Design Model Selection and Dimensioning of Anaerobic Digester for the OFMSW

Anthony Njuguna Matheri[1], *Member, IAENG*, Charles Mbohwa[2], Mohamed Belaid[3], *Member, IAENG*, Tumisang Seodigeng[4], and Jane Catherine Ngila[5]

Abstract— **In this study, we investigated the design model selection and dimensioning of the anaerobic digester for the co-digestion of different organics fraction of municipal solid waste (OFMSW) originating from the city's landfills. The waste quantification and characterization exercise were undertaken at the point of generation, so as to obtain the total amount of waste generated and to ascertain the waste composition. Via the application of the simple multi-attribute rating (SMART) technique of multiple-criteria decision analysis (MCDA) as a decision support tool base on cost, scalability, temperature regulation, ease of construction, operation, and maintenance. The most preferred model option for bioenergy design technology was selected from a list of potential alternatives available in the market. Continuous stirred tank reactor (digester) CSTR scored the highest with 79% and was selected for the design in OFMSW biogas production. The geometry of the biodigester parameters was comparable with the anaerobic digestion (AD) process.**

Keywords— **Anaerobic, Co-digestion, Digester, Mesophilic Temperature, MCDA**

I. INTRODUCTION

SOUTH Africa's electricity is produced mainly from coal because it is the most abundant source of energy. It is the most widely used primary source of fuel and contributes to about 77% of the country's primary energy needs [1]. Coal contributes to greenhouse gases emissions to the atmosphere that leads to global warming. Fossil fuels contribute to the increase in the concentration of carbon dioxide in the atmosphere, hence alternative energy sources (renewable energy) must be used in the place of fossil fuels [1]. The commercial production of biogas and other alternative renewable energy source such as solar energy, wind energy, hydropower, geothermal will definitely give a drive for the development of the economy [2]. Energy derived from biogas is used in the form of fuel, heat, and electricity [3, 4].

Biogas is a renewable source of energy derived from biodegradable substrates such as agricultural wastes, animal wastes, domestic wastes, crops and industrial waste. It is produced by anaerobic digestion, which is a biochemical process in the absence of oxygen. The main product of biogas is methane and carbon dioxide [5, 6].

II. BIOCHEMICAL PROCESS OF ANAEROBIC DIGESTION

Biogas production follows four fundamentals processes. These processes include hydrolysis, acidogenesis, acetogenesis and methanogenesis [7, 8]. Fig. 1 shows a simplified generic anaerobic digestion process [9].

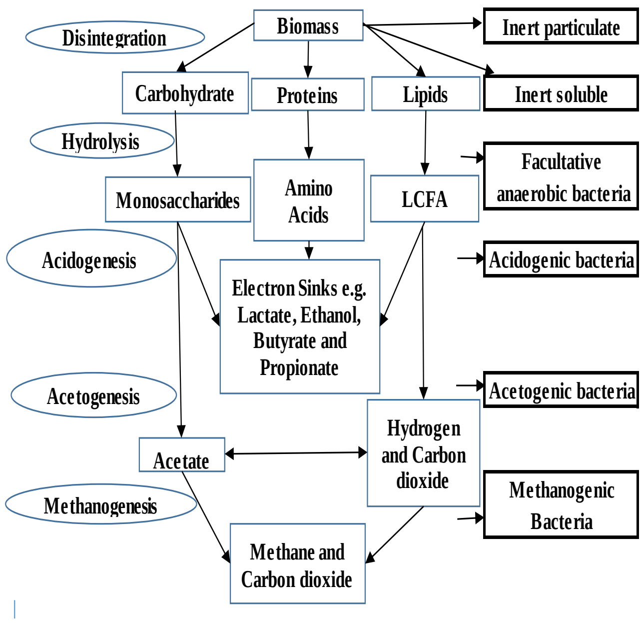

Fig. 1. Degradation steps of the anaerobic digestion process.

Manuscript received June 7, 2016; revised July 8, 2016. This work was supported in part by the University of Johannesburg, Process Energy Environmental station (PEETS) and City of Johannesburg, South Africa.

Anthony Njuguna Matheri; Ph.D. Student at the Department of Chemical Engineering; University of Johannesburg; Johannesburg 2028 South Africa; Cell: +27616986335 (tonynjuguna22@gmail.com)

Charles Mbohwa; Professor and Vice Dean at Faculty of Engineering and Build Environment (FEBE); University of Johannesburg; Johannesburg 2028 South Africa; (cmbohwa@uj.ac.za)

Mohamed Belaid; Senior lecturer and HOD at Department of Chemical Engineering; University of Johannesburg; Doornfortein, Johannesburg 2028 South Africa; (mbelaid@uj.ac.za)

Tumisang Seodigeng; Senior lecturer at Department of Chemical Engineering; Vaal University of Technology; Private Bag X021-Vanderbijilpark-1911, Andries Potgieter Blvd South Africa; (tumisangs@vut.ac.za)

Jane Catherine Ngila; Professor and HOD at Department of Analytical Chemistry; University of Johannesburg; P.O. Box 17011, Doornfortein, Johannesburg 2028 South Africa; (jcngila@uj.ac.za)

The anaerobic system is as the result of complex interactions among different of bacteria. The major functional groups of bacteria according to their metabolic reactions are [10]: Fermentative bacteria, hydrogen-producing acetogenic bacteria, hydrogen- consuming acetogenic bacteria, carbon dioxide reducing methanogens and aceticlastic methanogens.

In hydrolysis, large organic polymers such as fats, carbohydrates, and proteins are broken into fatty acids, simple sugar, amino acids respectively. This step is carried out by bactericides. Hydrolysis is followed by acidogenesis whereby low alcohol and organic acids are produced through fermentation process utilized by fermentative bacteria. This includes volatile fatty acids (acetic acid, butyric acid, and propionic acid), gases like carbon dioxide, ammonia and hydrogen and aldehydes. In the third step (acetogenesis), the products of acidogenesis are converted to acetic acid, hydrogen and carbon dioxide by acetogenic bacteria. Methanogenesis is the final stage whereby methanogenes bacteria converts hydrogen, acetic acid, and carbon dioxide to methane and carbon dioxide [11, 12]. Equation 1 shows a simplified generic anaerobic digestion [9].

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4 \quad (1)$$

III. PARAMETERS AFFECTING ANAEROBIC DIGESTION

The activity of biogas production depends on various parameters that include: temperature, partial pressure, pH, hydraulic retention time, C/N ratio, pre-treatment of feedstock, trace of metals (trace elements) and concentration of substrate [4, 11, 13].

IV. ANAEROBIC DIGESTERS CONFIGURATION

A. *Batch or Continuous Configuration*

AD can be performed as a batch or a continuous process depending on the substrates being digested and the configuration of the digester [14]. In a batch process, the substrate is added to the digester at the start of the process and sealed for the duration of the retention time. After digestion, biogas is collected and digester is partially emptied. They are not emptied completely to ensure inoculation of fresh substrate batch with bacteria from previous batch [14].

In a continuous digestion process, organic matter is constantly added in stages to the digester on a daily basis [15]. In this case, the end products are constantly removed resulting in constant biogas production [15]. A single or multiple digesters in a sequence may be used.

The selection of biogas digester depends on the dry matter (DM) content of the digested substrate. There are two AD technologies systems: wet digestion which is liquid digestion; when the average DM content of the substrate is less than 15% and dry digestion which is solid digestion; when the DM content of the substrate is more than 15% (usually from 20 to 40%). Wet digestion is applied for substrates like manure and sewage sludge, while dry digestion is applied for solid municipal bio-waste, solid animal manure, high straw content, household waste, and green cuttings, grass from landscape maintenance or energy crops [16, 17]. Table I shows the characteristics of anaerobic digesters technologies while Table II shows the comparison of various digesters types.

TABLE I
MAIN CHARACTERISTICS OF ANAEROBIC DIGESTERS TECHNOLOGIES

Characteristics	Technologies
Construction of digester	Covered lagoon, plug flow, complete mix, fixed film, UASB, vertical, horizontal and etc.
Temperature in digester	Psychrophilic, mesophilic and thermophilic.
Environment in digester	Wet and dry.
Process stages	One-stage, two-stages and multiple stages.
Loading (feeding) strategy	Batch, continuous and semi-batch.

TABLE II
COMPARISON OF VARIOUS DIGESTER TYPES

Tech	Digester type	Feedstock type	HRT (days)	Biogas yield	Tech level
Wet digestion	Covered lagoon	Thin manure	20-200	Poor	Low
	Plug flow	Think manure	20-40	Poor	Low
	Complete mix	Liquid and Solid	20-80	Good	Medium
	Fixed film	Liquid	1-20.	Good	High
	UASB	Liquid	0.5-2	Good	High
Dry digestion	Batch	Agricultural and municipal feedstock	20-30	Good	Medium
	Vertical		20-40	Good	High
	Horizontal		20-40	Good	High

V. CONDITIONS AFFECTING THE CHOICE OF A BIOGAS PLANT

Developing a biogas plant design is essentially the final stage of the planning process. However, it is mandatory for the designer to familiarize themselves with basic design considerations in advance. Ultimately, a successful plant design should be able to respond to quite a number of factors, and these includes:

ISBN: 978-988-14048-2-4
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

A. Climate

The design should respond to the prevailing climatic conditions of the location. Bearing in mind that biogas plants operate optimally at temperature ranges between 30°C to 40°C, in cooler regions, it is advisable for the designer to incorporate insulation and heating accessories to the design.

B. Substrate quality and quantity

The type and amount of substrate to be used on the plant will dictate the sizing of the digester as well as the inlet and outlet design.

C. Construction materials availability

If the materials required for the plant set up can be sourced locally at affordable rates so as to maintain the plant set up costs within manageable ranges, then the design is preferred to that whose materials have to be imported.

D. Ground conditions

Preliminary geotechnical investigations can guide the designer on the nature of the subsoil. In cases where the hard pan is a frequent occurrence, the design installation plan must be done in such a way that deep excavations are avoided because this would then increase the construction costs tremendously.

E. Skills and labour

Biogas technology is sophisticated and hence requires high levels of specialized skilled labour. The labour factor cuts across from the planner to the constructor up to the user. However, gaps can be reduced through training of the involved parties at a cost.

F. Standardization

Prior to the commissioning of the design, the planner must carefully study the prevailing standards already on the market in terms of product quality and pricing, especially for large scale projects.

VI. TECHNOLOGY SELECTION METHODS

A. Multi-criteria decision analysis (MCDA)

MCDA is an approach employed by decision makers to make recommendations from a set of finite seemingly similar options basing on how well they score against a pre-defined set of criteria [18]. MCDA techniques aim to achieve a decision goal from a set of alternatives using pre-set selection factors herein referred to as the criteria [19]. The selection criteria are assigned weights by the decision maker basing on their level of importance. Then using appropriate techniques the alternatives are awarded scores depending on how well they perform with regard to particular criteria. Finally, ranks of alternatives are computed as an aggregate sum of products of the alternatives with corresponding criteria. From the ranking, a decision is then made [20].

VII. METHODOLOGY

A. Waste quantification and Characterization

Waste generated in this feasibility study was quantified (Fig. 2) at the City of Johannesburg landfill A, Gauteng Province. This involved measurement of the waste at the point of generation to obtain the total amount of waste generated and the composition. Waste quantification was done in accordance with the standard methods of ASTM D 5231-92 [21].

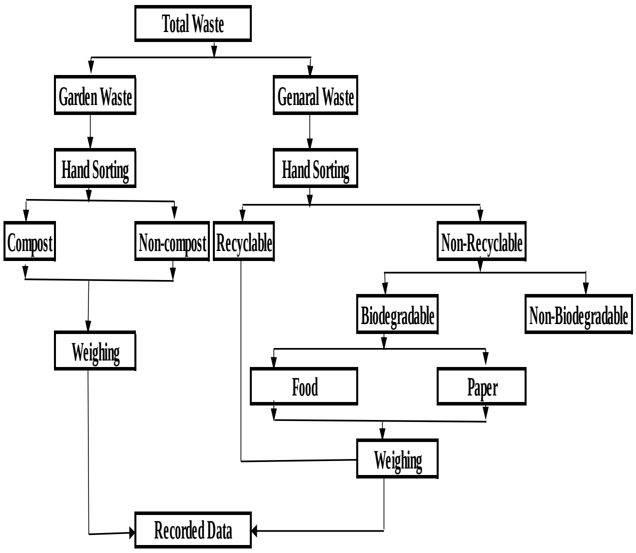

Fig 2. Feedstock quantification flows diagram

B. Multi-criteria decision analysis

Multiple criteria decision analysis (MCDA) technique was employed to select the most suitable biogas digester technology for OFMSW based on:

- Cost of the digester
- Local availability of the digester
- Temperature regulation ability
- OFMSW suitability
- Ease of construction
- Presence of agitation accessory

The digesters investigated include:

- Complete mix-Continuous stirred tank reactor (CSTR)
- Up-flow anaerobic sludge blanket (UASB)

ISBN: 978-988-14048-2-4
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

- Plug flow
- Covered lagoon
- Fixed film

C. Waste to Biogas Process Design

Using the results obtained from the feedstock analysis (feasibility study) and literature, the appropriate size of the biogas digester was determined using standard procedure considering feedstock quality and quantity.

VIII. RESULTS AND DISCUSSION

In this study, waste quantification exercise results are given. Using MCDA technique, a suitable biogas model was selected and from the substrate analysis, the appropriate size of biogas digester was determined.

A. Waste quantification

Results showed that 1,444,772 ton per annum of domestic waste was generated in the City of Johannesburg, South Africa Pikitup (2015) [22], of which from our investigation, the landfill comprised of 34% OFMSW portion made up of organic waste (Fig. 3). Of the total waste generated, 3%, 1%, 5%, 17% were the textile/fabric, special care waste, metals, and others general waste respectively. Organic waste was the most abundant component of the MSW, accounting for 34%. Recyclables (plastics, glass and paper/paperboards) was the second-largest component 19%, 9% and 12% respectively.

OFMSW and compost were the main substrates that were fed in the digesters for BMP. Utilising these organic wastes for energy production saves disposal sites air space. In addition, there are MSW management benefits from AD which include reduction of cost of transportation and compression of waste to landfills sites.

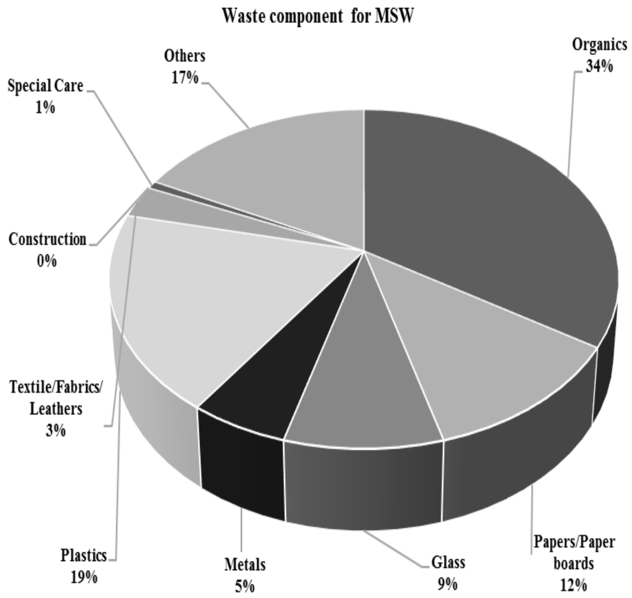

Fig. 3. Municipal solid waste quantification results, municipal landfill at City of Johannesburg

B. Bio-digester design

Using the results obtained from the substrate analysis and literature, the appropriate size of the biogas digester was determined using standard procedure considering substrate quality and quantity.

Using MCDA techniques, a suitable biogas model was selected from a list of potential alternatives as showed in the subsequent sections. The developed list of biogas digesters alongside a summary of their attributes is presented in Table III.

TABLE III
MCDA FOR BIODIGESTER SELECTION

Criteria		A		B		E		G		J		K		L		
Weight		**0.17**		**0.18**		**0.2**		**0.2**		**0.1**		**0.05**		**0.1**		
Digester Types		**S**	**Wt. S**	**S**	**Wt. S**	**S**	**Wt. S**	**S**	**Wt. S**	**S**	**Wt. S**	**S**	**Wt. S**	**S**	**Wt. S**	**Total Score**
1	**Complete Mix-CSTR**	**0.65**	**0.11**	**0.80**	**0.14**	**0.85**	**0.17**	**0.80**	**0.16**	**0.80**	**0.08**	**0.90**	**0.05**	**0.75**	**0.08**	**0.79**
2	**UASB**	**0.50**	**0.09**	**0.75**	**0.14**	**0.65**	**0.13**	**0.30**	**0.06**	**0.75**	**0.08**	**0.80**	**0.04**	**0.75**	**0.08**	**0.60**
3	**Plug flow**	**0.70**	**0.12**	**0.60**	**0.11**	**1.00**	**0.20**	**0.40**	**0.08**	**0.60**	**0.06**	**0.60**	**0.03**	**0.75**	**0.08**	**0.67**
4	**Covered lagoon**	**0.80**	**0.14**	**0.80**	**0.14**	**0.40**	**0.08**	**0.50**	**0.10**	**0.50**	**0.05**	**0.30**	**0.02**	**0.80**	**0.08**	**0.61**
5	**Fixed film**	**0.65**	**0.11**	**0.70**	**0.13**	**0.40**	**0.08**	**0.60**	**0.12**	**0.70**	**0.07**	**0.75**	**0.04**	**0.75**	**0.08**	**0.62**

Where; A-Cost, B-Local availability, E- Scalability, G-OFMSW suitability, J- Temperature regulation ability, K-Presence of agitation accessory, L- Ease of construction and S-Scores.

The project was fixed at OFMSW as a preselected type of feedstock. Therefore, the scalability of the plants and their suitability to handle OFMSW were taken to be the ruling factors for digester selection each having individually weighted factors of 0.2. Next in importance were the relative cost prices of the individual plants and their availabilities locally because both factors had a direct implication on the overall project cost. They weighed 0.17 and 0.18, respectively. Temperature regulation and ease of construction, operation and maintenance both weighed relatively lower at 0.1 because the technologies in consideration were relatively simple, easy to set up and therefore temperature as an operating factor can easily be regulated. The least important factor was the presence of agitation accessories weighing 0.05. CSTR scored highest with 0.79 and was selected for the design in OFMSW biogas production.

C. Digesters' design by volume and surface area

The design of the biogas plant is the process of determining the correct dimensions and geometry of the biodigester parameters required to satisfy a given loading rate conditions. This involves the use of suitable model to determine geometric equations:

Total weight of mixture;

$$W_t = (W_{vc} + W_{vc} + W_{vg}) + 2 \tag{2}$$

Force due to weight of mixture is Equation 3;

$$F = \left((av_{nc} * 10) + (av_{ns} * 3) + (av_{ng} * 3)\right) * 2 * 9.8 \tag{3}$$

Experimentally it was found that 36 kg of the visceral mixture would occupy 0.03 m^3 [23]. Fig. 4 shows the anaerobic digester with two domes.

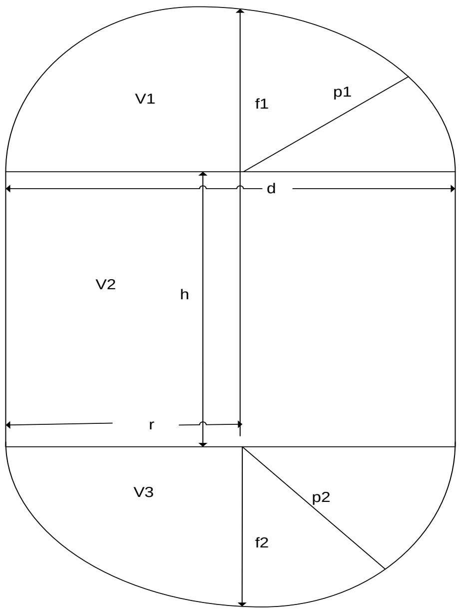

Fig. 4. Digester with two dome

Diameter of the digester cylinder is;

$$d = (\sqrt[3]{d_{cap}})^{1.173} \tag{4}$$

Volume of the digester top dome;

$$V_1 = \frac{(3r^2 + f_1^2) * \pi f_1}{6} \tag{5}$$

Where:
V_1 = Volume of the digester top dome
f = Height of dome
r = Radius of the digester

Volume of the digester cylinder;

$$V_2 = \pi r^2 h \tag{6}$$

Where:
V_2 = Volume of the digester cylinder
f = Height of digester
r = Radius of the digester

Volume of the digester bottom dome;

$$V_3 = \frac{(3r^2 + f_2^2) * \pi f_2}{6} \tag{7}$$

Where:
V_3 = Volume of the digester bottom dome
f = Height of dome
r = Radius of the digester

Surface area of digester top dome;

$$S_1 = 2\pi p_1 f_1 \tag{8}$$

Where:
S_1 = Surface area of the digester top dome
f = Height of dome
p = Radius of the digester

Surface area of the digester main cylinder body;

$$S_2 = \pi d h \tag{9}$$

Where:
S_2 = Surface area of the digester cylinder body
h = Height of digester
d = Diameter of the digester

Surface area of the digester bottom dome;

$$S_3 = 2\pi p_2 f_2 \tag{10}$$

Where:
S_3 = Surface area of the digester bottom dome
f = Height of dome
p = Radius of the digester

Determination of safety in operation

The mixture will act on two surface areas, that of the bottom sphere and that of the cylinder hence that designed area will be;

$$S_a = \pi d\,(0.5d + h) \tag{11}$$

Pressure will then be;

$$P = \frac{F}{\pi d(0.5d + h)} \tag{12}$$

For safety of plant without failure, the pressure or stress developed must be less than the bearing capacity multiplied by the strength of the concrete and divided by a factor of safety;

$$P < \frac{b_{cap} * f_c}{n} \tag{13}$$

Where:
n = Safety factor 10%
b_{cap} = Bearing capacity
f_c = Strength of concrete

Equation the expression gives;

$$\frac{F}{\pi d(0.5d + h)} < \frac{b_{cap} * f_c}{n} \tag{14}$$

IX. CONCLUSION

MCDA was applied towards choosing the digester type and upgrading technique. The result for digester type indicated that the "complete mix, continuously stirred anaerobic digester" was the most preferred with 79% preference to other anaerobic digester technologies. The design model and dimensioning of the biodigester was comparable with the anaerobic digestion process.

ACKNOWLEDGEMENT

The author wish to express their appreciation to Process Energy Environmental and Technology Station (PEETS) funded by South Africa National Energy Development Institute (SANEDI) and Technology Innovation Agency (TIA), City of Johannesburg (COJ) through Prof. Charles Mbohwa, Mr. Thabo Maahlatsi and Mr. Mlawule Mashego, Chemical Engineering and Applied Chemistry Departments at the University of Johannesburg for allowing us to work in their laboratories. Dr. Robert Huberts for assisting with some of the equipment for analysis. Dr. Jeffrey Bosire Orina, Martin Magu and Agbenyeku Emmanuel for technical support.

REREFENCES

[1] H. Allan., *"Grass productivity"*. Island Press Conservation Classics Series, Washington DC, 1998: p. 56-89.
[2] A.N. Matheri, M. Belaid, S. Tumisang, C.J. Ngila., *Role of Impact of Trace Elements on Anaerobic Co-digestion in Biogas Production.* 24th World Congress on Engineering (WCE 2016) London-UK, 2016.
[3] M.O.L. Yusuf, A. Debora, and D.E. Ogheneruona, *Ambient temperature kinetic assessment of biogas production from co-digestion of horse and cow dung.* Research in Agricultural Engineering, 2011. **57**(3): p. 97-104.
[4] G.K. Latinwo and S.E. Agarry, *Modelling the Kinetics of Biogas Production from Mesophilic Anaerobic Co-Digestion of Cow Dung with Plantain Peels.* International Journal of Renewable Energy Development (IJRED), 2015. **4**(1): p. 55-63.
[5] T.O. Omer and M.O. Fedalla, *Engineering design and Economic Evaluation of a family—sized biogas project in Nigeria.* Technovation, 2002.
[6] A.S. Sambo, B. Garba, and B.G. Danshehu, *Effect of some operating parameters on biogas production rate.* Renewable Energy, 1995. **6**(3): p. 343-344.
[7] A. Tiehm, K. Nickel, M. Zellhorn, Neis,U., *Ultrasonic waste activated sludge disintegration for improving anaerobic stabilization.* Water Research, 2001. **35**(8): p. 2003-2009.
[8] A.N. Matheri, M. Belaid, S. Tumisang, C.J. Ngila., *Modelling the Kinetics of Biogas Production from Co-digestion of Pig Waste and Grass Clippings.* 24th World Congress on Engineering (WCE 2016) London-UK, 2016.
[9] T.R. Sreekrishnan, S. Kohli, and V. Rana, *Enhancement of biogas production from solid substrates using different techniques—a review.* Bioresource technology, 2004. **95**(1): p. 1-10.
[10] M. Henze., *Biological wastewater treatment: principles, modelling and design.* London: IWA Publ, 2008: p. 401-437.
[11] R. Sundararajan, S. Jayanthi, and R. Elango, *Anaerobic digestion of organic fractions of municipal solid waste and domestic sewage of Coimbatore.* Indian Journal of Environmental Health, 1997. **39**(3): p. 193-196.
[12] I. Angelidaki, H.V. Hendriksen, I.M. Mathrani, J.E. Schmidt, A.H. Sorensen, B.K. Ahring., *The biogas process. Lecture notes for Energy from biomass (6362).* 1996.
[13] S. Rao, A. Retter, and P.J. Hobbs, *Effect of biomass hydrolysis on biogas production.*
[14] A. Schnurer and A. Jarvis, *Microbiological handbook for biogas plants.* Swedish Waste Management U, 2010. **2009**: p. 1-74.
[15] *Online]. Available: http://www.e-inst.com/bimass-to-biogas. [Accessed 15 January 2016].*
[16] T. Al Seadi, D. Rutz, H. Prassl, M. Kottner, T .Finsterwalder, S. Volk, R. Janssen., *Biogas Handbook.–University of Southern Denmark Esbjerg*. 2008, ISBN 978-87-992962-0-0.
[17] J. Rapport., et al., *Current anaerobic digestion technologies used for treatment of municipal organic solid waste.* University of California, Davis, Contractor Report to the California Integrated Waste Management Board, 2008.
[18] R. Kigozi, A.O. Aboyade, and E. Muzenda, *Technology selection of biogas digesters for OFMSW via multi-criteria decision analysis.* 2014.
[19] J. Chai, J.N.K. Liu, and E.W.T. Ngai, *Application of decision-making techniques in supplier selection: A systematic review of literature.* Expert Systems with Applications, 2013. **40**(10): p. 3872-3885.
[20] J.S. Dodgson., et al., *Multi-criteria analysis: a manual*. 2009: Department for Communities and Local Government: London.
[21] A.T.S.M, *ASTM D5231-92 (2008) Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste. (Waste Management Standard).* ASTM International, 2008.
[22] Pikitup, C.o.J., *http://joburg.org.za.* Accessed 2015.
[23] S. Umaru, A.F. Abubakar, and I. I.R., *Computer aided design of biogas plant for modern abattoirs.* 2012.