Multi-Criteria Analysis of Different Technologies for the Bioenergy Recovery from OFMSW

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Abstract— **In this study, the multi-criteria analysis model is demonstrated for evaluation and technologies from municipal solid waste (MSW) in City of Johannesburg (CoJ), South Africa. The technologies evaluation and alternation criteria for multi-criteria decision analysis (MCDA) area characterized by reviewing the literature and consulting experts in the renewable energy and waste management. MCDA was the approach employed by decision makers to make recommendation on technique employed to select the most suitable biogas digester technology for organic fraction of municipal solid waste (OFMWS) originating from the city's landfills base on scalability, relative cost prices, available, temperature regulation, agitation, ease of construction, operation and maintenance. The result for digester type indicated that the "complete mix, continuously stirred anaerobic digester" (CSAD) was preferred with 79% preference to other anaerobic digester technologies for energy recovery.**

Keywords— **Anaerobic digester, Design, bioenergy recovery, MCDA**

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I. INTRODUCTION

RAPID development in South Africa and other African nations has led to severe problems with management of municipal solid waste (MSW) due to its composition. The rapid population growth and urbanisation have resulted in increasing demand for clean (green) energy. This has given rise to numerous social and environment issue such as pollution from land usage, heavy metals, infection waste and hazardous air pollution [1]. Thus, there is an urgent requirement to reduce waste volume and mass increase the MSW bioenergy recovery so as to provide valuable energy recovery with greenhouse gas (GHG) emission reduction [2, 3].

II. BIOCHEMICAL PROCESS OF ANAEROBIC DIGESTION

Biogas production follows four fundamentals steps. These steps include; hydrolysis, acidogenesis, acetogenesis and methanogenesis [4, 5]. Fig. 1 shows a simplified generic anaerobic digestion process [6].

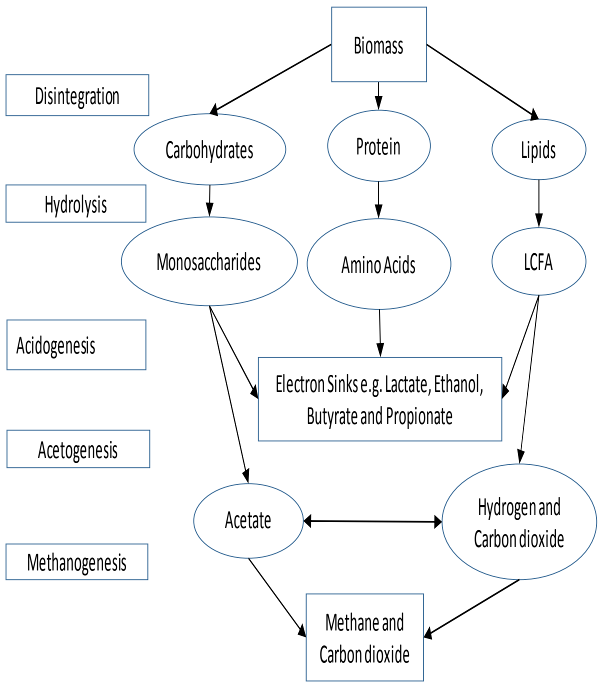

Fig 1. Degradation steps of the anaerobic digestion process.

The anaerobic digestion system is as the result of complex interactions among different type of bacteria. The major functional groups of bacteria according to their metabolic (activity) reactions are [7, 8]: Fermentative bacteria, hydrogen-producing acetogenic bacteria, hydrogen-consuming acetogenic bacteria, carbon dioxide reducing methanogens and aceticlastic methanogens.

Hydrolysis is a process where large organic polymers such as proteins, carbohydrates, and fats are broken down into amino acids, simple sugar, and fatty acids. The products of hydrolysis go through an acidogenetic process where low alcohols and organic acids are produced. Carbon dioxide, hydrogen, and acetic acid are produced in the acetogenic process which is required for the methanogetic process. Methanogenes converts the simple acids and the hydrogen produced by fermentative bacteria species to methane gas and carbon dioxide [9].

III. PARAMETERS AFFECTING ANAEROBIC DIGESTION

The activity of biogas production depends on various parameters like temperature, partial pressure, pH, hydraulic retention time, C/N ratio, pre-treatment of feedstock, trace of metals (trace elements) and concentration of substrate [9-12].

A. *Temperature*

Methane is formed over a wide range of temperatures from low temperature to high temperature though not over 65 °C. The three different temperature ranges for methane formation can be defined by the microbial activity.

Psychrophilic digesters were mostly used in the 1980s when biogas was used for heating purposes. At that time, at 23 °C, the average heating production was higher than that of mesophilic digesters [25]. In history, no anaerobic psychrophilic bacteria has been found at temperatures below 20 °C, because under these conditions the psychrophilic anaerobic digestion was not feasible, had low microbial activity and biogas production [26].

In recent years, mesophilic digesters are the most popular. The temperature of digesters depends mostly on the feedstock composition and the type of reactor, but it has been observed from literature that for maximum gas production rate, the temperature should be maintained at an approximately constant level [27]. A number of mesophilic and thermophilic anaerobic bacteria are described in the temperature ranges between 28 °C and 42 °C and between 43 °C and 55 °C, respectively. It has also been found that the thermophilic digesters have lower retention time which is due to the high catalytic activity of thermophiles [27][13]. Table 1 shows different thermal stages, process temperatures and typical hydraulic retention times for the AD process.

TABLE I
THERMAL STAGES, PROCESS TEMPERATURE, AND TYPICAL HYDRAULIC RETENTION TIMES

Thermal stages	Process temperature (^{0}C)	HRT(days)
Psychrophilic	<20	From 70-80
Mesophilic	From 30-42	From 14-40
Thermophilic	From 43-55	From 14-20

B. *pH*

The AD process is greatly affected by variation in levels of pH. Microbes cannot grow under high acidic conditions hence, anaerobic digester failure or low methane yield occurs. Optimization of digestion pH is preferred to be ranging from 6 to 7 [21, 22]. The first stage produces volatile fatty acids which lower the pH due to the chemical interaction of CO_2 and water (H_2O). Hydrogen carbonate ions are formed and restore stability. It is recommended to maintain alkalinity at roughly a 3000 mg/l for optimizing methane yield [20].

C. *Volatile fatty acid*

The VFA’s uptake play a crucial role in the whole degradation kinetics of organic waste digestion, as the accumulation of the intermediate products. VFAs is the rate-limiting step in the AD [14]. High concentrations VFAs in the digester inhibit methanogenic activity, lower the pH level and cause possible failure of the anaerobic digestion process [14].

D. *Carbon/Nitrogen ratio*

The feed at C: N ratio of 30:1 results in optimum methane yield. C: N ratio determines the occurrence of digestion [11, 23]. As carbon creates the energy source for the microorganisms, nitrogen results in the formation of ammonia gas. When the levels of C: N ratio is high, there is fast depletion of nitrogen (N) used by bacteria that produce methane, to satisfy their protein needs, therefore, resulting in less biogas production. When the pH level is greater than 8.5 promotes a toxic environment for the methanogenic bacteria to exist. To operate the anaerobic digester at optimum C:N ratio, biodegradable material of high C: N ratio should be blended with the biodegradable material of low C: N ratio [23].

E. *Retention time*

Retention time is the time required to degrade the organic matter (substrate) completely and for bacteria to grow. The retention time depends on process temperature and batch composition, meaning retention time for waste treated in a mesophilic condition than thermophilic conditions [15], the residence time is generally positively correlated with methane content. There are two important types of retention time that include; solid retention time (SRT) and hydraulic retention time (HRT). SRT is the average time the bacteria (solids) are in the anaerobic digester, and HRT is the volume of the biological reactor per influent flow rate in time, which is defined by following equation: Digestion time inside the reactor is one of the main factors influencing the CH_4 yield [15]. Effective hydraulic retention time depends on the type of substrate, loading rate, and reaches up to a couple of weeks. Shorter HRT usually results in accumulation of VFAs, whereas at HRT longer than optimal, the digester components are not effectively utilized [15].

F. The organic loading rate (OLR)

The organic loading rate (OLR) is the amount of volatile solids (VS) to be fed into the digester each day in a continuous AD process. As the OLR increases, the biogas yield increases to some extent but above the optimal organic loading rate, the VS degradation and biogas yield decreases due to overloading of the digester [16]. The maximum possible OLR depends on the process temperature and its retention time.

G. Trace elements

Mineral ions, especially of trace elements are among the materials that inhibit the growth of bacteria in a digester. A small amount of mineral (calcium, sodium, potassium, sulphur, magnesium and ammonium) stimulate the microorganisms growth, but higher concentrations have a toxic and inhibition effect [13]. Heavy metals such as zinc, nickel, cobalt, copper, lead, and chromium are essential for bacterial growth in very small quantities, but higher quantities have a toxic bacteria effect that inhibits the AD process. Organic solvents and antibiotic also inhibit the growth of bacteria. Recovery of digesters can only be achieved by flushing the content, cessation of feeding, or diluting the contents to lower the concentration of inhibitory substances to below the toxic level [13].

H. Ammonia

Studies in the past have shown that ammonia is an important source of nitrogen for bacteria, low concentrations of ammonia is valuable to the process [17], although some findings showed that the specific activity of methanogenic bacteria decreases with increasing concentrations of ammonia [17]. The mechanisms ammonia inhibition are the change in the intracellular pH, the increase of maintenance energy requirement as well as inhibition of a specific enzyme reaction [17]. And the high concentration of ammonia in the digester decreases the deamination activity of proteolytic bacteria [18].

I. Agitation/Mixing

Mixing is required for temperature distribution, to maintain fluid homogeneity and enhance process stability within a digester. The objectives of mixing are to combine the incoming substrate with the microbes, to reduce the formation of scum, and to avoid pronounced temperature gradients within the digester. Very rapid mixing can disrupt the microbial balance while too slow stirring can cause short-circuiting and inadequate mixing. [13].

J. Grinding

Grinding or breaking down of feedstock into small pieces before feeding them into the digesters increases the surface area of contact between substrate and microbes, decrease the retention time in digestion and enhance biogas production. These simplifying the digestion process [19].

K. Co-digestion

Studies show that co-digestion is a way of minimising hydraulic retention time and improving methane production [20]. The other substrate should be dominated by high levels of organisms that have the ability to hydrolyse lingo-cellulose material. Co-digestion of biomass waste can produce more methane than manure (inoculate supplier) itself, but the challenge in this process is to achieve completely break down of organic material in the stage of hydrolysis [20]. The importance of co-digestion is to stabilize conditions or other parameters in digestion process such as C:N ratio as well as pH, micronutrients, macronutrients, dry material and inhibitors [20].

L. Substrate pre-treatment

Pre-treatment is done to increase the efficiency of AD technology and increase the production of biogas [21]. Pre-treatment can be classified as mechanical, thermal, biochemical pre-treatment. Pre-treatment is necessary since the nature of a substrate has an effect on the rate of biogas production [21].

IV. TECHNOLOGY SELECTION METHODS

Several methods have been developed to give unbiased results when it comes to decision-making on a particular choice of technology. In principle, all methods are based on the steps summarized below [22];

- Identification of the problem,
- Identification of stakeholders,
- Seeking the unbiased opinions of the stakeholders in the form of solutions to the identified problem. The identified solutions are treated as alternatives and the key performance indicators of the chosen options become the selection criteria,
- Modelling the obtained solutions so as to obtain impartial results through detailed analyses. At the modelling stage is when the decision maker decides on which particular selection method to employ basing on the nature of the problem at hand.

In modern times, technology designs are probabilistic in nature and the evaluation criterion is multi-dimensional. This calls for complex tools that can capture all the dimensions of a decision problem. The existing technology selection methods include;

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. MCDA techniques aim to achieve a decision goal from a set of alternatives using pre-set selection factors herein referred to as the criteria [23]. 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 [24].

There are several variations in MCDA techniques used currently employing mathematics and psychology. These include; analytic hierarchy process (AHP), Simple multi-attribute rating technique (SMART) and Case-based reasoning (CBR)

AHP aims at organizing and analyzing complex decisions basing on their relative importance independent of each other. [25, 26]. Saaty [25] developed a scale of 1-9 to score alternatives basing on their relative importance as shown in Table II. However, the major drawback of the AHP is the alteration of ranks in cases where new alternatives are introduced into an already analyzed problem [25, 26].

TABLE II
SAATY'S SCALE INTENSITY 1-9

S	Definition	Explanation
1	EI	Two elements equally contribute to the intended objective.
3	MI	Basing on judgement and experience one element is favoured over the other.
5	SI	Basing on judgement and experience one element is strongly favoured over the other.
7	VSI	One element is very strongly favoured over the other and its dominance can be demonstrated in practice.
9	EIs	The evidence favouring one element over another is of the highest order of affirmation.

Where: S-scale, EI-Equal importance, MI-Moderate important, SI-Strong important, VSI-Very strong important, EIs-extreme important,

By applying the SMART technique, alternatives are ranked basing on ratings that are assigned directly from their natural scales [27, 28]. The advantage of the SMART technique over AHP is the fact that the decision-making model is developed independently of the alternatives. Therefore, the scoring of the alternatives is not relative and therefore introduction of new alternatives doesn't affect the ratings of the original ones making it a more flexible and simpler technique [28]. In CBR, problem solving is done basing judgement on similar past problems and experiences. Basically, the decision is made basing on what has happened before. [29].

V. METHODOLOGY

A. Waste to Biogas Process Design

The MCDA study has compared technologies to identify AD for the energy recovery from OFMSW in South Africa. Using the results obtained from the feasibility study, consultancy and literature. The application of MCDA has been demonstrated in this study and applied towards choosing the biogas digester type, using standard procedure considering feedstock quality and quantity.

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)
- Plug flow
- Covered lagoon
- Fixed film

VI. RESULTS AND DISCUSSION

A. Bio-digester Selection

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.

The project was fixed at OFMSW as a preselected type of substrate. 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.

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 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.

VII. CONCLUSION

The MCDA study has compared technologies to identify AD for the energy recovery from OFMSW in South Africa. The application of MCDA has been demonstrated in this study and applied towards choosing the digester type. The result for digester type indicated that the "complete mix continuously stirred anaerobic digester" (CSTR) was preferred with 79% preference to other anaerobic digester technologies for energy recovery for heat, electricity and liquid biofuel for the transport sector. It indicated that it has the best performance technology due high good performance and less treatment cost.

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