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Waste to energy bio-digester selection and design model for the organic fraction of municipal solid waste

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ABSTRACT

In this study, a feasibility study was carried out in terms of quantification-characterization of waste, biomethane potential from organic biomass and bio-digester selection and designing. From waste quantification, 38% was found to be an organic fraction of the municipal solid waste (OFMSW) of the 1.4 million tonnes per year. The composition of the waste was investigated using a laboratory batch anaerobic digester for biochemical methane potential (BMP) and the waste to energy bio-digester selection and design for the anaerobic co-digestion of different OFMSW originating from the City of Johannesburg landfills. The carbon to nitrogen (C/N) ratio of OFMSW was found to be below 13. Through co-digestion, the C/N ratio settled at 15. Laboratory experimental data from 500 ml batch anaerobic digester operating at a *meso*philic temperature of 37 °C and pH of 6.9 had a good productivity of methane of average 59% recommended in the literature and was used to derive the volume of digester and surface area. The artificial intelligence (AI) technique was applied to select the most preferred digester model. Using the application of the simple multi-attribute rating (SMART) technique of multiple-criteria decision analysis (MCDA) as a decision support tool, the most preferred option of a bio-digester model was selected from a list of potential alternatives available in the market. The continuous stirred tank reactor (CSTR) scored highest with 79% and was selected as the most preferred digester for the OFMSW digestion. The geometry of the biodigester parameters was found to be comparable and economically feasible with the process parameters, energy generation from the BMP and scale up model for the independent power producer (IPP).

1. Introduction

The energy demand globally is increasing due to population growth and industrialization. It has exponential growth over time with a predicted 85% increase between 2010 and 2030 globally. Approximately 85% of the world's energy supply is obtained from non-renewable fossil fuels sources such as coal, oil and natural gas. These fuels yield high quantities of greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2). The continuous use of fossil fuels is leading to the long-term potential risk of energy insecurity and simultaneously degrading the environment with the high CO_2 emissions [1–3]. According to Cornish [4] from energy systems, South Africa has the highest carbon emissions level in Africa due to coal energy generation as compared to large emitter like China with per capita emission much lower than South Africa. This call for the alternative source of energy that is renewable, clean (green) and sustainable like bioenergy, wind, solar, geothermal, hydropower and fuel cells [5]. With the regards to sustainable development goal (SDG-7), it is more desirable to create sustainable worldwide energy system [6]. Municipal solid waste (MSW), a by-product of the lifestyle of urban dwellers, comprises of wastes from household, offices, restaurants, market, industries among others hazardous waste [7,8]. The rapid development has led to severe problems with waste management and running out of the landfill airspace that requires urgent waste management mitigation measures. There are several obstacles confronting MSW management within the cities. Some of such obstacles are; interrelation of economic growth and urbanization; complexity of the waste stream due to different class of citizen living within the city; lack of adequate facilities that will expedite waste separation at source; overstretching of the superannuated infrastructure; and also the waste management technologies that are handy,

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are very costly compared to the cost of land-filling [7,8]. Separation of waste at the source and adopting zero waste economic incentive encourage household to reduce waste. The organic waste can be converted to energy using waste to energy alternative routes that include thermal conversion; gasification, incineration, pyrolysis and liquefaction and biological processes; fermentation, hydrolysis and anaerobic digestion for biogas and biomethane production [9].

Biogas is produced by the breakdown of biomass (organic compound) using microorganism under controlled variables [10]. The biomass is sourced from biodegradables compounds such as agriculture waste, animal waste, municipal solid waste, sewage sludge and industrial waste [11,12]. Biogas is a mixture of gases such as methane (60%), carbon dioxide (30%) and other traces of ammonia, hydrogen sulphide, hydrogen, carbon monoxide and oxygen. Energy derived from biogas and biomethane (upgraded biogas) is used in the form of heat, fuel, electricity and beverage grade CO_2 after carbon capture from biogas upgrade. Biogas production takes place in series of five fundamental steps namely: disintegration, hydrolysis, acidogenesis, acetogenesis and methanogenesis [13–15]. The various parameters that control the performance of the anaerobic digestion include; nature of substrate, optimum trace metals concentration, nutrient supply (carbon to nitrogen ratio), constant temperature, organic loading rate (OLR), agitation intensity, hydraulic retention time (HRT), partial pressure, an amount of inhibitors (e.g. ammonia) and exclusion of oxygen [15,16].

1.1. Anaerobic digesters

Anaerobic digestion (AD) can be performed as a continuous or a batch process depending on the biomass being digested and the digester configuration [17]. In a continuous digestion process, biomass is constantly added in phases to the digester on an interval while the end products are constantly removed. This results in constant biogas production. A multiple or single digester in a sequence may be used [18]. In a batch process, the biomass is added to the digester at the onset of the AD and is maintained over the hydraulic retention time [17]. The main characteristic of anaerobic digester technologies include: type of digester; covered lagoon, plug flow, complete mix, fixed film, up-flow anaerobic sludge blanket (UASB), vertical and horizontal digester, temperature range that include psychrophilic, *meso*philic and thermophilic, digester environ that include wet and dry digestion, process stages that include single, multiple stages and lastly loading rate strategy that include batch, continuous and semi-batch. The selection of bio-digester depends on the dry matter (DM) content of the biomass. The two AD technologies systems include dry digestion for the solid digestion of the biomass; the DM content of the substrate is more than 15% (usually from 20% to 40%). Wet digestion for the liquid digestion; the average DM content of the substrate is less than 15%. The wet digestion is applied to biomass like sewage sludge and liquid animal manure while dry digestion is applied to municipal organic waste, agriculture waste, household and restaurant organic waste [19,20]. Table 1 shows the comparison of various technology, digesters types, and substrate type with regards to the HRT, biogas yield and level of the technology [21].

1.2. Factors affecting the choice of a biogas plant

Bio-digester designing is essentially the final stage of the AD planning process. Ultimately, a successful bio-digester plant design should be able to respond to a number of factors that include climate conditions, substrate quality and quantity, availability of the construction materials, geotechnical, specialized skill labour and standardization [21]. Bearing in mind that bio-digesters operate optimally at temperature ranges between 30 °C and 40 °C for the mesophilic and 40 °C to 55 °C for the thermophilic in cooler regions, it is advisable for the designer to incorporate heating accessories and insulation to the design. The design should respond to the prevailing climatic conditions of the location. The organic loading rate to be used will dictate the sizing of the digester as well as the inlet and outlet design. Sourcing the feedstock locally minimize the cost and this lower the operational cost and thus maximizing the firm profits. To guide the designer on the nature of the subsoil, the geotechnical investigation is highly required. Biogas technology requires high levels of specialized skilled labour. The labour factor cuts across from the contractors, planner to the operators. The gaps can be bridged through training of the involved parties at a cost. The planners must carefully study the prevailing standards currently on the market in terms of pricing and product quality for the large scale projects prior to commissioning [21].

1.3. Anaerobic digester design model selection

The modern technology designs are probabilistic in nature and the evaluation criterion is multi-dimensional. The anaerobic digester design model has a secure niche in the artificial intelligence (AI) research and techniques. This utilizes the principle component of analysis to enhance the overall performance using the artificial neural network (ANN) [23–25]. This calls for complex technology that can capture all the dimensions of decision making. The most effective and existing technology selection methods include; multi-criteria decision analysis (MCDA) approach that is employed by decision makers and stakeholders to make recommendations from a set of finite seemingly similar options base on the highest score against a pre-defined set of criteria. This techniques aim to achieve a decisive goal from a set of alternatives using pre-set selection factors herein referred to as the criteria [26]. The selection criteria are assigned weights base on their highest level of importance. 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. The decision is then made based on ranking [27].

Several variations in MCDA technique employs the mathematical and psychology. These include; case-based reasoning (CBR), simple multi-attribute rating technique (SMART) and analytic hierarchy process (AHP). AHP aims at analyzing and organizing complex decisions

Table 1
Comparison of various digester types [21,22].

Technology	Digester type	Substrate type	HRT (days)	Biogas yield	Technology 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		20–30	Good	Medium
	Vertical	Agricultural and municipal feedstock	20–40	Good	High
	Horizontal		20–40	Good	High