas production from varied substrate types should be undertaken.

There is need of modelling and optimisation using specific substrates such as water hyacinth, cow dung and municipal solid waste so as to sustainably deal with the issues of environmental sustainability as well as energy demand and supply. This study notes that many previous works used arbitrary suppositions from a selection of uninformed different mixing ratios in co-digestion. Optimisation of the anaerobic biogas production process needs to be done so as to arrive at informed optimal substrate blend ratios and reaction parameters through co-digestion. Mathematical modelling can help researchers and the entire biogas fratenity to optimise operations more effectively and forecast biogas production in a variety of scenarios, conditions and/or constraints. The use of modelling and simulation in conjunction with analytical tools such as those in MATLAB will go a long way in planning, controlling, and predicting anaerobic co-digestions. The modelling and simulations can be coupled to optimisation of different specific target objectives such as maximising biogas output, minimising energy cost, minimising environmental detriments, amongst many others. The majority of the models in literature lack this coupling and this needs to be deeply looked into.

A lot of research and development is yet to be done with respect to mathematical modelling and application of optimisation tools in biogas production. As such it will be of interest to further develop, evaluate and compare the empirical, biological and mathematical models with regards to biogas prediction and optimisation. In line with the development of models and optimisation of the biogas production process, a wide spectrum of control options needs to be incorporated in the models in a bid to regulate the entire process for better optimal gas yields. Some control systems and/or strategies are lacking in the overall anaerobic biogas production optimisations. Incorporation of some simple controllers such as the on-off switching devices to advanced ones like the proportional integral derivative (PID) devices and fuzzy logic among others can lead to entire bio-process automation and enhancement.

The resultant AD process biogas outputs are dependent upon the amount, nature and standard of the biomass fed into the system. Thus the overall optimal yields are affected by the time of the year and the environment from which the substrates are derived from since these dictate the amount and quality of the same. Biogas production and optimisation models developed to date do not account for the geographical *(environmental)* and seasonal *(time)* variation of substrates. This offers an opportunuty for research in this direction.

This current study also highlights, from reviewing of previous works the necessity of accelerating integration of RETs into the existing energy supply mix. It is hereby reported that lots of research have been done on hybridisation of solar, wind, diesel, grid and in other instances coupled with storage such as batteries. However, the hybridisation of biogas with these and other conventional fuel supply alternatives like liquid petroleum gas (LPG) and other distributed renewable energy supply sources to meet energy and/or fuel demand is still at infancy in terms of research and development and as such is presented as an avenue for possible further research work.

Most of the previous works majored on experimental investigations and prospects of optimising single phase mono-digestion processes inclusive of the factors that affect the same. This agrees with [154] who also gave demerits to the laboratory experimental approaches owing to inconsistency in specific conditions under which the experiments are carried out. It is however realised in this study that research gaps do exist in regard to optimisation of co-digestion processes using biogas production models incorporating the concept of a multi-stage AD reaction mechanism inclusive of the factors that affect the same, mainly the pH and temperature parameters. This is as well being presented herein as a future research work direction.

There is need of taking a multi-objective approach when it comes to the techno-economic analysis of the anaerobic biogas production process. The modelling and optimisation will be more effective if all technical and economic parameters and conditions are employed. Given the current bid to combat climate change world-over, environmental aspects such as CO_2 equivalent emissions avoided can also be incorporated into the overall techno-economic analysis and this will contribute immensely towards the research and development of anaerobic biogas production technology.

2.9 CONCLUSION

Literature on anaerobic digestion was reviewed in this chapter. The literature survey showed that co-digestion requires a significant amount of additional research into a variety of biomass resources that have yet to be explored, as well as their specific blend proportions. It was also identified that modelling and optimisation of anaerobic digestion with seasonal fluctuations in the co-digestion feedstocks has not been addressed, despite the fact that this is a critical component for biogas enhancement. It was established that regulating and controlling key process factors including temperature, pH, and carbon to nitrogen ratio is critical for achieving the highest potential biogas yield. Previous research on the subject matter has not addressed the aspect of biogas hybridisation with other energy sources. This is yet to be thoroughly researched. The survey of literature reveals that the majority of researches are focused on mono-digestion. This study highlights that the function of feedstock co-digestion, modelling, and optimisation together with multi-stage anaerobic digestion is not well researched and needs significant further investigations. When conducting a techno-economic assessment of the anaerobic biogas generation process, it is necessary to use a multi-objective approach. If all technical and economic parameters and variables are included, the modelling and optimization will be more effective.

CHAPTER 3 BIOGAS POTENTIAL DETERMINATION AND PRODUCTION OPTIMISATION THROUGH OPTIMAL SUBSTRATE RATIO FEEDING IN CO-DIGESTION OF WATER HYACINTH, MUNICIPAL SOLID WASTE AND COW DUNG

3.1 CHAPTER OVERVIEW

This chapter is based on our published work [63], entitled "Biogas potential determination and production optimisation through optimal substrate ratio feeding in co-digestion of water hyacinth, municipal solid waste and cow dung". A model for biogas potential determination is presented for water hyacinth (WH), municipal solid waste (MSW), and cow dung (CD) substrates. The model application was mixing ratio optimisation, which uses data collected from Norton (a peri-urban town in Zimbabwe). The formulated model is further developed for the determination of biogas production potential from WH, MSW, and CD co-digestion mixture as well as the subsequent optimisation of the co-digestion mix ratios of these substrates. A linear programming mathematical optimisation was done. The objective was to find substrate blend ratios in the co-digestion mixture that maximises biogas production. In this study biogas is assumed to comprise of methane, carbon dioxide, ammonia and hydrogen sulphide.

Section 3.2 introduces the chapter. Section 3.3 gives the materials and methods, Section 3.4 gives a case study, Section 3.5 gives the results & discussion and Section 3.6 conludes the chapter.

3.2 INTRODUCTION

Biofuels such as biogas have a potential to extend and diversify energy supply, thus reducing dependence on imported fuels and pollution levels [155]. Biogas is a biofuel produced by the process of anaerobic digestion. A wide range of waste streams, agricultural, municipal, and food industrial wastes including industrial and municipal waste waters, as well as plant residues, can be feedstock for anaerobic digestion [10]. The substrate has to have the dietary rations for the microorganisms for it to be biodegraded optimally. Therefore substrate composition is very crucial in the anaerobic digestion process to optimally produce biogas.

Tetteh et al., [122] employed a response surface methodology to evaluate and enhance biogas potential by optimising pH, temperature, hydraulic retention time (HRT) and feedstock to innoculum ratio (F/I) on biogas production from miscunthus fuscus and cow dung in a batch co-digester. They found the optimal parameters to be pH of 6, temperature of 30 °C, HRT of 20 days and F/I ratio of 3:1. Feng et al., [156] and Jiya et al., [127] also optimised biogas production by using the response surface methodology, however none of them looked at the co-digestion feed mixture ratios. García-Gen et al., [123] used an experimental and heuristic methodology in an adaptive linear programming approach to optimise substrate blends from co-digestion of glycerine, gelatin and pig manure targeting at maximising chemical oxygen demand (COD) conversion into methane. Gaida et al., [125] developed an Anaerobic Digestion Model No.1 (ADM1) based simulation model, developed and applied a nonlinear model predictive control (NMPC) scheme with the inco-operation of a state estimator to optimally control substrate feed of agricultural biogas plants. Álvarez et al., [157] applied the solver method from Excel^{TM} as a linear programming tool in combination with experimental methodology to maximise the substrate biokinetic potential from co-digestion of pig manure, fish waste and bio-diesel waste.

The search for appropriate models to be used in optimisation and control theory is now a high priority to optimise fermentation processes [72]. The modelling of biochemical processes remains difficult because there is no biological laws or universal models, unlike physics, where known and validated models exist for centuries which can be the basis for the construction of mechanistic models [72]. The bacteria involved in biogas production process are very sensitive to changes in their environment hence making it a challenge to predict and control the process [18]. Thorin, et al., [18], concluded that for anaerobic digestion processes, the available detailed models such as the ADM1 among others are too complex for practical use and recommended the use of a combination of empirical and physical/biological models as a possible approach.

Major aspects in present-day anaerobic co-digestion, particularly interactions between system performance and co-substrate ratios for optimal biogas yields still remain underdeveloped [93]. Optimisation of anaerobic digestion processes for biogas production can be enhanced through mathematical models [91]. In addition to improving energy availability modelling and optimisation of biogas production will also improve environmental sustainability [9]. Process monitoring and control have been noted as further improvements needed for the biogas production process [158].

Research on new types of substrates and co-digestion combinations in appropriate ratios has not been done adequately and this study seeks to make contribution to this gap by having this established so as to substantially increase biogas production. Of major importance is the carbon to nitrogen C:N ratio. Different researchers reported different optimal C:N ratio ranges in literature depending on substrate type and reaction conditions; 10–23 [159], 15–30 [160], 25–30 [161], 20–30 [162], 15.5–19 [163]. This entails the need of modelling and optimisation of the production process taking into consideration the substrates involved.

According to the authors' best knowledge, the three substrates: water hyacinth (WH), municipal solid waste (MSW) and cow dung (CD) have not been co-digested together and no modelling nor optimisation for this trio substrate combination was done for biogas production enhancement. These wastes have been specifically chosen in a bid to deal with the negative implications they pose to the environment and atmosphere by way of value adding via anaerobic co-digestion and ultimately generating a biofuel in the form of biogas.

WH poses detrimental problems by infesting water bodies. It clogs within the rivers, lakes, ponds and dams forming intertwined mats. This hampers other activities such as fishing, boat riding and as well reduces biodiversity since other creatures which have water as their habitat can no longer survive. Proper management of MSW is paramount to both developed and developing countries in residential areas where the majority of the population has no access to waste collection services [164]. New legislation has to be put in place and existing policies revised so as to keep up with expected MSW environmental standards [164]. In addition to emitting hazardous greenhouse gases to the atmosphere, if not collected and dumped in a proper way, MSW also causes leaching and produces odours just like cow dung. Utilisation of MSW for biogas generation is a proven route of waste management that reduces the negative effects to the environment [165, 166, 167]. Cow dung and other animal manures emit 55–65 % methane into the atmosphere and this affects global warming 21 times more than CO_2 does [168]. Of all the substrates for biogas production, cow dung is the major source, however, mordern research on its co-digestion with other wastes has shown increased ultimate biogas yields [169, 170, 171]. WH and MSW are rich in nutrients for biogas production, however, their lignocellulosic recalcitrant nature renders them resistive to micro-bacterial degradation hence reduced gas yields. Co-digesting WH and MSW with CD gives enough access and potential to micro-organisms to foster optimised degradation and digestion [172, 173, 174]. In addition CD brings with it some buffering effect to the entire co-digestion reactions in the digester [175].

Literature shows that the enhancement and optimisation of biogas production for individual as well as co-digestions has mainly been done through heuristic, metaheuristic and artificial intelligence optimisation techniques and it appears that little work has been reported on the mathematical programming optimisation technique, and apparently no work in particular reports the co-digestion of water hyacinth, municipal solid waste and cow dung in one reactor chamber. For the heuristic experimental approaches, individual and/or combinations of substrates were considered without the use of informed mixing proportions. With due respect to such previous works, this study takes these as trial and error approaches.

This research reports an elemental composition mathematical programming modelling approach for biogas production and the respective novel optimisation methodology through co-digestion of water hyacinth, municipal solid waste and cow dung with the incooperation of substrate blending ratios. A stoichiometric (elemental composition) biogas prediction model is first developed and then a MATLAB tool based linear programming optimisation approach is developed and intergrated to maximise biogas production through determination and application of optimal co-digestion substrate feed ratios. The purpose of this work is to provide an easy non-complex model for determining biogas potential from water hyacinth, municipal solid waste and cow dung as well as to provide the optimal co-digestion substrate mixing ratios of the same which lead to improved ultimate biogas yield. The methodology and approach used herein can apply to any other biomass residues.

This study finds application in determination of the feasibility of biogas projects as well as in already existing biogas plants in terms of co-digestion blend ratios and as such substitutes to a greater extend the necessity of using complex and time consuming models such as ADM1 and other experimental approaches needing sophisticated equipment and methodologies. This will go a long way in value adding to the decision making of individuals, communities as well as small-scale and big companies to venture and invest in biogas production. Biogas production via anaerobic digestion is a cost-effective route for waste-to-energy conversion, however, the abundant natural gas and liquid petroleum gas makes it less cost competitive [176]. The bigger the biogas plant, the better the economic benefits attainable from it [177].

3.3 MATERIALS AND METHODS

3.3.1 Theory and Assumptions

It is assumed that:

- temperature is constant;
- pH is constant;
- the biomass material only consists of carbon, hydrogen, oxygen, nitrogen and sulphur;
- methane, carbon dioxide, ammonia and hydrogen sulphide are the only products;
- there is perfect mixing;
- digestion goes to completion;
- there is no ash accumulation;
- for MSW, only the organic fraction of it from food wastes and market wastes among other biodegradables in combination is utilisable for biogas production.

The assumptions stated herein this section hold for all the case studies presented in this thesis. In practice, temperature can be maintained by using solar water heaters to heat the anaerobic digester in combination with using a mechanical stirrer. The mechanical stirrer will also ensure that the digester constituents are almost perfectly mixed. At laboratory scale, the use of temperature controlled water bath is recommended for maintaining constant temperature. As the biogas production process reactions proceed, the hydrogen ion potential would vary as such the pH will alternate. To keep it the pH constant both in real practice and at laboratory scale, some buffering is done usually with sodium hydroxide or potassium hydroxide. If the assumptions listed above are not put in place the overall process reactions will become complex and too sophisticated and so becomes the model formulations and optimisations. This is one of the challenges prevalent with existing models, their complexity is too deep. This thesis aims to deal with such problems. Deviations from the listed assumptions will also have a negative bearing on the overall biogas yield and thus the primary research objectives will not be realised.

Biogas is a mixture of gases comprising mainly of methane and carbon dioxide and is produced by the process of anaerobic digestion. Table 3.1 shows the biochemical reactions in anaerobic digestion. The process consists mainly of four stages which are hydrolysis, acidogenesis, acetogenesis and methanogenesis [178].

Table 3.1. Biochemical reactions in anaerobic digestion.

Hydrolysis
$C_6H_{10}O_4 + 2H_2O \longrightarrow C_6H_{12}O_6 + H_2$
Acidogenesis
$C_6H_{12}O_6 \longleftrightarrow 2CH_3CH_2OH + 2CO_2$
$C_6H_{12}O_6 + 2H_2 \longleftrightarrow 2CH_3CH_2COOH + 2H_2O$
$C_6H_{12}O_6 \longrightarrow 3CH_3COOH$
Acetogenesis
$CH_3CH_2COO^- + 3H_2O \longleftrightarrow CH_3COO^- + H^+ + HCO_3^- + 3H_2$
$C_6H_{12}O_6 + 2H_2O \longleftrightarrow 2CH_3COOH + 2CO_2 + 4H_2$
$CH_3CH_2OH + 2H_2O \longleftrightarrow CH_3COO^- + 3H_2 + H^+$
Methanogenesis
$CH_3CH_2COOH \longrightarrow CH_4 + CO_2$
$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O$
$2CH_3CH_2OH + CO_2 \longrightarrow CH_4 + 2CH_3COOH$

Complex biomass materials are broken down into simple monomers with the aid of enzymes in the hydrolysis stage. Starch hydrolysis is catalysed by a combination of amylase enzymes while cellulose hydrolysis is catalysed by cellulases such as exo-glucanases, endo-glucanases and cellobiases.

Enzymatic hydrolysis of proteins is aided by protease and peptidases collectively known as proteinases. Lipid hydrolysis is facilitated by triglyceride lipases [179, 180]. In acidogenesis the monomers produced in hydrolysis (amino acids, simple sugars and fatty acids) are fermented and anaerobically oxidised by acidogenic bacteria. Intermediate products such as volatile fatty acids are anaerobically oxidised by acetogenic bacteria in the acetogenesis stage. In methanogenesis methane is produced from the products of acidogenesis and acetogenesis with the aid of methanogenic bacteria. These biochemical reactions are interrelated and depend on each other as depicted in Table 3.1.

In the course of biogas generation there are a lot of multifaceted interlinks within the processes as the reactions progress. A number of different parameter conditions are required, consequently complicating the model development processes [181]. As such available models differ with respect to complexity and purpose. Buswell & Mueller [75] developed a mechanism of methane fermentation which was a model for predicting methane and carbon dioxide. This model considered carbon, hydrogen and oxygen as the only elements present in the biomaterial. Equation (3.1) shows the Buswell and Mueller model equation.

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right) H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right) CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right) CO_2, \tag{3.1}$$

where n, a and b are the percentage composition by mass of carbon, hydrogen, and oxygen respectively and obtained from ultimate analysis.

In 1977, Boyle [182] modified the Buswell & Mueller equation and included nitrogen and sulphur as part of the elemental constuents of the biomaterial composition. Equation (3.2) shows the Boyle's biogas prediction equation.

$$\begin{aligned} C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right) H_2O \Rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right) CH_4 \\ + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right) CO_2 + dNH_3 + eH_2S. \end{aligned} \tag{3.2}$$

The constants a, b, c, d and e in $C_aH_bO_cN_dS_e$ are given by the ultimate analysis mass (or percentage composition by mass) of each of the elements devided by the relative atomic mass (Ar) of each of the elements as depicted below:

$$a = \frac{\text{Carbon ultimate mass}}{Ar_C} \triangleq \frac{\text{Carbon ultimate mass}}{12.017}, \tag{3.3}$$

$$b = \frac{\text{Hydrogen ultimate mass}}{Ar_H} \triangleq \frac{\text{Hydrogen ultimate mass}}{1.0079}, \tag{3.4}$$

$$c = \frac{\text{Oxygen ultimate mass}}{Ar_O} \triangleq \frac{\text{Oxygen ultimate mass}}{15.999}, \tag{3.5}$$

$$d = \frac{\text{Nitrogen ultimate mass}}{Ar_N} \triangleq \frac{\text{Nitrogen ultimate mass}}{14.0067}, \tag{3.6}$$

$$e = \frac{\text{Sulphur ultimate mass}}{Ar_S} \triangleq \frac{\text{Sulphur ultimate mass}}{32.065}. \tag{3.7}$$

3.3.2 Baseline study - biogas prediction and modelling

This subsection entails the methodology for the biogas prediction and modelling without co-digestion nor optimisation applied. In this baseline study volumes are in (ml) and masses are in (g). The waste streams which are the raw materials for biogas production vary significantly due to seasonal and geographical location leading to a dissimilarity of biogas potentials among different studies for the same substrates [6]. For this reason, a single set of ultimate analysis results is used from literature for each of the substrates and it is assumed that this data matches with the Zimbabwe case presented in this research. Table 3.2 gives the ultimate analysis values used in this study.

Table 3.2. Ultimate analysis percentage composition by mass [183], [184], [185]

Element	WH (%)	MSW (%)	CD (%)
C	33.13	48.00	39.09
H	4.35	6.40	4.61
O	29.71	37.60	26.68
N	1.66	2.60	0.83
S	0.37	0.40	0.25

The Boyle's modified Buswell & Mueller equation, represented by Equation (3.2) is adopted in this study.

Achinas and Euverink [186] reported that the relative molecular mass (Mr) of the biomass material with formular $C_aH_bO_cN_dS_e$ is given by:

$$Mr_{C_aH_bO_cN_dS_e} = a \times Ar_C + b \times Ar_H + c \times Ar_O + d \times Ar_N + e \times Ar_S \text{ in gmol}^{-1}, \tag{3.8}$$

where Ar_C, Ar_H, Ar_O, Ar_N and Ar_S are constants defined in Equations (3.3) - (3.7). Similarly the relative molecular masses (Mr) of the each of the reactants and products can be calculated as shown in Equations (3.9) - (3.13).

$$Mr_{H_2O} = 2 \times Ar_H + 1 \times Ar_O \text{ in gmol}^{-1}, \tag{3.9}$$

$$Mr_{CH_4} = Ar_C + 4 \times Ar_H \text{ in gmol}^{-1}, \tag{3.10}$$

$$Mr_{CO_2} = 1 \times Ar_C + 2 \times Ar_O \text{ in gmol}^{-1}, \tag{3.11}$$

$$Mr_{NH_3} = 1 \times Ar_N + 3 \times Ar_H \text{ in gmol}^{-1}, \tag{3.12}$$

$$Mr_{H_2S} = 2 \times Ar_H + 1 \times Ar_S \text{ in gmol}^{-1}. \tag{3.13}$$

Biogas is assumed to comprise of methane (CH_4), carbon dioxide (CO_2), ammonia (NH_3) and hydrogen sulphide (H_2S) [182]. Given that at standard temperature and pressure 1 mole of any gas occupies 22.4 L [187], each of these biogas constituents can be calculated as shown in Equations (3.14) - (3.17) [186, 188].

$$\text{Total biomethane } (CH_4) = \frac{22.4 \times 1000 \times \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right)}{Mr_{C_aH_bO_cN_dS_e}}, \tag{3.14}$$

$$\text{Total carbon dioxide } (CO_2) = \frac{22.4 \times 1000 \times \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right)}{Mr_{C_aH_bO_cN_dS_e}}, \tag{3.15}$$

$$\text{Total ammonia } (NH_3) = \frac{22.4 \times 1000 \times d}{Mr_{C_aH_bO_cN_dS_e}}, \tag{3.16}$$

$$\text{Total hydrogen sulphide } (H_2S) = \frac{22.4 \times 1000 \times e}{Mr_{C_aH_bO_cN_dS_e}}. \tag{3.17}$$

$$\text{Total Biogas production potential} = \text{Total } (CH_4) + \text{Total } (CO_2) + \text{ Total } (NH_3) + \text{Total } (H_2S). \tag{3.18}$$

The adopted Boyle's modified Buswell & Mueller Equation (3.2), assumes 100 % biomass disintergration and digestion which is not so with almost all biomasses. There is always some undigestible component within every substrate which is collected at the end of the digestion process as spent slurry. Lignocellulosic biomass materials are mainly composed of hemicellulose, lignin and cellulose. Hemicellulose degradation can be in the range of 77.2–85 % [189]. Lignin and cellulose are much more difficult to degrade, as such pretreatments to the biomass materials are necessary. To cater for the descrepancy in biodegradation, this study uses a factor of 0.8 adopted from [186] as an adjustment to the ultimate potential biogas yield .

3.3.3 Optimisation

This subsection entails the methodology for the codigestion, modelling and subsequent optimisation using the linear programming optimisation approach.

3.3.3.1 Problem formulation

Taking Equation (3.2) as the general reaction equation for the biogas production process, Equations (3.19), (3.20) and (3.21) can be derived to represent water hyacinth, municipal solid waste and cow dung biogas production processes respectively.

$$\begin{aligned} C_{a_1}H_{b_1}O_{c_1}N_{d_1}S_{e_1} + \left(a_1 - \frac{b_1}{4} - \frac{c_1}{2} + \frac{3d_1}{4} + \frac{e_1}{2}\right) H_2O \Rightarrow \left(\frac{a_1}{2} + \frac{b_1}{8} - \frac{c_1}{4} - \frac{3d_1}{8} - \frac{e_1}{4}\right) CH_4 \\ + \left(\frac{a_1}{2} - \frac{b_1}{8} + \frac{c_1}{4} + \frac{3d_1}{8} + \frac{e_1}{4}\right) CO_2 + d_1NH_3 + e_1H_2S, \end{aligned} \tag{3.19}$$

$$\begin{aligned} C_{a_2}H_{b_2}O_{c_2}N_{d_2}S_{e_2} + \left(a_2 - \frac{b_2}{4} - \frac{c_2}{2} + \frac{3d_2}{4} + \frac{e_2}{2}\right) H_2O \Rightarrow \left(\frac{a_2}{2} + \frac{b_2}{8} - \frac{c_2}{4} - \frac{3d_2}{8} - \frac{e_2}{4}\right) CH_4 \\ + \left(\frac{a_2}{2} - \frac{b_2}{8} + \frac{c_2}{4} + \frac{3d_2}{8} + \frac{e_2}{4}\right) CO_2 + d_2NH_3 + e_2H_2S, \end{aligned} \tag{3.20}$$

$$\begin{aligned} C_{a_3}H_{b_3}O_{c_3}N_{d_3}S_{e_3} + \left(a_3 - \frac{b_3}{4} - \frac{c_3}{2} + \frac{3d_3}{4} + \frac{e_3}{2}\right) H_2O \Rightarrow \left(\frac{a_3}{2} + \frac{b_3}{8} - \frac{c_3}{4} - \frac{3d_3}{8} - \frac{e_3}{4}\right) CH_4 \\ + \left(\frac{a_3}{2} - \frac{b_3}{8} + \frac{c_3}{4} + \frac{3d_3}{8} + \frac{e_3}{4}\right) CO_2 + d_3NH_3 + e_3H_2S. \end{aligned} \tag{3.21}$$

The objective is to find the substrate blend ratios in the co-digestion mixture that maximises the production of biogas. A linear programming optimisation approach is proposed in the following mathematical formulation.

$$\min_x f^T x \quad \text{such that} \quad \begin{cases} A.x \leq b, \\ A_{eq}.x = b_{eq}, \\ lb \leq x \leq ub, \end{cases} \tag{3.22}$$

where f, x, b, b_{eq}, lb and ub are vectors, and A and A_{eq} are matrices, and $f^T x$ is called the objective function and the equalities and inequalities are called constraints.

3.3.3.2 Objective function and Constraints

The objective is to maximise the biogas output from the substrate mixture and as such determine the optimal substrate mass blend ratios.

The objective function is expressed as:

$$f^T x = -(V_1 x_1 + V_2 x_2 + V_3 x_3), \tag{3.23}$$

where the number of moles of the substrates are the decision variables denoted by:

$$X \text{ (moles)} = [x_1 \;\; x_2 \;\; x_3]^T. \tag{3.24}$$

In the optimisations volumes are in (m^3), masses are in (kg) and the units of x_1, x_2 and x_3 are moles. In Equation (3.24), x_1 is the number of moles of water hyacinth, x_2 is the number of moles of municipal solid waste and x_3 is the number of moles of cow dung.

V_1 is the volume of biogas from WH expressed as:

$$V_1 \text{ (m}^3\text{)} = \frac{(22.4\times 10^{-3})\times(CO_{2_1} + NH_{3_1} + H_2S_1 + CH_{4_1})}{Mr_{WH}}. \tag{3.25}$$

V_2 is the volume of biogas from MSW expressed as:

$$V_2 \text{ (m}^3\text{)} = \frac{(22.4\times 10^{-3})\times(CO_{2_2} + NH_{3_2} + H_2S_2 + CH_{4_2})}{Mr_{MSW}}. \tag{3.26}$$

V_3 is the volume of biogas from CD expressed as:

$$V_3 \text{ (m}^3\text{)} = \frac{(22.4\times 10^{-3})\times(CO_{2_3} + NH_{3_3} + H_2S_3 + CH_{4_3})}{Mr_{CD}}. \tag{3.27}$$

$CO_{2_{1,2,\&3}}$, $NH_{3_{1,2,\&3}}$, $H_2S_{1,2,\&3}$and $CH_{4_{1,2,\&3}}$ are the number of moles of carbon dioxide, ammonia, hydrogen sulphide and methane for WH, MSW and CD respectively and Equations (3.28) - (3.39) show how to determine these moles. Mr_{WH}, Mr_{MSW} and Mr_{CD} are as denoted in equations (3.40), (3.41) and (3.42) respectively.

$$CH_{4_1} = \frac{a_1}{2} + \frac{b_1}{8} - \frac{c_1}{4} - \frac{3d_1}{8} - \frac{e_1}{4}, \tag{3.28}$$

$$CO_{2_1} = \frac{a_1}{2} - \frac{b_1}{8} + \frac{c_1}{4} + \frac{3d_1}{8} + \frac{e_1}{4}, \tag{3.29}$$

$$NH_{3_1} = d_1, \tag{3.30}$$

$$H_2S_1 = e_1, \tag{3.31}$$

$$CH_{4_2} = \frac{a_2}{2} + \frac{b_2}{8} - \frac{c_2}{4} - \frac{3d_2}{8} - \frac{e_2}{4}, \tag{3.32}$$

$$CO_{2_2} = \frac{a_2}{2} - \frac{b_2}{8} + \frac{c_2}{4} + \frac{3d_2}{8} + \frac{e_2}{4}, \tag{3.33}$$

$$NH_{3_2} = d_2, \tag{3.34}$$

$$H_2S_2 = e_2, \tag{3.35}$$

$$CH_{4_3} = \frac{a_3}{2} + \frac{b_3}{8} - \frac{c_3}{4} - \frac{3d_3}{8} - \frac{e_3}{4}, \tag{3.36}$$

$$CO_{2_3} = \frac{a_3}{2} - \frac{b_3}{8} + \frac{c_3}{4} + \frac{3d_3}{8} + \frac{e_3}{4}, \tag{3.37}$$

$$NH_{3_3} = d_3, \tag{3.38}$$

$$H_2S_3 = e_3, \tag{3.39}$$

$$Mr_{WH}\ (\text{kgmol}^{-1}) = a_1 * Ar_C + b_1 * Ar_H + c_1 * Ar_O + d_1 * Ar_N + e_1 * Ar_S, \tag{3.40}$$

$$Mr_{MSW}\ (\text{kgmol}^{-1}) = a_2 * Ar_C + b_2 * Ar_H + c_2 * Ar_O + d_2 * Ar_N + e_2 * Ar_S, \tag{3.41}$$

$$Mr_{CD}\ (\text{kgmol}^{-1}) = a_3 * Ar_C + b_3 * Ar_H + c_3 * Ar_O + d_3 * Ar_N + e_3 * Ar_S. \tag{3.42}$$

The constraints are described in (3.43), (3.56), (3.57), (3.58) and (3.59). Equation (3.43) is the reactor volume constraint which is fixed at 1 m^3 specifically for the purpose of restricting the co-digestion substrate quantities to a unit volume for easy of determination of substrate blending mass ratios.

$$h(x) = V_A x_1 + V_B x_2 + V_C x_3 - 1 = 0, \tag{3.43}$$

where V_A is the volume of WH and its respective volume of water at any instant denoted as:

$$V_A\ (\text{m}^3) = V_{WH} + \left(\frac{(22.4 \times 10^{-3}) \times H_2O_1}{Mr_{WH}} \times V_{H_2O} \right), \tag{3.44}$$

where:

$$H_2O_1\ (\text{moles}) = a_1 - \frac{b_1}{4} - \frac{c_1}{2} + \frac{3d_1}{4} + \frac{e_1}{2}, \tag{3.45}$$

$$V_{WH} = \frac{m_{WH}}{\rho_{WH}}, \tag{3.46}$$

$$m_{WH} = Mr_{WH} \times n_{WH}. \tag{3.47}$$

ρ_{WH} is the density of water hyacinth. V_{H_2O} in Equations (3.44), (3.48) and (3.52) is the volume of water to be added to each substrate per each mole of the respective substrate and has units of m^3mol^{-1} and V_B is the volume of MSW and its respective volume of water at any instant denoted as:

$$V_B\ (\text{m}^3) = V_{MSW} + \left(\frac{(22.4 \times 10^{-3}) \times H_2O_2}{Mr_{MSW}} \times V_{H_2O} \right), \tag{3.48}$$

where:

$$H_2O_2\ (\text{moles}) = a_2 - \frac{b_2}{4} - \frac{c_2}{2} + \frac{3d_2}{4} + \frac{e_2}{2}, \tag{3.49}$$

$$V_{MSW} = \frac{m_{MSW}}{\rho_{MSW}}, \tag{3.50}$$

$$m_{MSW} = Mr_{MSW} \times n_{MSW}. \tag{3.51}$$

ρ_{MSW} is the density of municipal solid waste. V_C is the volume of CD and its respective volume of water at any instant denoted as:

$$V_C\ (\mathrm{m}^3) = V_{CD} + \left(\frac{(22.4 \times 10^{-3}) \times H_2O_3}{Mr_{CD}} \times V_{H_2O} \right), \tag{3.52}$$

where:

$$H_2O_3\ (\mathrm{moles}) = a_3 - \frac{b_3}{4} - \frac{c_3}{2} + \frac{3d_3}{4} + \frac{e_3}{2}, \tag{3.53}$$

$$V_{CD} = \frac{m_{CD}}{\rho_{CD}}, \tag{3.54}$$

$$m_{CD} = Mr_{CD} \times n_{CD}. \tag{3.55}$$

ρ_{CD} is the density of cow dung.

Inequalities in (3.56), (3.57) and (3.58) show the the lower and upper bounds constraints for WH, MSW and CD respectively.

$$V_{WH}^{min} \leqslant x_1 \leqslant V_{WH}^{max}. \tag{3.56}$$

$$V_{MSW}^{min} \leqslant x_2 \leqslant V_{MSW}^{max}. \tag{3.57}$$

$$V_{CD}^{min} \leqslant x_3 \leqslant V_{CD}^{max}. \tag{3.58}$$

Inequalities in (3.59) gives the C:N ratio constraint

$$(\mathrm{C{:}N})^{min} \leqslant \frac{a_1.x_1 + a_2.x_2 + a_3.x_3}{d_1.x_1 + d_2.x_2 + d_3.x_3} \leqslant (\mathrm{C{:}N})^{max}, \tag{3.59}$$

where a_1, a_2 and a_3 are the WH, MSW and CD carbon ultimate compositions respectively; and d_1, d_2, and d_3 are the WH, MSW and CD nitrogen ultimate compositions respectively.

3.4 CASE STUDY

Water hyacinth, an invasive species is invading fresh water bodies thereby out-competing other species and decreasing biodiversity. Municipal solid waste is currently being disposed of in waste dumps and landfills and this is resulting in the formation of landfill gas which is a more intoxicating gas than carbon dioxide such that its greenhouse effect is about 21 times greater over a 100 year time frame [190]. Municipal solid waste and cow dung have been implicated in poor aesthetic quality of the environment and pollution of surface and ground water sources [8]. These wastes can be value added via the anaerobic digestion process to produce biogas thereby reducing direct CO_2 and CH_4 emissions into the atmosphere. However, if not properly managed, there are chances that these greenhouse gases can escape via leaks from the digester, field application of untreated slurry and uncovered digestate storage tanks [191, 192]. Overally GHG emissions are reduced by anaerobic digestion, however, proper management and efficient operation of the entire process is of paramount importance to achieve huge benefits in GHG reductions. The biogas has to be treated or purified so that CO_2 and other impurities such as H_2S can be captured and/or removed.

Lake Chivero in Zimbabwe near Norton is used as the water hyacinth resource base. The estimated total wet mass of water hyacinth in Lake Chivero is 197 400 t/yr and dry mass is 23 688 t/yr [9]. In this study dried water hyacinth is used as it was proved to produce more biogas as compared to wet mass of the same [9]. The density of water hyacinth is 85 kg/m^3 which gives a total available volume of 278 682.35 m^3/yr of dry water hyacinth.

Waste generation rate is estimated to be 0.5 kg per person per day [193]. Norton, a peri-urban town in Zimbabwe is used as a case study area for this research and has a population of 52 054 [194]. Total waste generated is therefore $0.5 \times 52\,054 = 26\,027$ kg/day $= 9\,499.9$ t/yr. Computation using a density of 217.5 kg/m^3 gives a volume of 43 677.7 m^3/yr for the municipal solid waste resource.

Norton is part of Chegutu district which has a total of 87 603 cattle. It is assumed that Norton owns 25 % of Chegutu's cattle. Each cow produces 908 kg/yr of dung. The total mass of cow dung is computed to be 19 885 881 kg/yr. The density of cow dung is 400 kg/m^3 which gives a volume of 49 714.70 m^3/yr.

The retention time is assumed to be 30 days implying that the digester has to be fed 12 times per year. As such each yearly volume of substrate is devided by 12 times yeilding maximum quantities of 2.32×10^4 m^3, 3.64×10^3 m^3 and 4.143×10^3 m^3 for water hyacinth, municipal solid waste and cow dung respectively. The minimum feed for each substrate is taken as zero.

Table 3.3. Case data for volumes

Parameter	WH (m^3)	MSW (m^3)	CD (m^3)
V_{min}	0	0	0
V_{max}	2.32×10^4	3.64×10^3	4.143×10^3

Table 3.3 shows the minimum and maximum volumes used as part of the case data and these are as such also taken to depict the lower and upper volume bounds respectively. Distinct researchers reported diverse ranges of C:N ratio for optimal biogas generation for specific substrates. The ranges reported are 15–30, 25–30, 20–30 and 15.5–19 [159, 160, 161, 162, 163]. This implies that each substrate and/or substrate combinations in co-digestions have perculiar C:N ratio range for optimality different from any other substrates. In this study a minimum value, $(C:N)^{min}$ of 10 and a maximum value, $(C:N)^{max}$ of 35 were set and the simulations in the optimisation were allowed to pick an optimal C:N ratio for the substrate combinations (WH, MSW and CD) being co-digested.

To obtain the model parameters used in the determination of reacting moles for the co-digestion substrate mixture, the relative atomic masses were converted from gmol^{-1} to kgmol^{-1}, Equations (3.3), (3.4), (3.5), (3.6) and (3.7) were applied, the emperical formula concept was used (deviding each resultant value by the minimum of the resultant values) and finally the parameter values shown in Table 3.4 are arrived at by deviding the obtainable results by 1000 thus making the units to be consistent.

Table 3.4. Model parameters for determination of reacting moles

WH		MSW		CD	
parameter	value	parameter	value	parameter	value
a_1	0.2389	a_2	0.3202	a_3	0.2687
b_1	0.3740	b_2	0.5090	b_3	0.4150
c_1	0.1609	c_2	0.1884	c_3	0.1219
d_1	0.0103	d_2	0.0149	d_3	0.0263
e_1	0.001	e_2	0.001	e_3	0.001

The relative atomic masses (Ar) used in the model are as defined in Equations (3.3) - (3.7) and then converted to units of (kgmol^{-1}). The densities used in the model are as shown in Table 3.5

Table 3.5. Densities

Substrate/material	Density, ρ (kgm^{-3})	Source
WH	85	[195]
MSW	217.5	[183]
CD	400	[196]
H_2O	997	[197]

The final linear programming problem in the standard form as in Equation (3.22) with all the parameters is as shown in Equations (3.60) - (3.66).

$$f^T = 22.4\times10^{-3}\times\left[-\frac{\left(CO_{2_1}+NH_{3_1}+H_2S_1+CH_{4_1}\right)}{Mr_{WH}} \quad -\frac{\left(CO_{2_2}+NH_{3_2}+H_2S_2+CH_{4_2}\right)}{Mr_{MSW}} \quad -\frac{\left(CO_{2_3}+NH_{3_3}+H_2S_3+CH_{4_3}\right)}{Mr_{CD}}\right] \tag{3.60}$$
$$= \begin{bmatrix}-0.9342 & -0.9885 & -1.1053\end{bmatrix},$$

where $CO_{2_{1,2,\&3}}$, $NH_{3_{1,2,\&3}}$, $H_2S_{1,2,\&3}$ and $CH_{4_{1,2,\&3}}$ are as denoted in Equations (3.28) - (3.39). Mr_{WH}, Mr_{MSW} and Mr_{CD} are as denoted in Equations (3.40), (3.41) and (3.42).

The carbon to nitrogen ratio inequality constraint Equation (3.59), was linearised and 2 inequalities were arrived at as shown in Equation (3.61).

$$A = \begin{bmatrix} 10(d_1-a_1) & 10(d_2-a_2) & 10(d_3-a_3) \\ (a_1-35d_1) & (a_2-35d_2) & (a_3-35d_3) \end{bmatrix} \tag{3.61}$$
$$= \begin{bmatrix} -0.1362 & 0.1714 & 0.0062 \\ -0.1206 & -0.2006 & -0.6500 \end{bmatrix},$$

$$b = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \tag{3.62}$$

$$\begin{aligned} A_{eq} = & \Bigg[V_{WH} + \left(\frac{\left(22.4\times10^{-3}\right)\times H_2O_1}{Mr_{WH}} \times V_{H_2O} \right) \quad V_{MSW} + \left(\frac{\left(22.4\times10^{-3}\right)\times H_2O_2}{Mr_{MSW}} \times V_{H_2O} \right) \\ & V_{CD} + \left(\frac{\left(22.4\times10^{-3}\right)\times H_2O_3}{Mr_{CD}} \times V_{H_2O} \right) \Bigg] \\ = & \begin{bmatrix} 7.5509\times10^{-5} & 4.0881\times10^{-5} & 2.3376\times10^{-5} \end{bmatrix}, \end{aligned} \tag{3.63}$$

where: H_2O_1, H_2O_2 and H_2O_3 are as denoted in Equations (3.45), (3.49) and (3.53) respectively.

$$b_{eq} = \begin{bmatrix} 1 \end{bmatrix}, \tag{3.64}$$

$$lb = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \tag{3.65}$$

$$ub = \begin{bmatrix} 2.32\times10^{4} \\ 3.64\times10^{3} \\ 4.143\times10^{3} \end{bmatrix}. \tag{3.66}$$

The biogas production process has to be operated at a large scale for it to compete with conventional sources such as natural gas and liquid petroleum gas which are cheaper and at the same time have more calorific values. However, for the purposes of this study the digester volume is taken as unit (1 m^3) as indicated in Equation (3.43) so as to arrive at the intended objective of ascertaining the substrate co-digestion blending ratios per unit volume of reactor.

3.5 RESULTS AND DISCUSSION

The results presented are as per dry water hyacinth, wet cow dung and wet organic fraction of municipal solid waste substrate feeds.

3.5.1 Baseline results

Table 3.6. Biogas potential prediction for water hyacinth, municipal solid waste and cow dung

Component	WH (Nml/gVS)		MSW (Nml/gVS)		CD (Nml/gVS)	
	S_b	A_b	S_b	A_b	S_b	A_b
CH_4	455.11	364.09	502.38	401.91	543.95	435.16
CO_2	437.05	349.64	439.44	351.55	459.59	367.67
NH_3	38.35	30.68	43.77	35.01	98.03	78.42
H_2S	3.73	2.99	2.94	2.35	3.73	2.99
B_{tot}	934.24	747.40	988.53	790.83	1105.3	884.24

S_b = stoichiometric biogas yield; A_b = adjusted biogas yield

Table 3.6 gives the mono-digestion theoretical and adjusted biogas constituents as well as the total biogas potential (B_{tot}) for WH, MSW and CD respectively. The theoretical values are arrived at by using Equations (3.14) – (3.18) for each of the substrates and the adjusted values are obtained by multiplying the theoretical values by a factor of 0.8 so as to cater for the non-biodegradable fractions of the substarates which remain undigested [186]. Figure 3.1 is drawn from Table 3.6 and shows the quantity of each gas component constituent in the biogas for each of the substrates. It can be deduced from the three substrates that cow dung produces the highest amount of biogas followed by municipal solid waste and water hyacinth produces the least as depicted in Table 3.6 and Figure 3.1. Biogas generation from cow dung is highest due to the fact that some partial digestion would have already happened on the bio-material in the stomach of the cattle and it is lowest in water hyacinth due to the complex lignin, cellullose and hemicelluloses within its structure which renders it to be recalcitrant in nature. Figures 3.2, 3.3 and 3.4 display pictorial results of the percentage composition of the biogas constituent gases (methane, carbon doxide, ammonia and hydrogen sulphide) from water hyacinth, municipal solid waste and cow dung respectively as drawn from Table 3.6. A similar trend is observed from the results that methane constitutes the highest percentage, followed by carbon dioxide then ammonia and lastly hydrogen sulphide. This tallies with what was reported by Anuar [198], Rasi [199], Vanegas and Bartlett [200] as well as by Kossmann and Pönitz [201] among many other researchers.

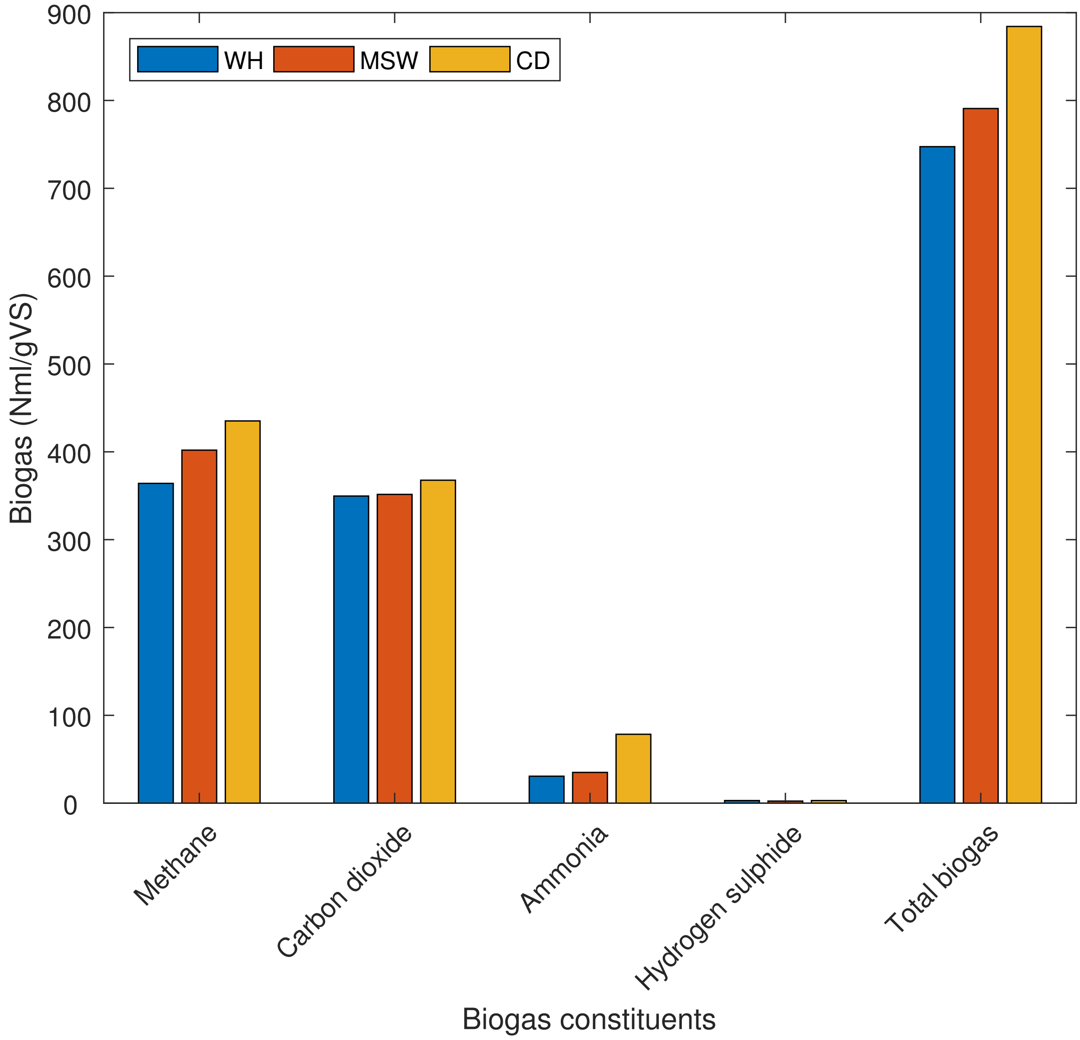

Figure 3.1. Biogas potential prediction by gas constituent from individual substrates.

3.5.2 Co-digestion and optimisation results

Table 3.7 shows the optimal substrate moles and the respective blend ratios for the co-digestion of water hyacinth, municipal solid waste and cow dung.

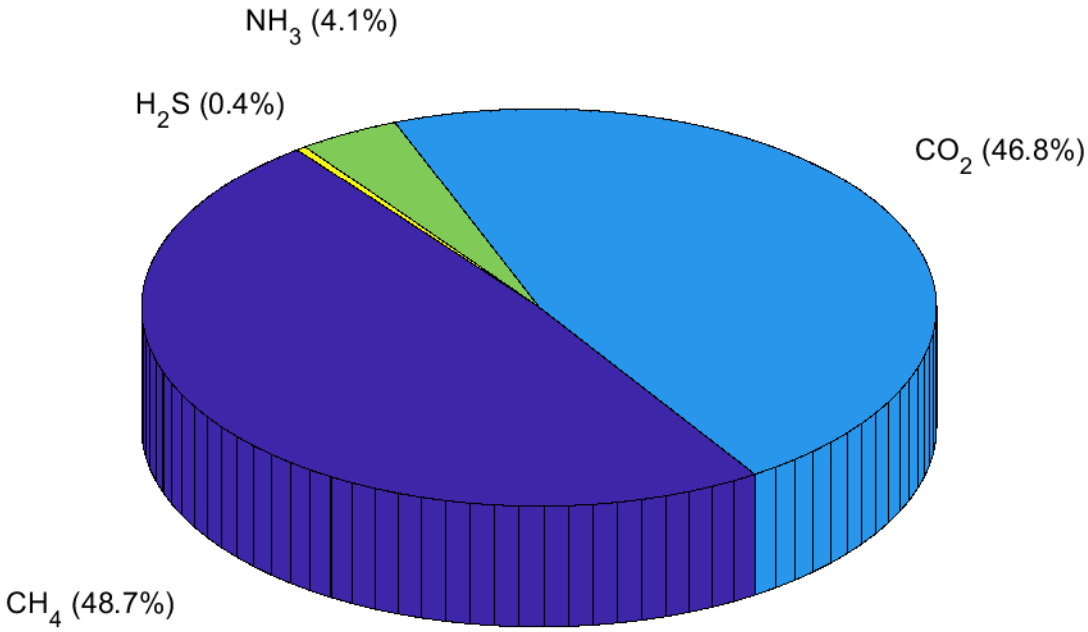

Figure 3.2. Water Hyacinth biogas percentage composition.

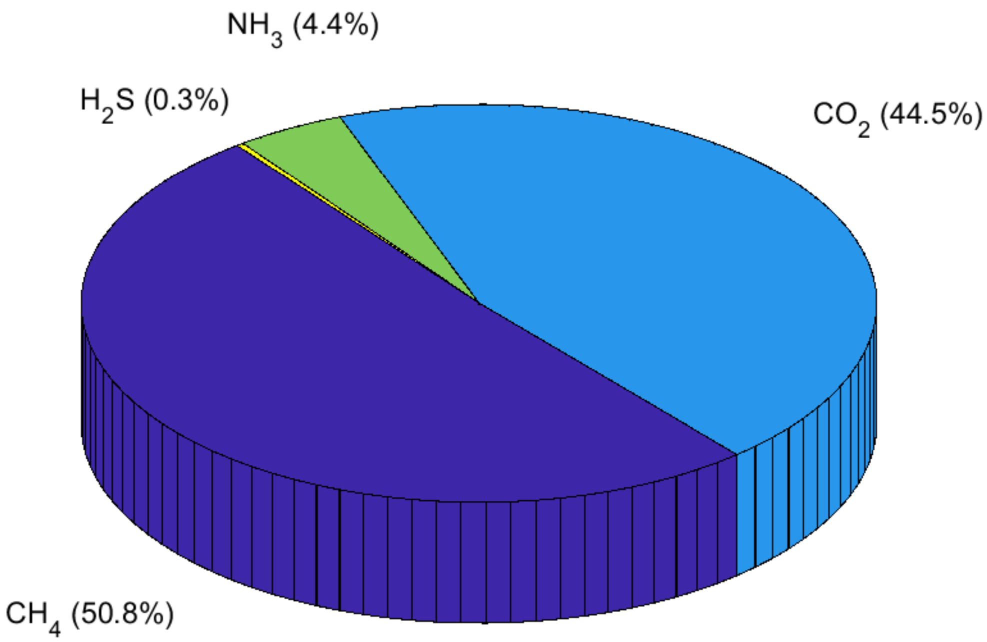

Figure 3.3. Municipal Solid Waste biogas percentage composition.

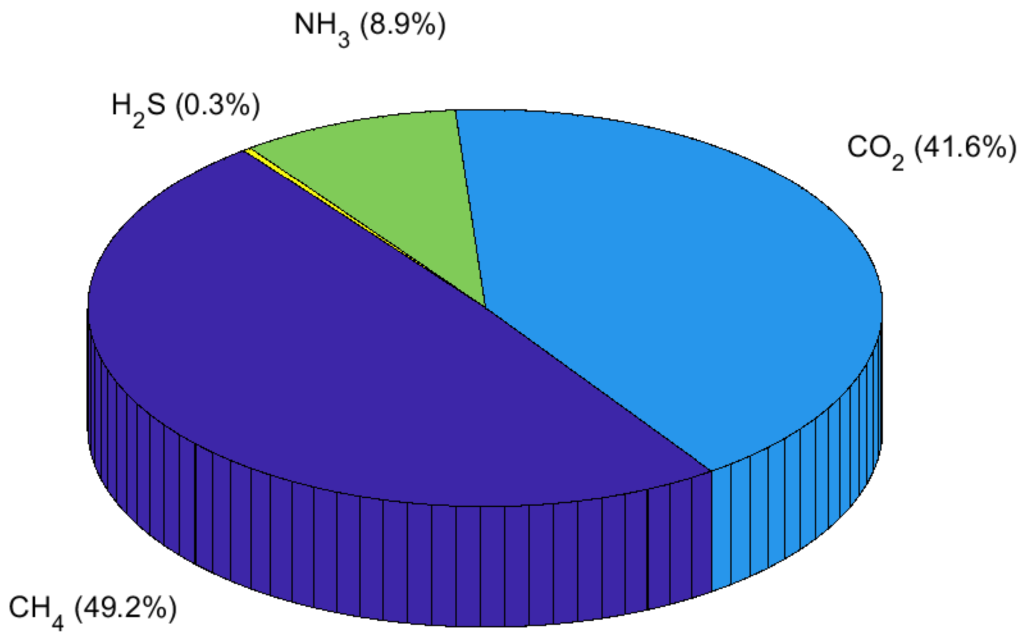

Figure 3.4. Cow Dung biogas percentage composition.

Table 3.7. Optimisation results summary

Parameters	WH	MSW	CD
Optimal substrate moles	9 990.1	3 640	4 143
Molar masses (kg/mol)	0.006	0.0076	0.006
Optimal masses (kg)	59.94	27.66	24.86
Optimal mass ratios (%)	53.27	24.64	22.09
Optimal C:N ratio		17.57:1	
Optimal biogas yield (m^3)		17 511	
Adjusted optimal biogas yield (m^3)		14 008.8	

Linear programming optimisation using the linprog dual-simplex algorithm in MATLAB gave optimal substrate blends of $x_1 : x_2 : x_3$ as 9 990.1 moles : 3 640 moles : 4 143 moles for the co-digestion of water hyacinth, municipal solid waste and cow dung respectively for a 1 m^3 digester. The model gave the optimal C:N ratio for the codigestion mixture as 17.57:1. The computed molar masses from the model are 0.006 kg/mol, 0.0076 kg/mol and 0.006 kg/mol for water hyacinth, municipal solid waste and cow dung respectively. Using these results and applying the stoichiometric relationship; mass = number of moles $\times$ molar mass [202], the quantities of each substrate to be fed for each cubic meter digester are found to be 59.9406 kg : 27.664 kg : 24.858 kg. This translates to optimal percentage substrate mass blend ratios of 53.27 : 24.64 : 22.09 for water hyacinth, municipal solid waste and cow dung respectively for any digester volume.

3.5.3 Discussion

From Table 3.6, with units converted from Nml/gVS to m^3/kg, the total biogas potential predictions were found to be 0.747 m^3/kg, 0.790 m^3/kg and 0.884 m^3/kg for water hyacinth, municipal solid waste and cow dung respectively. For the purpose of comparing the baseline biogas output to the optimised output, the baseline is subjected to the same masses of the individual substrates which were fed to a 1 m^3 digestion chamber. Table 3.8 shows the individual substrates' biogas yields as well as the total biogas or sum of these mono-digestion quantities.

Table 3.8. Baseline biogas output

Parameters	WH	MSW	CD
Biogas potential (m^3/kg)	0.747	0.790	0.884
Substrate masses (kg)	59.94	27.66	24.86
Substrate biogas yield (m^3)	44.78	21.85	21.97
Total biogas yield (m^3)		88.60	

In Table 3.8, the biogas potentials are taken from Table 3.6 and the individual substrate masses are taken from Table 3.7.

The optimised co-digestion system herein takes 112.46 kg of substrate blend mixture and gives a biogas yield of 14 008.8 m^3. Upon applying the adjustiment factor of 0.8 to the yield as explained in the last paragraph of *Subsection 3.3.2*, 1 kg of co-digestion substrate blend mixture yields 124.56 m^3 of biogas which translates to 124 560 Nml/gVS. Equation (3.67) shows the calculation of the percentage increase from the baseline result to the optimisation result.

$$\begin{aligned} \text{Percentage increase} &= \frac{\text{Optimised yield} - \text{Total baseline yield}}{\text{Total baseline yield}} \times 100 \\ &= \frac{14\,008.8 - 88.60}{88.60} \times 100 \\ &= 157.11\%. \end{aligned} \tag{3.67}$$

Based on the simulation results, this study reports that co-digestion of water hyacinth, municipal solid waste and cow dung as well as application of optimisation to the substrate feed ratios increases the biogas yield by 157.11 % when compared to mono-digestion of the same. Varied percentage increases are reported in literature from co-digestion depending on the types and number of substrates as well as conditions the reactions are subjected to. Most of the reports are on co-digestion of only two substrates under thermophilic conditions. Astals et al., [203], reported an increase of 400 % on output biogas from co-digestion of pig manure and crude gycerol. Yen and Brune, [204], reported an increase of 104.2 % from co-digestion of algal sludge and waste paper. Li et al., [205] reported an increase of 44 % from co-digestion of kitchen waste and cow manure.

Cow dung has a water content in the range of 70 % – 90 % [206] and water hyacinth has a water content of about 90 % [9]. These high percentages of water have a net positive effect on anaerobic digestion. However, cattle manure has residual lignin complexes from fodder which is somehow resistant to anaerobic digestion [207]. Water hyacinth is constituted of lignin, cellulose and hemicelluloses which makes it recalcitrant in nature leading to its poor digestion individually [208]. Co-digestion has a complimentary effect to the pros and cons of each of the substrates herein discussed leading to the higher combined biogas output realised.

Optimal substrate mix ratios realised from the optimisation done led to optimal carbon to nitrogen (C:N) ratio within the substrate blend among other benefits such as stabilisation of the process. For this study the optimal C:N ratio was found to be 17.57:1. This agrees to the ranges reported by [159, 160, 163] even though the substrates are different. Different values were simulated for $(C{:}N)^{min}$ and $(C{:}N)^{max}$. $(C{:}N)^{min}$ values of 17 and below had no effect on the optimal C:N ratio while on the other hand for values between 18 and 23 the optimisation picked that specific value set as the minimum of the range while at the same time reducing the proportion of the third substrate (CD) towards zero and increasing the mass ratios of the other two substrates. $(C{:}N)^{min}$ values of 24 and above led to infeasible solutions. $(C{:}N)^{max}$ values of 18 and above had no effect on the optimal C:N ratio as well as the resultant mass ratios, the simulations picked a value of 17.57 as the optimal one. $(C{:}N)^{max}$ values of

17 and below led to infeasible solutions. The carbon to nitrogen (C:N) ratio complimentary synergistic positive effect to the digestion process is one of the major explanations to the increase in biogas output from the co-digested substrates in comparison to the individual mono-digestion biogas output.

3.6 CONCLUSION

This study investigated and established an optimal substrate blend ratio for the co-digestion of water hyacinth, municipal solid waste and cow dung and a model for the blend mixture which produces optimum biogas was developed from first principles. A prediction of the expected biogas yield from the individual substrates as well as from the co-digestion substrates mixture was done. Modelling and optimisation results showed that the use of optimal substrate mixing ratios in co-digestion improves the biogas yield when compared to using individual substrates in mono-digestions.

CHAPTER 4 CO-DIGESTION OF WATER HYACINTH, MUNICIPAL SOLID WASTE AND COW DUNG: A METHANE OPTIMISED BIOGAS-LIQUID PETROLEUM GAS HYBRID SYSTEM

4.1 CHAPTER OVERVIEW

This chapter builds upon the previous preceding chapter and is based on our published work [209] entitled, "Co-digestion of water hyacinth, municipal solid waste and cow dung: A methane optimised biogas–liquid petroleum gas hybrid system". The novel aspect of incorporation of biomass co-digestion feedstock seasonal variations into the simulation, modelling and optimisation is employed. Further, in the objective function, unwanted biogas components (CO_2, H_2S and NH_3) have been minimised and the major desired component (CH_4) has been maximised. The incorporation of seasonal variations and the control of biogas quality is unique to this study. Hybridisation of biogas with other energy sources such as solar have been investigated in previous works [210, 211, 212, 213], however, hybridisation of biogas with other conventional fuels such as liquid petroleum gas (LPG) is still at infancy. Research works on this could hardly be found in literature. This was seen as a huge research gap which was then explored in this study.

Section 4.2 gives the chapter introduction. In Section 4.3 the modelling and optimisation materials and methods are given, the algorithm is presented in Section 4.4, Section 4.5 gives a case study, Section 4.6 gives the results & discussion and Section 4.7 concludes the chapter.

4.2 INTRODUCTION

The heating, cooling and transport sectors, which account for 80 % of global total final energy consumption, are lagging behind in view of meeting Sustainable Development Goal 7 (SDG 7) - (affordable and clean energy) and thus require accelerated action towards the renewable energy transformation [214]. One lucrative avenue towards solving the issue is venturing into biofuels such as biogas which is a form of bioenergy. Bioenergy can be regarded as the most substantial renewable energy source due to its cost-effective advantages and its great potential as an alternative to fossil fuels [215]. It is a renewable energy that is derived from biomass material which is any biological organic matter obtained from plants or animals. Bioenergy is obtained from a broad variety of resources and produced in many diverse routes [216].

Biomass energy sources include but are not limited to terrestrial plants, aquatic plants, timber processing residues, municipal solid wastes, animal dung, sewage sludge, agricultural crop residues and forestry residues. These different types of biomass have to be linked to the various energy flows and conversions in order to meet both renewable energy needs and solve waste management challenges [217]. Bioenergy is one of the most versatile among other renewable energies since it can be made available in solid, liquid and/or gaseous forms [218]. Biogas is one such bioenergy source in the form of a gaseous biofuel. In contrast with other biofuels, biogas production is flexible to different substrates on condition that they are biodegradable. Biogas is produced by the process of anaerobic digestion of biodegradable organic matter. Anaerobic digestion is the breakdown of biomass materials with the aid of bacteria in the absence of oxygen producing a mixture of gases [219]. Production of biogas through the anaerobic digestion process is an environmental friendly process utilising the increasing amounts of organic wastes produced [220]. This technology reduces greenhouse gas emissions and as such a sustainable form of energy, biogas, a biofuel is obtained [2].

Rozy et al., [221], experimentally investigated the effect of varying physicochemical parameters on biogas production from water hyacinth (WH) in combination with cow dung and obtained enhanced yield parameters. They however, emphasised the need to enhance and optimise methane generation from WH and other such substrates. In anaerobic co-digestion combinations, it is of paramount importance to know the mass ratio of each substrate to be fed in the blend mixture so as to achieve the highest possible proportion of methane in the output biogas. In as much as WH is a nuisance to waterways and sources, municipal solid waste (MSW) and cow dung (CD) are as well pausing some detrimental effects to the environment. Anaerobic co-digestion of these bio-materials among others leads to increased biogas yields when compared to mono-digestion of the same due to enhanced bio-degradability, bio-accessibility, and bio-availability among other synergisms in the process reactions [222].

Biogas production can be enhanced by utilisation of high-methane potential substrates, enzymes and microbial addition, optimisation of process conditions and parameters, co-digestion of various substrates, pre-treatment of the feed material and separating the digestion process into phases (multi-stage digestion) [59]. Dependable anaerobic co-digestion modelling is essential to clearly forecast the consequence of blending substrates in a reactor and do away with possible undesirable outcomes from blending combinations established on arbitrary and/or heuristic conclusions. To optimise is to determine the maximum or minimum values of a specified function that is subject to certain constraints [106]. Hagos et al., [107], highlighted that process optimisation and improvement of biogas production still needs more investigations to be done and that the use of modelling and simulation ways can lead to realisation of substantial enhancement of biogas yields. Diverse optimisation approaches are established in literature in a bid to obtain the best reaction conditions, best reaction parameters and best substrate ratios for different feed stocks so as to enhance and optimise the biogas production process. Sreekrishnan et al., [30], also notes that use of additives, recycling of slurry and slurry filtrate, variation of operational parameters like temperature, hydraulic retention time (HRT) and particle size of the substrate and use of fixed film/biofilters are some of the techniques for enhancing biogas production.

The conventional method of optimisation of anaerobic digestion comprise of laboratory batch experiments varying reaction conditions and parameters as well as co-digestion of varied feed stocks to evaluate the digestibility and biogas potential of different substrates. Co-digestion of varied substrates has shown that an improved biogas production potential can be realised as compared to mono-digestion of single substrates [60]. Artificial Neural Networks (ANNs) and Genetic Algorithms (GA) are some of the modern tools that are used to solve complex problems which cannot be unravelled by conventional solutions [223]. Linear programming approaches [115], response surface methodologies [116], as well as simplex-centroid mixture design and central composite design [224], are some of the optimisation approaches which have been applied in anaerobic digestion.

There has been a considerable increase in demand for energy in developing countries like Zimbabwe while the supply and/or generation capacity is lagging behind [225]. As a result consumers are shifting to alternative renewable energy options and also to other available fossil derived and imported fuels such as Liquid Petroleum Gas (LPG). The availability of non-renewable forms of energy such as LPG, derived from fossil fuels will continue to decrease while at the same time their costs will continue to increase [226]. The interchangeability of fuels has to be compared in terms of the Wobbe Index (WI) when considering shifting from one fuel to the other. The Wobbe Index (WI) is an indicator of the interchangeabiity of fuel gasses. It is the key pointer to the replacement of one fuel with another and is very useful in comparing the burning efficiency of fuel gases [227].

This research deduced from previous works/studies that solar PV-Biogas hybrid systems have been developed and optimised to ease the energy demand mainly being fostered by inadequate conventional energy supplies. Nawaz et al. [228], carried out a feasibility study on a solar photovoltaic-biogas hybrid system and also did an optimisation of the same. Kwok et al. [229], investigated the hybridisation of solar, wind and biogas in a bid to optimise energy generation from these renewable energy sources. In some instances the solar PV-Biogas systems have been tied with the grid to minimise energy costs and at the same time ensuring consistent supply of energy at all times [230]. It was also however, realised that not much has been reported and/or researched with respect to integrating optimised biogas systems and LPG for heating, lighting and power purposes. According to the authors' literature survey, no research was found to report on optimised biogas-LPG hybrid systems. In order to meet the growing energy demands and to do away with waste disposal problems, the production of biogas and the respective optimisation of its bio-methane major constituent is of uttermost importance in addition to hybridisation of the energy supply alternatives such as LPG [156].

In Chapter 3, which is based on our published work [63], a model for determining biogas production potential from water hyacinth (WH), municipal solid watse (MSW), and cow dung (CD) was presented and an optimisation of the co-digestion mixing ratios of these substrates was carried out in a bid to obtain the highest possible amount of biogas from the co-digestion mixture. The same substrates are used in the work presented in this current chapter and the assumptions stated in Chapter 3 also hold for this chapter. However, the model developed and being reported in its own novel way in this current chapter differs with the previous one in the following ways:

- Seasonal variations of the substrates are taken into consideration in the modelling and optimisation.
- Methane is maximised whilst carbon dioxide, ammonia, and hydrogen sulphide are minimised

to obtain more methane in the biogas mixture and thus improving the quality of the biogas produced.

- The enhanced biogas produced is hybridised with Liquid Petroleum Gas (LPG) to supply some gas demand

It is hereby being emphasised that according to the authors' knowledge and research investigations, no previous studies are reported to have looked at the effect of substrate/feedstock seasonal variations on co-digestion and at the same time incorporate the same in modelling and optimisations. As such, this current research is unique and innovative in that regard and the findings are one of their own kind, contributing immensely to the anaerobic digestion research niche. The purpose and contribution of this current work is the development of a model which facilitates the attainment of high quality biogas constituted of a high proportion of methane while at the same time taking into consideration the seasonality changes of the substrates. Consequently, the resultant co-digestion substrate blending ratios vary for each month and so does the biogas yield unlike in the previous work where a single average blend ratio and an annual average biogas output was obtained. The high quality optimised biogas produced is channeled towards the gas requirements of a community in a hybrid system with Liquid Petroleum Gas (LPG) where LPG meets the rest of the demand not met by the biogas. This work contributes to the reduction of reliance on imported energy and adds great value by supplying a high quality bio-methane gas thereby substituting a great proportion of LPG consequently reducing import costs as well as minimising environmental pollution. The model developed in this study and its accompanying methodology can be easily followed and replicated in many other countries, and can be applied with many other varied biomass resources.

4.3 MODELLING AND OPTIMISATION

4.3.1 Problem formulation

The Buswell & Mueller modified equation [182] shown in Equation (4.1) is herein taken as the biogas production reaction equation.

$$\begin{aligned} C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right) H_2O \Rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right) CH_4 \\ + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right) CO_2 + dNH_3 + eH_2S, \end{aligned} \tag{4.1}$$

where the constants a, b, c, d and e in $C_aH_bO_cN_dS_e$ are obtained from the ultimate analysis of each of the elements devided by the relative atomic mass (Ar) of each of the elements as depicted in Equations (4.2) to (4.6).

$$a = \frac{\text{Carbon ultimate mass}}{Ar_C} \triangleq \frac{\text{Carbon ultimate mass}}{12.017}, \tag{4.2}$$

$$b = \frac{\text{Hydrogen ultimate mass}}{Ar_H} \triangleq \frac{\text{Hydrogen ultimate mass}}{1.0079}, \tag{4.3}$$

$$c = \frac{\text{Oxygen ultimate mass}}{Ar_O} \triangleq \frac{\text{Oxygen ultimate mass}}{15.999}, \tag{4.4}$$

$$d = \frac{\text{Nitrogen ultimate mass}}{Ar_N} \triangleq \frac{\text{Nitrogen ultimate mass}}{14.0067}, \tag{4.5}$$

$$e = \frac{\text{Sulphur ultimate mass}}{Ar_S} \triangleq \frac{\text{Sulphur ultimate mass}}{32.065}. \tag{4.6}$$

For the three materials under co-digestion in this study Equations (4.7), (4.8) and (4.9) are formulated to represent the biogas generation reactions from WH, MSW and CD respectively [63].

$$\begin{aligned} C_{a_1}H_{b_1}O_{c_1}N_{d_1}S_{e_1} + \left(a_1 - \frac{b_1}{4} - \frac{c_1}{2} + \frac{3d_1}{4} + \frac{e_1}{2}\right)H_2O \Rightarrow \left(\frac{a_1}{2} + \frac{b_1}{8} - \frac{c_1}{4} - \frac{3d_1}{8} - \frac{e_1}{4}\right)CH_4 \\ + \left(\frac{a_1}{2} - \frac{b_1}{8} + \frac{c_1}{4} + \frac{3d_1}{8} + \frac{e_1}{4}\right)CO_2 + d_1NH_3 + e_1H_2S, \end{aligned} \tag{4.7}$$

$$\begin{aligned} C_{a_2}H_{b_2}O_{c_2}N_{d_2}S_{e_2} + \left(a_2 - \frac{b_2}{4} - \frac{c_2}{2} + \frac{3d_2}{4} + \frac{e_2}{2}\right)H_2O \Rightarrow \left(\frac{a_2}{2} + \frac{b_2}{8} - \frac{c_2}{4} - \frac{3d_2}{8} - \frac{e_2}{4}\right)CH_4 \\ + \left(\frac{a_2}{2} - \frac{b_2}{8} + \frac{c_2}{4} + \frac{3d_2}{8} + \frac{e_2}{4}\right)CO_2 + d_2NH_3 + e_2H_2S, \end{aligned} \tag{4.8}$$

$$C_{a_3}H_{b_3}O_{c_3}N_{d_3}S_{e_3} + \left(a_3 - \frac{b_3}{4} - \frac{c_3}{2} + \frac{3d_3}{4} + \frac{e_3}{2}\right) H_2O \Rightarrow \left(\frac{a_3}{2} + \frac{b_3}{8} - \frac{c_3}{4} - \frac{3d_3}{8} - \frac{e_3}{4}\right) CH_4 + \left(\frac{a_3}{2} - \frac{b_3}{8} + \frac{c_3}{4} + \frac{3d_3}{8} + \frac{e_3}{4}\right) CO_2 + d_3NH_3 + e_3H_2S. \tag{4.9}$$

A MATLAB toolbox, the Optimisation Interface (OPTI) [231] was used to construct the optimisation problem and the Solving Constraint Integer Programs (SCIP) solver was applied to solve the formulated optimisation problem. The objective is to improve the quality of biogas produced by maximising methane while at the same time minimising carbon dioxide, ammonia and hydrogen sulphide. The optimised biogas is then integrated with LPG in a hybrid system for supplying gas to the community. The objective function and the constraints are inputed into the optimisation model which then gives the number of moles for WH, MSW and CD respectively for each month which are then used for computing the monthly Stoichiometric masses of each of the co-digestion materials to be fed into the digester to obtain the optimum methane.

4.3.2 Objective function

The objective function is expressed as

$$\sum_{j=1}^{N}\sum_{i=1}^{3} G_i(x_{i,j}), \tag{4.10}$$

where j is time in months from January through to December, N is number of months which is equal to 12. i is the substrate material index. $i = 1$ for substrate material WH, $i = 2$ indicates substrate material MSW, and $i = 3$ indicates substrate material CD. $x_{i,j}$ are the number of moles of substrate material i in the j^{th} month. $G_i(x_{i,j})$ is the monthly biogas produced from material i in month j. For a particular month j, the total biogas (G_{tot}) produced is expressed as:

$$G_{tot,j} = G_1(x_{1,j}) + G_2(x_{2,j}) + G_3(x_{3,j}), \tag{4.11}$$

where

$$G_1(x_{1,j}) = (22.4 \times 10^{-3}) \times \left(\frac{CO_{2_{1,j}} + NH_{3_{1,j}} + H_2S_{_{1,j}} - CH_{4_{1,j}}}{Mr_{WH}}\right), \tag{4.12}$$

$$G_2(x_{2,j}) = (22.4 \times 10^{-3}) \times \left(\frac{CO_{2_{2,j}} + NH_{3_{2,j}} + H_2S_{_{2,j}} - CH_{4_{2,j}}}{Mr_{MSW}}\right), \tag{4.13}$$

$$G_3(x_{3,j}) = (22.4 \times 10^{-3}) \times \left(\frac{CO_{2_{3,j}} + NH_{3_{3,j}} + H_2S_{_{3,j}} - CH_{4_{3,j}}}{Mr_{CD}}\right). \tag{4.14}$$

In Equations (4.12), (4.13 and (4.14); $CO2_{\{1,2,3\},j}$, $NH3_{\{1,2,3\},j}$, $H_2S_{\{1,2,3\},j}$ and $CH4_{\{1,2,3\},j}$ are the number of moles of carbon dioxide, ammonia, hydrogen sulphide and methane for WH, MSW and CD respectively and Equations (4.15) to (4.26) show how to determine these moles.

$$CH4_{1,j} = \left(\frac{a_1}{2} + \frac{b_1}{8} - \frac{c_1}{4} - \frac{3d_1}{8} - \frac{e_1}{4}\right)x_{1,j}, \tag{4.15}$$

$$CO2_{1,j} = \left(\frac{a_1}{2} - \frac{b_1}{8} + \frac{c_1}{4} + \frac{3d_1}{8} + \frac{e_1}{4}\right)x_{1,j}, \tag{4.16}$$

$$NH3_{1,j} = d_1 x_{1,j}, \tag{4.17}$$

$$H_2S_{1,j} = e_1 x_{1,j}, \tag{4.18}$$

$$CH4_{2,j} = \left(\frac{a_2}{2} + \frac{b_2}{8} - \frac{c_2}{4} - \frac{3d_2}{8} - \frac{e_2}{4}\right)x_{2,j}, \tag{4.19}$$

$$CO2_{2,j} = \left(\frac{a_2}{2} - \frac{b_2}{8} + \frac{c_2}{4} + \frac{3d_2}{8} + \frac{e_2}{4}\right)x_{2,j}, \tag{4.20}$$

$$NH3_{2,j} = d_2 x_{2,j}, \tag{4.21}$$

$$H_2S_{2,j} = e_2 x_{2,j}, \tag{4.22}$$

$$CH4_{3,j} = \left(\frac{a_3}{2} + \frac{b_3}{8} - \frac{c_3}{4} - \frac{3d_3}{8} - \frac{e_3}{4}\right)x_{3,j}, \tag{4.23}$$

$$CO2_{3,j} = \left(\frac{a_3}{2} - \frac{b_3}{8} + \frac{c_3}{4} + \frac{3d_3}{8} + \frac{e_3}{4}\right)x_{3,j}, \tag{4.24}$$

$$NH3_{3,j} = d_3 x_{3,j}, \tag{4.25}$$

$$H_2S_{3,j} = e_3 x_{3,j}, \tag{4.26}$$

where Mr_{WH}, Mr_{MSW} and Mr_{CD} are the relative molecular masses of WH, MSW and CD respectively and these are as denoted in Equations (4.27) to (4.29). These relative molecular masses are assumed to be constant and as such are not affected by seasonal variations.

$$Mr_{WH}\ (\text{kgmol}^{-1}) = a_1 * Ar_C + b_1 * Ar_H + c_1 * Ar_O + d_1 * Ar_N + e_1 * Ar_S, \tag{4.27}$$

$$Mr_{MSW}\ (\text{kgmol}^{-1}) = a_2 * Ar_C + b_2 * Ar_H + c_2 * Ar_O + d_2 * Ar_N + e_2 * Ar_S, \tag{4.28}$$

$$Mr_{CD}\ (\text{kgmol}^{-1}) = a_3 * Ar_C + b_3 * Ar_H + c_3 * Ar_O + d_3 * Ar_N + e_3 * Ar_S. \tag{4.29}$$

4.3.3 Constraints

The objective function is subject to the constraints of carbon to nitrogen ratio (C:N) as shown in Inequalities (4.30), the reactor volume (V_R) constraint as shown in Equation (4.31) and gas demand satisfaction constraint as stated in Equation (4.41).

$$(\text{C:N})^{min} \leqslant \left(\frac{a_1 + a_2 + a_3}{d_1 + d_2 + d_3}\right) \sum_{i=1}^{3} x_{i,j} \leqslant (\text{C:N})^{max}, \tag{4.30}$$

where a_1, a_2 and a_3 are the WH, MSW and CD carbon ultimate compositions respectively; and d_1, d_2, and d_3 are the WH, MSW and CD nitrogen ultimate compositions respectively.

$$\begin{aligned} &\left[\left(V_{WH,j} + \left(\frac{(22.4\times10^{-3}) \times H_2O_{1,j}}{Mr_{WH}} \times R_{H_2O_{(1,j)}}\right)\right) x_{1,j}\right. \\ &+ \left(V_{MSW,j} + \left(\frac{(22.4\times10^{-3}) \times H_2O_{2,j}}{Mr_{MSW}} \times R_{H_2O_{(2,j)}}\right)\right) x_{2,j} \\ &\left.+ \left(V_{CD,j} + \left(\frac{(22.4\times10^{-3}) \times H_2O_{3,j}}{Mr_{CD}} \times R_{H_2O_{(3,j)}}\right)\right) x_{3,j}\right] = V_R, \end{aligned} \tag{4.31}$$

where:

$$H_2O_{1,j}\ (\text{moles}) = \left(a_1 - \frac{b_1}{4} - \frac{c_1}{2} + \frac{3d_1}{4} + \frac{e_1}{2}\right) x_{1,j}, \tag{4.32}$$

$$H_2O_{2,j}\text{ (moles)} = \left(a_2 - \frac{b_2}{4} - \frac{c_2}{2} + \frac{3d_2}{4} + \frac{e_2}{2}\right)x_{2,j}, \tag{4.33}$$

$$H_2O_{3,j}\text{ (moles)} = \left(a_3 - \frac{b_3}{4} - \frac{c_3}{2} + \frac{3d_3}{4} + \frac{e_3}{2}\right)x_{3,j}, \tag{4.34}$$

Volume of WH in month j is given by:

$$V_{WH,j} = \frac{m_{WH,j}}{\rho_{WH}}, \tag{4.35}$$

where:

$$m_{WH,j} = Mr_{WH} \times n_{WH,j}. \tag{4.36}$$

ρ_{WH} is the density of water hyacinth.

Volume of MSW in month j is given by:

$$V_{MSW,j} = \frac{m_{MSW,j}}{\rho_{MSW}}, \tag{4.37}$$

where:

$$m_{MSW,j} = Mr_{MSW} \times n_{MSW,j}. \tag{4.38}$$

ρ_{MSW} is the density of municipal solid waste.

Volume of CD in month j is given by:

$$V_{CD,j} = \frac{m_{CD,j}}{\rho_{CD}}, \tag{4.39}$$

where:

$$m_{CD,j} = Mr_{CD} \times n_{CD,j}. \tag{4.40}$$

ρ_{CD} is the density of cow dung.

$R_{H_2O_{(1,j)}}$, $R_{H_2O_{(2,j)}}$ and $R_{H_2O_{(3,j)}}$ are the ratios or the proportions of water to be added to the WH, MSW and CD substrates respectively in order to attain the required total solids content and V_R is the reactor volume in m^3.

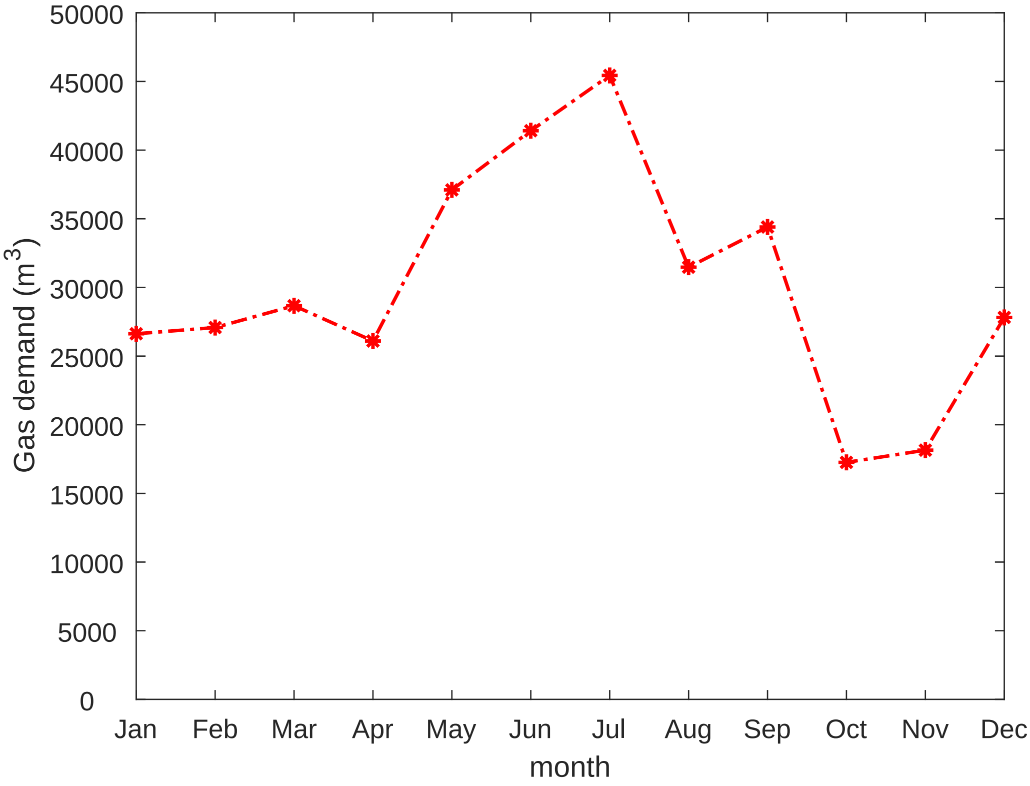

Figure 4.1. Monthly gas demand [234]

$$\begin{aligned}\Bigg[(22.4\times 10^{-3})\times\Bigg(\bigg(\frac{CO_{2_{1,j}}+NH_{3_{1,j}}+H_2S_{1,j}-CH_{4_{1,j}}}{Mr_{WH}}\bigg)x_{1,j} \\ +\bigg(\frac{CO_{2_{2,j}}+NH_{3_{2,j}}+H_2S_{2,j}-CH_{4_{2,j}}}{Mr_{MSW}}\bigg)x_{2,j} \\ +\bigg(\frac{CO_{2_{3,j}}+NH_{3_{3,j}}+H_2S_{3,j}-CH_{4_{3,j}}}{Mr_{CD}}\bigg)x_{3,j}\Bigg)\Bigg] \\ +\text{LPG}_j=\text{Gas demand}_j,\end{aligned} \tag{4.41}$$

where LPG is imported energy that balances up the demand not met by the biogas; bio-methane in this case and the gas demand is depicted as monthly consumption as shown in Figure. 4.1. WI for LPG is around 85 MJ/m^3 and that of methane from biogas is 36 MJ/m^3 [232]. This shows that LPG and methane from biogas cannot be directly interchanged. According to Ananthakrishnan et al., [233], 1 m^3 of biogas is equivalent to 0.45 kg of LPG. As such when substituting LPG with biogas this factor was taken into consideration.

Inequalities (4.42), (4.43) and (4.44) show the lower and upper bounds constraints for WH, MSW and CD respectively.

$$V_{WH,j}^{min} \leqslant V_{WH,j} \leqslant V_{WH,j}^{max}, \tag{4.42}$$

$$V_{MSW}^{min} \leqslant V_{MSW,j} \leqslant V_{MSW}^{max}, \tag{4.43}$$

$$V_{CD}^{min} \leqslant V_{CD,j} \leqslant V_{CD}^{max}. \tag{4.44}$$

The modelling and optimisation is summarised in Figure 4.2. The function to be optimised and its respective constraints are fed into the optimisation model. The optimisation model in turn gives the respective optimal number of moles $x_{i,j}$ ($x_{1,j}$, $x_{2,j}$ and $x_{3,j}$) for WH, MSW and CD respectively. In Figure 4.2, $n_{1,j} \triangleq x_{1,j}$, $n_{2,j} \triangleq x_{2,j}$ and $n_{3,j} \triangleq x_{3,j}$. These Stoichiometric moles obtainable from the optimisation model are then used in computations of the respective optimal substrate mass blend ratios m_1, m_2 and m_3 for WH, MSW and CD to be fed to the digester/reactor, where $m_{i,j} = x_{i,j} \times Mr_i$.

4.4 ALGORITHM

A linear programming optimisation approach was adopted to solve the objective function using the canonical form [235]. The mathematical formulation is as shown below.

$$\min_x f^T x \quad \text{such that} \quad \begin{cases} A.x \leq b, \\ A_{eq}.x = b_{eq}, \\ lb \leq x \leq ub, \end{cases} \tag{4.45}$$

where f, x, b, b_{eq}, lb and ub are vectors, and A and A_{eq} are matrices, and $f^T x$ is the objective function and the equalities and inequalities are the constraints.

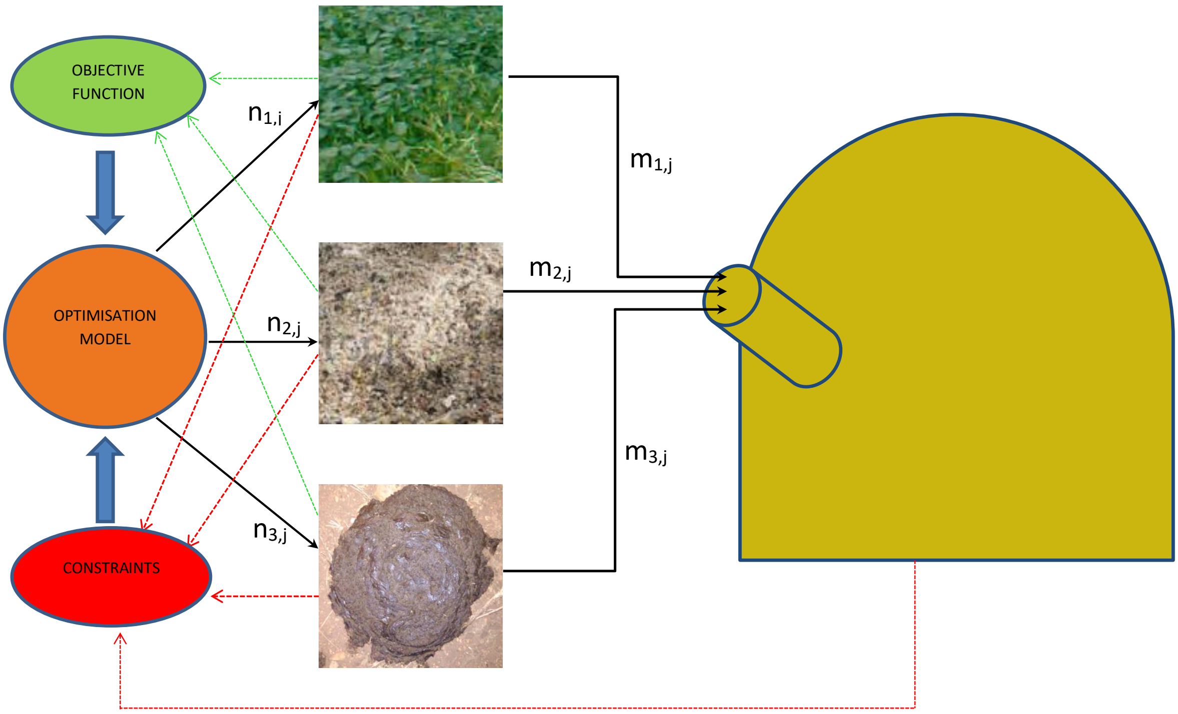

Figure 4.2. Model layout diagram.

$$X = \Big[x(1), \quad \cdots, \quad x(N), \quad x(N+1), \quad \cdots, \quad x(2N), \quad x(2N+1), \quad \cdots, \quad x(3N), \quad x(3N+1), \quad \cdots, \quad x(4N) \Big]^T_{4N\times 1}, \tag{4.46}$$

where $x(1), \cdots, x(N), x(N+1), \cdots, x(2N), x(2N+1), \cdots, x(3N), x(3N+1), \cdots, x(4N)$ are the number of moles of WH, MSW, CD and LPG respectively. $x(1), \cdots, x(N) \triangleq x_{1,j}$, $x(N+1), \cdots, x(2N) \triangleq x_{2,j}$, $x(2N+1), \cdots, x(3N) \triangleq x_{3,j}$, $x(3N+1), \cdots, x(4N) \triangleq LPG_j$

$$f^T = \Big[0.0239 \times Ones\,(1,N),\ -0.0162 \times\ Ones\,(1,N),\ 0.0175 \times Ones\,(1,N),\ zeros(1,N) \Big]_{1\times 4N}. \tag{4.47}$$

$$A_1 = \left[\begin{array}{cccc|cccc|cccc|cccc} r_{1,j} & 0 & \cdots & 0 & r_{2,j} & 0 & \cdots & 0 & r_{3,j} & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \\ 0 & r_{1,j} & \cdots & 0 & 0 & r_{2,j} & \cdots & 0 & 0 & r_{3,j} & \cdots & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & r_{1,j} & 0 & 0 & \cdots & r_{2,j} & 0 & 0 & \cdots & r_{3,j} & 0 & 0 & \cdots & 0 \end{array}\right]_{N\times 4N}, \tag{4.48}$$

where:

$$r_{1,j} = (10d_1 - a_1), \tag{4.49}$$

$$r_{2,j} = (10d_2 - a_2), \tag{4.50}$$

$$r_{3,j} = (10d_3 - a_3). \tag{4.51}$$

$$b_1 = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}_{N\times 1}. \tag{4.52}$$

$$A_2 = \left[\begin{array}{cccc:cccc:cccc:cccc} r_{\bar{1},j} & 0 & \cdots & 0 & r_{\bar{2},j} & 0 & \cdots & 0 & r_{\bar{3},j} & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \\ 0 & r_{\bar{1},j} & \cdots & 0 & 0 & r_{\bar{2},j} & \cdots & 0 & 0 & r_{\bar{3},j} & \cdots & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & r_{\bar{1},j} & 0 & 0 & \cdots & r_{\bar{2},j} & 0 & 0 & \cdots & r_{\bar{3},j} & 0 & 0 & \cdots & 0 \end{array}\right]_{N\times 4N}, \quad (4.53)$$

where:

$$r_{\bar{1},j} = (a_1 - 35d_1), \quad (4.54)$$

$$r_{\bar{2},j} = (a_2 - 35d_2), \quad (4.55)$$

$$r_{\bar{3},j} = (a_3 - 35d_3). \quad (4.56)$$

$$b_2 = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}_{N\times 1}. \quad (4.57)$$

$$A = [A_1; A_2]_{2N \times 4N}. \tag{4.58}$$

$$b = [b_1; b_2]_{2N\times 1} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}_{2N\times 1}. \tag{4.59}$$

$$A_{eq_1} = \left[\begin{array}{cccc|cccc|cccc|cccc} \alpha_{1,j} & 0 & \cdots & 0 & \beta_{2,j} & 0 & \cdots & 0 & \gamma_{3,j} & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \\ 0 & \alpha_{1,j} & \cdots & 0 & 0 & \beta_{2,j} & \cdots & 0 & 0 & \gamma_{3,j} & \cdots & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \alpha_{1,j} & 0 & 0 & \cdots & \beta_{2,j} & 0 & 0 & \cdots & \gamma_{3,j} & 0 & 0 & \cdots & 0 \end{array}\right]_{N\times 4N}, \tag{4.60}$$

where $A_{eq_{1,j}}$ is the first equality constraint. $\alpha_{1,j}$, $\beta_{2,j}$ and $\gamma_{3,j}$ are the sums of volumes of water hyacinth, municipal solid waste and cow dung and the respective quantity of water to be added to each substrate as denoted below.

$$\alpha_{1,j} = V_{WH,j} + \left(\frac{(22.4 \times 10^{-3}) \times H_2O_{1,j}}{Mr_{WH}} \times R_{H_2O_{(1,j)}} \right), \tag{4.61}$$

$$\beta_{2,j} = V_{MSW,j} + \left(\frac{(22.4 \times 10^{-3}) \times H_2O_{2,j}}{Mr_{MSW}} \times R_{H_2O_{(2,j)}} \right), \tag{4.62}$$

$$\gamma_{3,j} = V_{CD,j} + \left(\frac{(22.4 \times 10^{-3}) \times H_2O_{3,j}}{Mr_{CD}} \times R_{H_2O_{(3,j)}} \right). \tag{4.63}$$

$$b_{eq_1} = \begin{bmatrix} 150 \\ 150 \\ \vdots \\ 150 \end{bmatrix}_{N\times 1}. \tag{4.64}$$

$$A_{eq_2} = \left[\begin{array}{c|c|c|c} 0.0239 \times ones\ (N,N) & -0.0162 \times ones\ (N,N) & 0.0175 \times ones\ (N,N) & eye(N,N) \end{array} \right]_{N\times 4N}. \tag{4.65}$$

$$b_{eq_2} = \begin{bmatrix} D_1 \\ D_2 \\ \vdots \\ D_N \end{bmatrix}_{N\times 1}, \tag{4.66}$$

where D_1, D_2 ... D_N are the respective gas demands for each month from January up to December.

$$A_{eq} = [A_{eq_1}; A_{eq_2}]_{2N\times 4N}. \tag{4.67}$$

Table 4.1. Case study data values

Parameters	C	H	O	N	S	ρ (kgm^{-3})	Source
WH	33.13	4.35	29.71	1.66	0.37	85.00	[184]
MSW	48.00	6.40	37.60	2.60	0.40	217.50	[183]
CD	45.32	5.87	27.38	5.16	0.45	400.00	[185, 196]

$$b_{eq} = [b_{eq_1}; b_{eq_2}]_{2N\times 1}. \tag{4.68}$$

The initial starting guess is denoted as

$$x_0 = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}_{4N\times 1}. \tag{4.69}$$

4.5 CASE STUDY

The WH substrate is obtained from Lake Chivero in Harare - Zimbabwe. MSW is obtained from Norton, an urban town in Zimbabwe. Cow dung is obtained from cattle in the Norton part of Chegutu district. Figure. 4.3 gives the monthly (seasonal) available substrate resources for WH, MSW and CD. Table 4.1 gives the Case study data values used in this research.

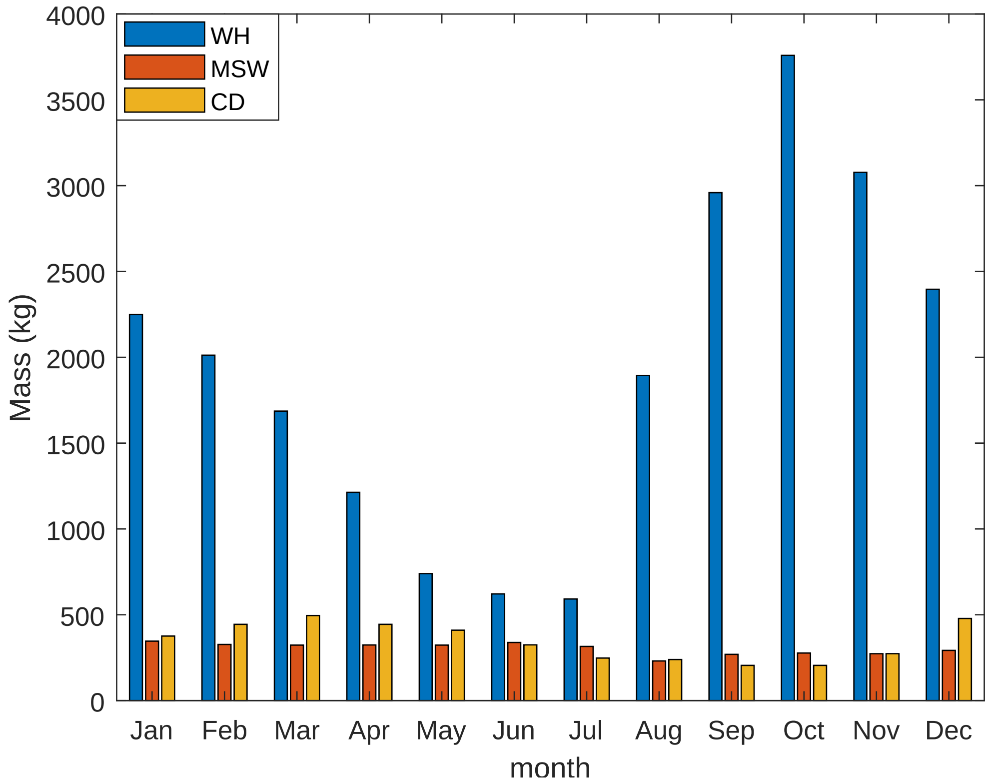

Figure 4.3. Substrate monthly resources.

$$lb = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}_{4N \times 1}, \tag{4.70}$$

where $N = 12$. The lower bounds (lb) are as shown in equation (4.70) and the upper bounds (ub) are as shown in Table 4.2. These lower and upper bounds are congruent to constraint Inequalities (4.42), (4.43) and (4.44).

4.6 RESULTS AND DISCUSSION

The SCIP solver in conjunction with 'Spatial Branch and Bound using IPOPT and SoPlex' algorithm gave the global sub-optimal mole ratios for the co-digestion of water hyacinth, municipal solid waste and cow dung as shown in Table 4.3. Using the results in Table 4.3 and applying the Stoichiometric relationship; mass = number of moles $\times$ molar mass [202], substrate mass blending ratios presented in

Table 4.2. Upper bound *(ub)* limits

Month	WH $(moles)$	MSW (moles)	CD (moles)	LPG (moles)
January	374 911.10	45 463.84	62 661.13	50 000
February	335 446.77	42 938.07	74 054.06	50 000
March	281 143.86	42 432.92	82 598.76	50 000
April	202 256.25	42 533.95	74 054.06	50 000
May	123 327.60	42 432.92	68 357.60	50 000
June	103 592.28	44 453.53	54 116.43	50 000
July	98 660.82	41 422.61	41 299.38	50 000
August	315 714.61	30 309.23	39 875.26	50 000
September	493 304.08	35 360.76	34 178.80	50 000
October	626 611.42	36 371.07	34 178.80	50 000
November	513 036.24	35 865.92	45 571.73	50 000
December	399 464.23	38 391.69	79 750.53	50 000

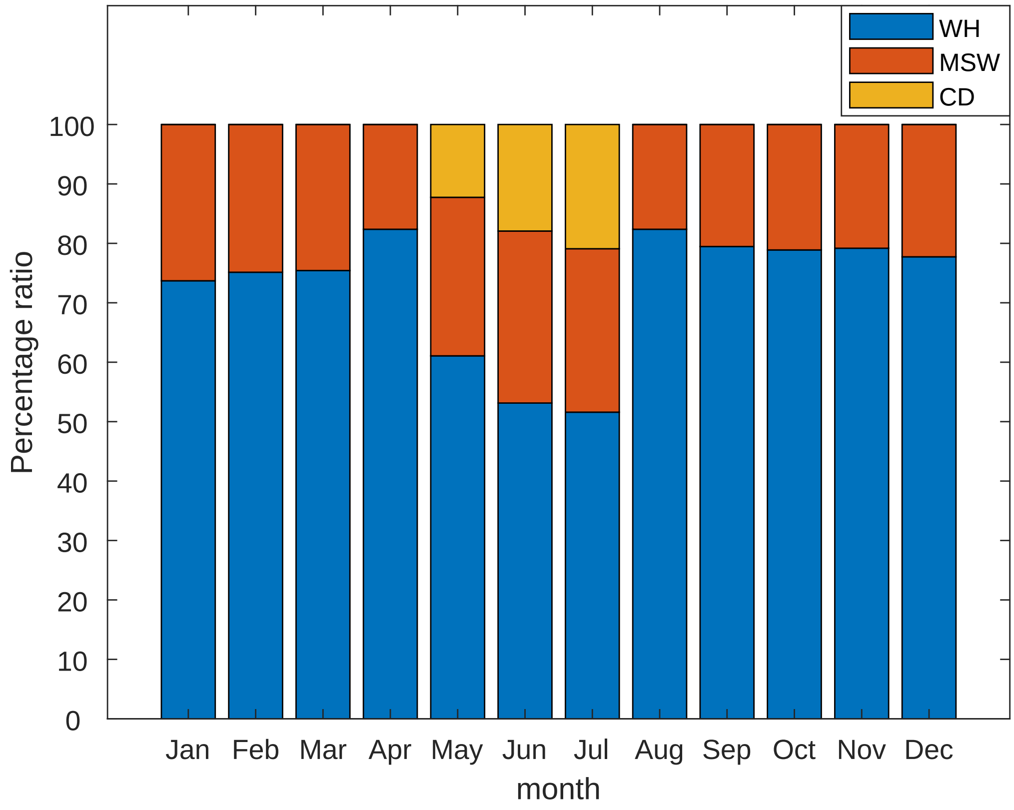

Figure 4.4. Combined substrates monthly substrate feed ratios.

Table 4.4 are arrived at. The mass blending ratios in Table 4.4 translate to optimal percentage substrate mass blend ratios shown in Table 4.5 for the co-digestion of water hyacinth, municipal solid waste and cow dung. Figure. 4.4 which is derived from Table 4.5 shows a graphical presentation of the optimal percentage substrate mass blend ratios which maximises the methane component in the output biogas yield.

Figure. 4.5 shows the monthly optimised biogas production. Summation of the monthly biogas potential yields gives an annual total of 38 465.68 m^3. This is an increase by 174.58 % when compared to an annual average of 14 008.8 m^3 from the previous study [63], which did not take into account seasonality changes in co-odigestion substrate availability. The results of this study agrees with Lovrak et al. [236], who highlighted that there is a great need to consider seasonalities when evaluating the biogas potential of lignocellulosic agricultural wastes in a study in which they proposed a GIS-based technique for assessing the spatial distribution of biogas generation capacity while considering seasonality variations in feedstock production. Shukla et al. [237] also reported getting the highest biogas yields in summer

Table 4.3. Monthly mole ratios

Month	WH (moles)	MSW (moles)	CD (moles)	LPG (moles)
January	161 744.86	45 463.84	0.00	29773.56
February	164 747.61	42 938.07	0.00	30339.76
March	165 348.16	42 432.92	0.00	31950.29
April	165 228.05	42 533.95	0.00	29377.11
May	123 327.6	42 432.92	24 748.64	39807.65
June	103 592.28	44 453.53	34 957.24	43788.13
July	98 660.82	41 422.61	39 983.92	47833.00
August	179 761.36	30 309.23	0.00	35299.08
September	173 755.86	35 360.76	0.00	38000.12
October	172 554.76	36 371.07	0.00	20814.42
November	173 155.31	35 865.92	0.00	21726.42
December	170 152.56	38 391.69	0.00	31279.86

Table 4.4. Monthly co-digestion masses

Month	WH (kg)	MSW (kg)	CD (kg)	Total mass (kg)
January	970.47	345.53	0.00	1 315.99
February	988.49	326.33	0.00	1 314.81
March	992.09	322.49	0.00	1 314.58
April	991.37	323.26	0.00	1 314.63
May	739.97	322.49	148.49	1 210.95
June	621.55	337.85	209.74	1 169.14
July	591.96	314.81	239.90	1 146.68
August	1 078.57	230.35	0.00	1 308.92
September	1 042.54	268.74	0.00	1 311.28
October	1 035.33	276.42	0.00	1 311.75
November	1 038.93	272.58	0.00	1 311.51
December	1 020.92	291.78	0.00	1 312.69

Table 4.5. Monthly co-digestion percentage blend ratios

Month	% ratio (WH:MSW:CD)
January	73.74 : 26.26 : 0.00
February	75.18 : 24.82 : 0.00
March	75.47 : 24.53 : 0.00
April	75.41 : 24.59 : 0.00
May	61.11 : 26.63 : 12.26
June	53.16 : 28.90 : 17.94
July	51.62 : 27.45 : 20.92
August	82.40 : 17.60 : 0.00
September	79.51 : 20.49 : 0.00
October	78.93 : 21.07 : 0.00
November	79.22 : 20.78 : 0.00
December	77.77 : 22.23 : 0.00

months in a study in which they investigated the effect of seasonal variation on biogas production from different food wastes. This present study further highlights that seasonality changes have to be considered not only for lignocellulosic agricultural wastes but for all biomass feedstocks especially when anaerobic co-digestion is the biomass-to-energy conversion route being applied. This implies that storage arrangements have to be put in place for accummulating the feedstocks in times of plenty for later use in times when the resources are insufficient and/or when demand is very high.

Biogas production is higher in summer months than in winter months owing to the overally higher co-digestion substrate quantities in the summer season and the opposite is true for the winter season. This trend is also attributed to by the high light intensities in the summer months which facilitate enhanced photosynthesis consequently generating more sugars which are a key component in the biochemical reactions of biogas production. The findings of this study agrees with D'Este et al. [238], who also reported higher methane yields in summer months in a study which focussed on seasonal and spatial variations of algae as a potential biomass feedstock for biogas production. In this present study, the optimised biogas generated is channeled to feed part of the community's gas demand and as such the amount of LPG imports are reduced. The reduction in LPG quantities implies that there will be reduced carbon emissions since biogas is from renewable sources and is regarded as carbon neutral. Figure. 4.6 shows the resultant LPG gas needed to satisfy the demand in the biogas-LPG gas hybrid system.

The demand profile (as seen in Figure. 4.1) shows highest gas consumption in winter and lowest gas consumption in summer. This is a typical demand profile analogous to the electricity demand profile which shows similar trends for the winter and summer seasons [239]. The optimised biogas is more of bio-methane since it constitutes of maximised methane (CH_4) component in the biogas and minimised carbon dioxide (CO_2), ammonia (NH_3) and hydrogen sulphide (H_2S). Figure. 4.7 shows the effect of optimised biogas-LPG hybridisation on gas demand. It can be deduced that methane-optimised biogas production followed by subsequent hybridisation reduces the LPG gas demand.

Table 4.6 shows the monthly LPG gas costs before optimisation and hybridisation as well monthly LPG gas costs after hybridisation and optimisation.

Figure. 4.8 shows the effect of optimisation and hybridisation on LPG costs. The monthly percentage cost savings are shown in this Figure and it ranges from 6.93 % to 18.24 %.

Table 4.6. LPG costs before and after hybridisation

Month	LPG costs before hybridisation ($)	LPG costs after hybridisation ($)
January	5257.96	4636.43
February	5347.43	4725.90
March	5661.00	5039.47
April	5153.76	4532.23
May	7326.86	6705.33
June	8177.89	7556.36
July	8973.05	8351.51
August	6215.07	5593.54
September	6793.13	6171.60
October	3408.35	2786.82
November	3583.97	2962.44
December	5492.86	4871.33

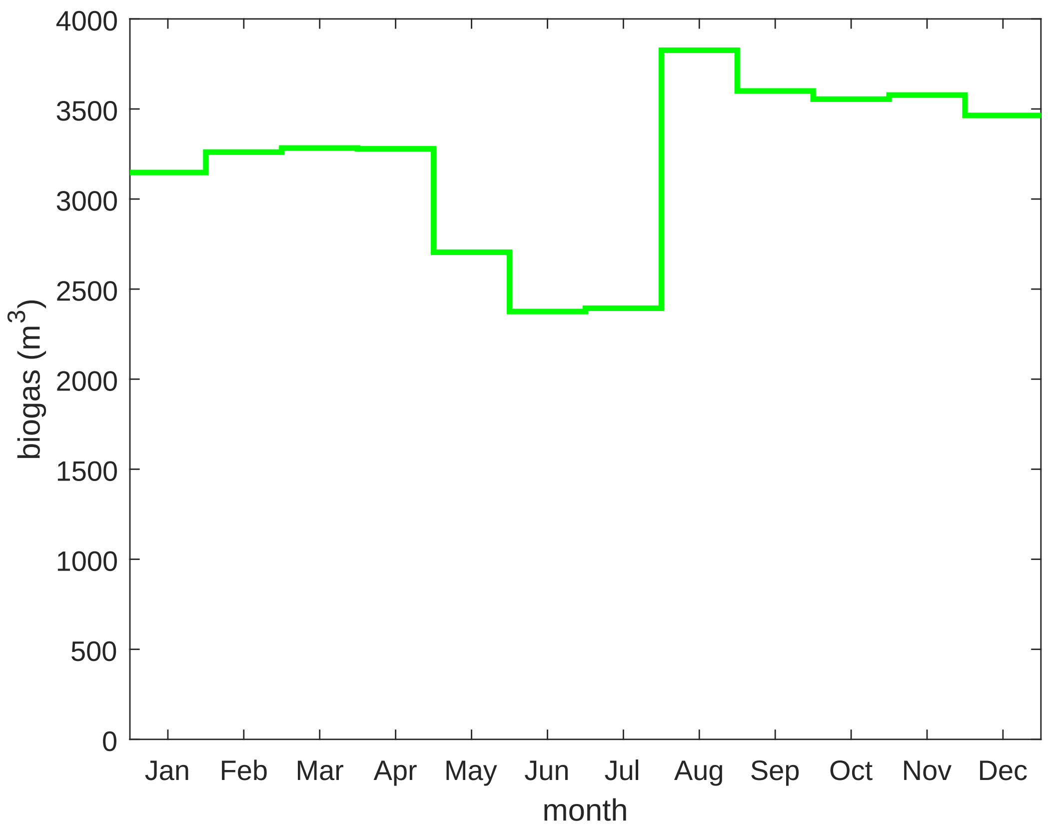

Figure 4.5. Optimised biogas production.

May, June and July are characterised by the least cost savings due to the high gas demand during these winter months mainly for the purposes of heating and cooking. October and November have huge cost savings due to the lower gas demand during the summer season. Globally, only a few countries are priviledged to be endowed with oil and petroleum resources, whereas the bulky of the nations rely on importing the same to cater for their transportation, industial, agricultural and domestic fuel requirements. The results of this study are of critical importance to such a dire pillar of the economy in providing a home-grown optimal solution to fuel challenges.The methane-optimised biogas will go a long way in substituting fossil derived fuels which are posing detrimental climatic effects by way of emmiting hazadous pollutants. Hybridising the optimised biogas with other conventional fuels such as LPG will guarantee continuous availability of the fuel and meeting of the demand at all times.

In-depth research on co-digestion for increasing the yield of biogas and meeting the requirements of load over the whole year have been undertaken in previous studies [39, 240, 241]. However, the approaches taken to ascertaining the co-substrate blend ratios has mainly been uninformed experimental

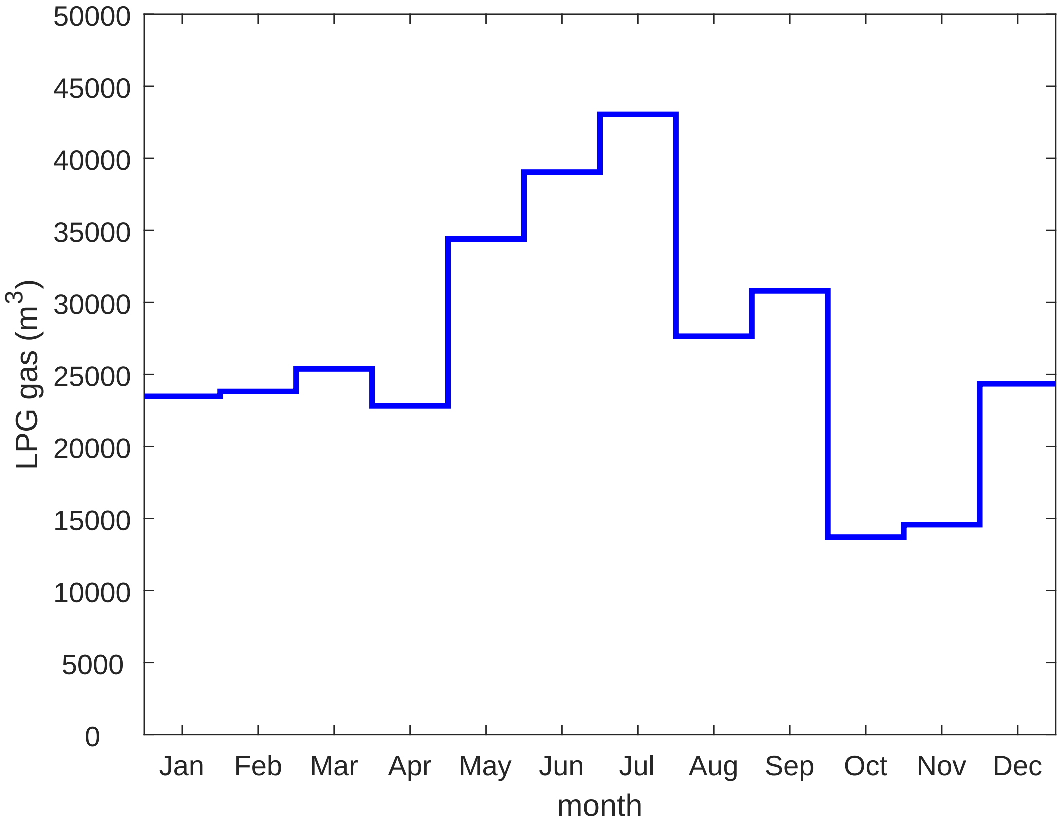

Figure 4.6. Resultant LPG gas needed.

guesses whereby two or three substrates are apportioned into certain proportions and the mixture that gives the highest biogas was taken be having the optimal blend ratio. This is the optimal ratio of what has been put in place but not necessarily the optimal ratios for the substrates under investigation. More so, the modelling and optimisation strategies employed in some few studies which employed this approach did not consider the variability of the different substrate quantities across seasons of the year. This work contributes the novel aspect of optimal monthly substrate mix ratios and the incorporation of biomass co-digestion feedstock quantity seasonality changes into the modelling and optimisation of anaerobic digestion research domain.

This research is unique in that it incorporates substrate seasonal fluctuations and enhances biogas quality by maximising the principal preferred methane component of biogas while simultaneously minimising the undesired components; carbon dioxide, hydrogen sulphide, and ammonia in the modelling and optimisation. The concept of integrating the methane-optimised biogas in a hybrid system with liquid petroleum gas to supply a gas demand is another unique contribution of this study.

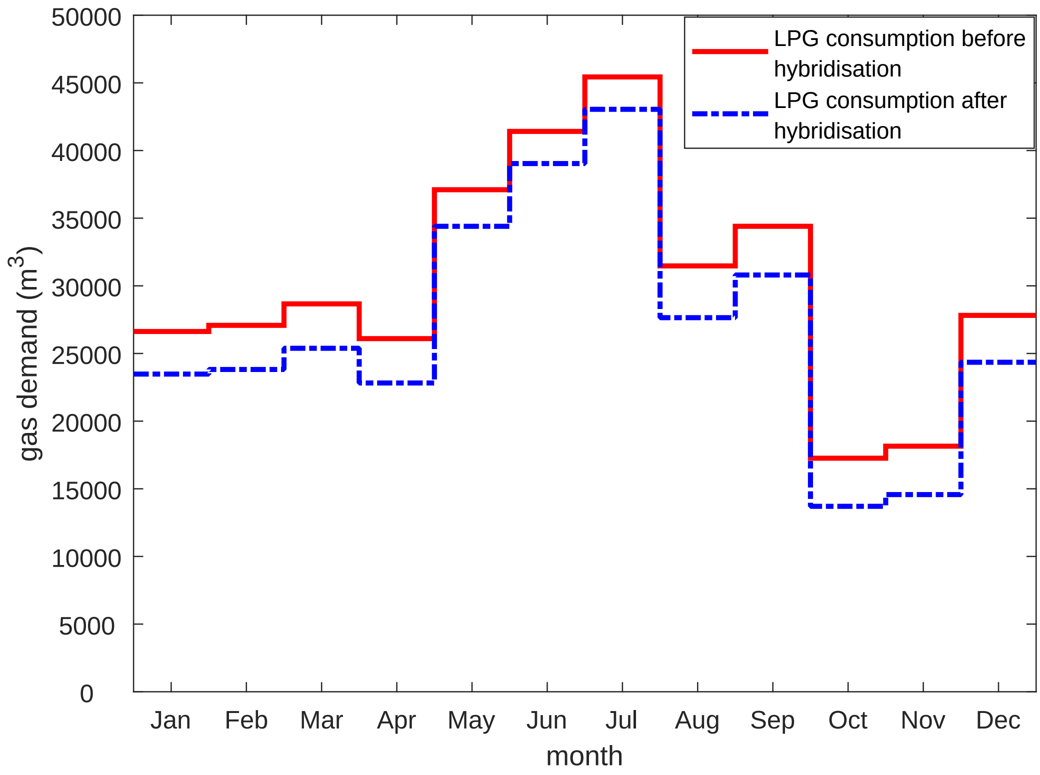

Figure 4.7. Hybridisation effect on gas demand.

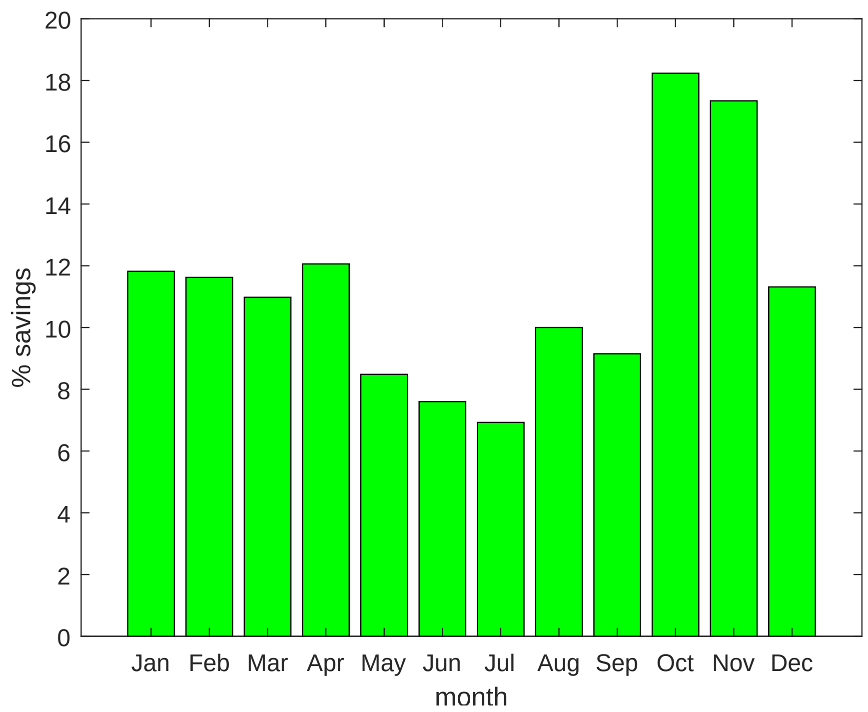

Figure 4.8. Monthly cost savings.

To date, to the authors' best knowledge, the methodology and approach taken in this current work has neither been published nor reported in the previous works by any other researchers and as such is a unique contribution to the biogas fraternity. A case study is used to validate the proposed modelling and optimisation and the results show that the objective of the research is achieved and the findings are the first of their own kind.

The model developed herein this study and its accompanying optimisation and hybridisation methodologies are not limited to the case study location, it is applicable to other geographical locations world-over having varied seasonal changes. Numerous bio-degradable biomass materials from varied sources can also be used as co-digestion substrates with this model. It is also possible to hybridise the methane-optimised biogas with any other conventional or non-conventional fuel in a bid to reach some meaningful trade-off between fuel costs, demand satisfaction and environmental consequenses.

4.7 CONCLUSION

Incorporation of modelling and optimisation in addition to hybridisation of these systems leads to enhanced energy yields, reduction in energy costs as well as improved environmental sustainability. Biogas demand is higher in winter months than in summer months due to increased heating requirements during this period. More cost savings were realised in the summer season than in the winter season in a case study as more biogas was produced in summer than in winter. This study concludes that the employment of mathematical analytic tools in combination with modelling and optimisation and the incoporation of seasonality changes in substrate availability into the modelling and optimisation of biogas production in co-digestions increases the overal biogas yields. It is hereby being emphasised that the hybridisation of the optimally generated biogas with conventional fuels such as liquid petroleum gas goes a long way in the reduction of fuel import costs and meeting of demand. The model developed herein this work can be applied with any other bio-degradable materials in co-digestion combinations and the methodology is applicable in other countries with the same or different geographical and environmental conditions.

CHAPTER 5 CONCLUSION AND FUTURE WORK

5.1 CONCLUSIONS

Optimisation of biogas production from the co-digestion of water hyacinth (*Eichhornia crassipes*), municipal solid waste and cow dung was investigated in this study. Some analytical assessments were done and conclusions on optimisations were arrived at based on feasible analysis and results obtained from formulated models, calculations and simulations conducted with the aid of the MATLAB tool without physical experiments.

Chapter 2 discusses the status, current trends and future perspectives of anaerobic biogas production was reviewed. Co-digestion, modelling, and optimisation were the main focal areas in a bid to explore the enhancement of the anaerobic biogas production process. It is concluded that co-digestion needs a great deal of further research on varied feedstocks and optimal mix ratios. Modelling and optimisation incorporating co-digestion feedstock seasonal variations needs more investigations, research and development. Control of process conditions is key to achieving optimal biogas yields. It is highlighted from the literature study that hybridisation of biogas with conventional and non-conventional energy sources needs to be explored in depth. The majority of research investigations to date are more centred on mono-digestion. Coupling of co-digestion, modelling, and optimisation needs significant further research studies in the direction of biogas yield enhancement.

In Chapter 3, a model for the determination of biogas production potential from Water Hyacinth (WH), Municipal Solid Waste (MSW), and Cow Dung (CD) as well as the subsequent optimisation of the co-digestion mix ratios of these substrates is formulated and further developed. Baseline biogas potential yields of 747.4 Nml/gVS, 790.83 Nml/gVS and 884.24 Nml/gVS were obtained from WH, MSW and CD respectively. A linear programming mathematical optimisation was done. The objective is to find substrate blend ratios in the co-digestion mixture that maximises biogas production. Optimal co-digestion results in percentage substrate blending ratios of 53.27:24.64:22.09 for WH, MSW and CD respectively in a case study. 1 kg of substrate mixture yields 124.56 m^3 of biogas which translates to 124 560 Nml/gVS. Co-digestion and optimisation of substrate blend mix proportions increased the biogas output by 157.11 %. The biogas fratenity benefits in having an informed optimal co-digestion model that foretells substrate blending ratios.

Chapter 4 presents the formulation, development and solving of a novel methane-optimised biogas-liquid petroleum gas hybrid system. Herein, biogas is produced from the anaerobic co-digestion of water hyacinth, municipal solid waste and cow dung. A model that incorporated seasonal variations of biomass feedstocks was developed; an optimisation problem was formulated and solved using the Optimisation Interface tool (OptiTool) in combination with the Solving Constraint Integer Programs (SCIP) toolbox in Matrix Laboratory (MATLAB). The biogas production reactions are optimised in such a way that the methane component of the biogas is maximised, and the other components minimised by the integration of a model which necessitates the feed in of optimal substrate masses as per the ratios ascertained for the substrates considered thereby yielding a high quality combustible biogas product. The methane-optimised biogas is channelled towards some community gas demand and liquid petroleum gas comes in to fill the discrepancy between the methane-optimised biogas and the gas demand. Consideration of seasonality changes in the availability of substrates in the modelling and optimisation led to an increase of 174.58 % in annual biogas output. A 6.97 % annual lowest cost savings was realised in winter and 18.24 % annual highest cost savings was realised in summer from the methane-optimised biogas-liquid petroleum gas hybrid system.

5.2 FUTURE WORK

- Dynamic modelling of anaerobic co-digestion employing model predictive control (MPC) needs to be tapped in in future works since the biochemical reactions of the process leads to continuous change of state due to the alternating kinetics as the process reactions proceed. There has to be development of an approach which kind of have an optimisation layer and a control layer whereby a present optimisation is informed by some preceding information from the control layer and the cycle goes on like that in a bid to have the desired outcome which is optimal biogas yield at all times.
- In future studies, the modelling and optimisation of anaerobic co-digestion has to encompass issues of regulation and control of key process conditions and parameters such as hydraulic retention time, temperature, loading rates, and pH among other factors which affect the rate of

reactions and ultimately the overall biogas yield. The mathematical formulations and development of optimisation problems have to cater for varying process conditions and parameters and the effect of the same on the ultimate biogas yield has to be analysed.

- Multi-stage anaerobic digestion has been reported to improve biogas yields in mono-digestions by many researchers. However, only a few studies explored the multi-stage approach when it comes to co-digestion. As such multi-stage anaerobic co-digestion adds to the integral part of forseen future works. The development of co-digestion models and subsequent optimisations have to consider segmenting the biochemical reactions into phases or layers such that each phase is optimised for enhanced biogas yields. For instance the temperature and pH requirements of the initial and final stages of the digestion process are not the same and this has to be dealt with accordingly to maximise the final resultant biogas quantities.
- In-depth studies on CO_2 equivalent emission reductions emanating from anaerobic co-digestion need to be conducted. The world is shifting towards cleaner, green and energy efficient power generating technologies. Anaerobic co-digestion technology brings in a huge contribution to this initiative. To market this technology further towards commercial adoption, its benefits in combating climate change have to be made known and some ways to achieve that is by quantifying carbon credits, determining the carbon emissions avoided amongst other interventions. Development of simulation models and optimisations which encompass CO_2 equivalent emissions amongst other climate and/or environmental aspects in the objective functions and/or constraints is paramount.
- Simulations, modelling and optimisations supported by mathematical analytical tools such as those in MATLAB, as was done in this thesis can be regarded as experimental in their own regard and the results can be trusted. However, physical laboratory experimental approaches can be employed in future works to support novel endeavors such as those explored in this study. As was discussed in the literature section, pH, temperature, total solids, loading rates, pretreatment of biomass materials and the management of volatile fatty acids (VFAs) amongst many other factors affecting biogas production have a huge bearing on the overall output biogas. These need to be incorporated in the experimental investigations.
- In this study techno-economic aspects of anaerobic digestion were discussed. However, it is recommended that detailed development of modelling and optimisation strategies be further investigated to the extent of employing case studies of real anaerobic digestion projects. This will go a long way in informing and guiding the biogas stakeholders inclusive of investors in

decision making with regards to venturing into this noble renewable energy technology and/or to prioritise projects if more than one are available to be tapped into.

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