Economic Benefits of Scaling Up a Smart Anaerobic Digester for Biogas Recovery from Industrial Wastewater

Lindokuhle Ngema, Sydney Mandla Khanyile, Devona Sathiyah, Emmanuel Kweinor Tetteh and Sudesh Rathilal

***Abstract*—** With a strong shift from conventional energy production methods due to climate change and CO_2 emission restrictions, there is an increase in demand for exploring alternative methods to produce green energy. As a result, the application of anaerobic digestion (AD) technology gained significant interest in wastewater treatment with its potential for producing biogas that can be converted into green electricity. Upscaling and industrialization of biogas technologies hold the key to maximizing environmental, economic and energy benefits from AD technologies. In this study, a 50 L smart anaerobic digestion pilot plant was developed for the valorization of industrial wastewater into bioenergy. The optimum operating conditions employed resulted in the production of 0.493 m^3/gTDS high quality biogas with methane content above 90% and over 60% overall reduction in COD concentration. The annual operating costs for the system exceeded the annual revenue based on biogas production, resulting in the negative net positive value of R104592.4 for the system. The upscaling of the AD system from 5 L system to 50 L increased the annual revenue generated and decreased the investment payback period from 29.5 years to 18 years. This suggests that further upscaling can reduce the payback period for initial investment and start generating profit at the early stages of the project’s lifespan, thus making the system economically viable. Additional value to the system can be recovered by converting the digestate into fertilizers and generating more revenue.

***Keywords*—** Anaerobic Digestion, Wastewater, Biogas, Cost-Benefits Analysis, Energy Production, Cash Flow.

I. INTRODUCTION

Anaerobic digestion (AD) and biogas production are two such critical technologies facing increasing relevance for the future, particularly in this period of transition to sustainable and renewable sources of energy (Kabeyi and Olanrewaju 2022). Apart from the energy production during the AD process, waste management, carbon footprint reduction and sustainability makes the AD technology relevant and aligns with the United Nation’s 2030 SDG goals number 6, 7 and 13. Production of biogas provides a low-carbon alternative for traditional fuels, making it less dependent on fossil fuels while ensuring large CO_2 reduction in sectors for power generation, wastewater treatment and transportation. Biogas is a clean and storable source of energy that can enhance grid stability, especially when combined with other renewables, such as wind and solar (Häring *et al.* 2017; Obileke *et al.* 2021). Production of biogas by AD technology has the potential to solve the current energy problems with a potential of storing the clean energy in the form of biogas for application at peak demand. Through AD, the organic waste varying from food waste, wastewater sludge and other organic waste is converted into valuable energy and thus reducing load on waste management techniques and saving costs. The land-filling of organic waste naturally produces methane during decomposition, one of the potent greenhouse gases (Javad Asgari *et al.* 2011; Rodrigo-Ilarri and Rodrigo-Clavero 2020). The application of AD processes reduces landfilling of organic waste, which in turn reduces the amount of methane produced and escaping to the atmosphere, hence lowering the overall environmental footprint. The digestate derived from the AD process is a nutrient-rich mixture that can be dried and used as a bio-fertilizer. This enables circular economy in the agricultural sector whereby waste is converted into a resource to enrich the soil without the use of synthetic fertilizers (Sharma *et al.* 2023).

Anaerobic digestion with the focus on biogas production becomes a key process for sustainable energy production. Upscaling and industrialization of biogas production facilities hold the key to maximizing environmental, economic, and energy benefits from AD technologies (Bossink *et al.* 2023). Biogas, as a renewable energy source, warrants continuous sustainable energy for applications from domestic heating to industrial feedstock. Currently, most biogas production facilities operate at small-scale capacity, and therefore hinder their potential impact and efficiency to the global energy challenges. Industrial-scale biogas production plants can provide larger volumes of biogas to meet the current demand for electricity generation and transportation. This will contribute to significant carbon footprint reductions and minimize reliance on fossil fuels.

Biogas production plants in the Southern Africa region, holds immense economic and environmental benefits (Mukumba *et al.* 2016). Considering the growing population and the increasing demand for energy, the fossil fuels are depreciating

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and the clean energy from biogas becomes an urgent requirement for both sustainable energy and waste management. The feasibility and economic viability of up-scaling and industrialization of biogas production in Africa is dependent on the sustainability of energy price, availability of wastes, conditions of infrastructure, and policy frameworks that enables valorization of organic waste (Gbadeyan *et al.* 2024). Large-scale biogas plants would create vast opportunities for renewable energy and economic growth in Southern Africa. The current challenges with up-scaling of the biogas production plants includes high initial capital costs, infrastructure requirements and inconsistency in feedstocks (Roopnarain and Adeleke 2017). To overcome these challenges, optimization of the AD systems and proper policies is necessary to attract investments for initial capital costs. In this study, the economic benefits of upscaling an anaerobic digester to a smart AD system designed for biogas production.

II. Materials and methods

A. Chemicals and wastewater samples

Wastewater and activated sludge samples were sourced from the local municipal wastewater treatment and sugar refinery plants located in Durban, Kwa-Zulu Natal. A Hach spectrophotometer was used to examine the physicochemical properties of wastewater with COD, colour and turbidity of 1877 mg/L, 7858 Pt-Co and 762 NTU respectively. Higher organic content measured in mg-COD/L makes this stream suitable for producing biogas by anaerobic digestion treatment. Magnetite catalyst and stock solutions (acid and base) for regulating pH were prepared in house by following procedures developed and modified by (Tetteh *et al.* 2021; Amo- Duodu *et al.* 2024).

B. Experimental setup and procedure

A 50 L anaerobic digestion system was designed for the treatment of industrial wastewater to produce biogas. The schematic layout of the 50 L AD system is presented in Fig 1. This system consists of a feed storage tank containing wastewater that is pumped into the AD tank. To control the temperature, hot water from the water bath is pumped and circulated to the heating jacket and a temperature sensor is mounted inside to monitor the temperature of the mixed liquor. The pH is also controlled by a pH sensor that sends the signal to the controller to dose acid or base to meet the desired range. Biogas produced was collected using a downward displacement cylinder and a tedlar bag. The treated effluent was collected in the storage/settling tank and characterized for contaminants before discharging. The optimum operating conditions used were hydraulic retention time (21 days), pH (7.01) and catalyst load (0.42 g/L) adopted from the previous optimization study for AD treatment of wastewater (Ngema *et al.*).

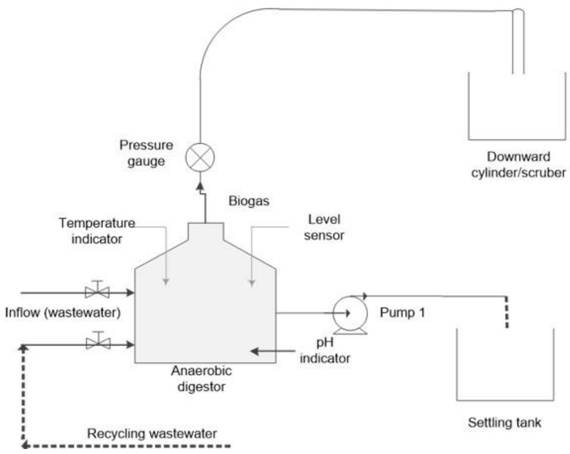

Fig. 1 The up-scale 50 L smart AD system for biogas recovery

III. Results and discussion

In anaerobic digestion (AD), the bacterial community removes contaminants via biodegradation of organic contents to produce methane-rich biogas and reduce costs for effluent and sludge discharge (Lee *et al.* 2017). At the end of AD, the effluent was characterized and the removal percentages for the contaminants were 61.4% (COD), 64.8% (Turbidity) and 60.89% (Colour). The challenges in the removal of contaminants was due to the presence of the common complex organic compounds in sugar wastewaters that are difficult to breakdown by the micro-organisms (Fito *et al.* 2018). The presence of these compounds limits the conversion of COD into methane and may require pre-treatment to enhance removal during anaerobic digestion. The produced biogas was characterized using the gas analyzer and the quality is presented in Fig 2.

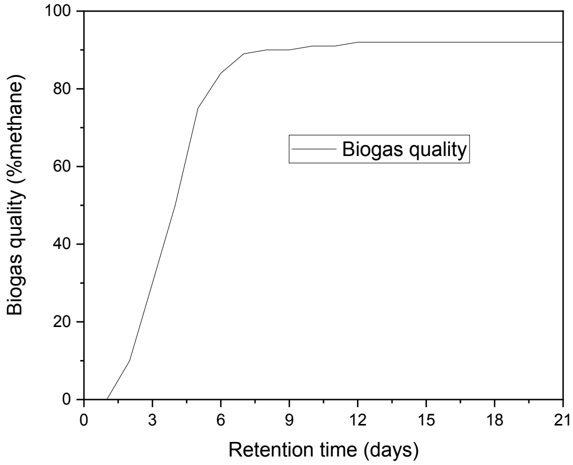

Fig. 2 Composition of biogas produced from the 50 L AD

Biogas was produced over the period of 21 days and the quality of biogas reached a maximum of 92% methane content within the first week of production. High methane content indicates efficient conversion of organic content into methane by microorganisms. This is a result of optimal anaerobic conditions with close monitoring of operating conditions and balance solid-liquid ratios. The achieved biogas quality indicates the low concentration of impurities and may not require further upgrading before converting to electricity. The energy value of high quality biogas averages at 13.4 kWh based on methane content (Garcia *et al.* 2019). Therefore, the energy value of the 92% methane rich biogas is estimated to be 12.27 kWh.

A. Evaluation of capital and operating costs

The capital required to purchase and commission the 5 L and 50 L AD reactors was R17 460 and R103 520 respectively. The costs covered the AD tank, pH and temperature sensors and water jacket for supplying heat into the system. The monthly and annual costs for the operation of the biogas system is presented in Table 1. The operating costs were calculated based on the unit cost of electricity adopted from South Africa's electricity tariffs for households at peak and off-peak seasons with an average of R3.76 per kWh.

TABLE I
ANNUAL OPERATING COSTS FOR THE SMART AD SYSTEM

Item	Power usage (kW)	Operating hours per day	Unit cost	Monthly costs (21 days)	Annual costs
Feed pump	0.37	0.17	R3.76 per kWh	R4.97	R59.60
Acid/base dosing pump	0.2	0.25	R3.76 per kWh	R3.95	R47.38
Water bath	1.5	6.5	R3.76 per kWh	R769.86	R9 238.32
Gas analyser	0.25	2	R3.76 per kWh	R39.48	R473.76
Chemicals					R547.44
Total					**R10 366.5**

B. Evaluation of economic benefits for upscaling of AD

The key indicator to the benefits of an anaerobic digester is the amount of biogas produced that can be converted into electricity. The produced biogas was quantified using the downward displacement cylinder and characterized using the gas analyzer for methane content. The biogas quality achieved was 90% methane at optimum operating conditions with a net energy value of 12.27 kWh. Considering the cost of electricity at R3.76 per kWh, the annual energy and revenue generated was calculated as using equations (1 & 2) and presented in Table 2. The total revenue generated by the 5 L and 50 L systems are R592.93 and R5731.65 respectively.

$$\text{Annual energy production} = \text{biogas } (m^3) \times \text{Net energy value} \times \text{HRT} \quad (1)$$

$$\text{Annual revenue} = \text{Annual energy production} \times \text{electricity price} \quad (2)$$

TABLE II
SUMMARY AND ANNUAL ENERGY AND REVENUE GENERATED BY THE TWO AD SYSTEMS

AD size	Biogas (m^3/gTDS)	Annual energy produced (kWh)	Annual revenue (rands)
5 L	0.051	157.694	592.93
50 L	0.493	1524.38	5731.65

The next critical factor on the project's investment is the payback period that is calculated using the initial capital and annual revenue as shown in equation 3.

$$\text{Payback period} = \text{Initial investment} / \text{Annual revenue} \quad (3)$$

The calculated payback period for the 5 L AD system is 29.4 years while the payback on the 50 L system comes down to 18.1 years. This suggests that upscaling of the AD generates more revenue, and reduces the payback period on investment, thus reducing the risk on investment. Similar studies by (Spyridonidis *et al.* 2020) proved that upscaling increases revenue and reduces payback period if operating cost are reduced with improvements over the lifespan of the project. The Benefit-Cost ratio (BCR) is another indicator of the financial viability of the project and is calculated by dividing the total annual benefits by the annual operating costs. The BCR of 1 and above indicates that the project is economically viable and may be recommended for investment. In this study, the BCR for the 5 L and 50 L system is 0.06 and 0.55, indicating that the cost of operation outweighs the total benefits, however, there are other non-economic benefits to be considered that justifies the importance of up-scaling and industrialization of this AD system.

C. Net present value (NPV)

The net present (NPV) value was calculated to evaluate the profitability of the project. The NPV represents the difference between the value of the cash flow and the total costs over the 30-year period for the project lifespan. The average discount rate used is 5% for the return on investment. To evaluate NPV for the two AD systems, the net cash flow (CFt) was calculated as follows:

$$\text{CFt} = \text{annual revenue} - \text{operational costs} \quad (4)$$

The net cashflow for the 5 L system is R-9773.57 and R-4634.85 for the 50 L AD system. This suggests that both systems are operating at a loss with operating costs exceeding the revenue generated from biogas. The positive net value for the two AD systems is presented in Table 3.

TABLE III
SUMMARY OF CASH FLOW AND NET POSITIVE VALUE

AD	Cash flow (rands)	Net Positive value (rands)
5 L	-9773.57	-17460
50 L	-4634.85	-104592.4

The negative NPV for these two AD systems indicates that the capital costs and cost for operating the system exceeds the projected financial benefits from biogas produced. The negative NPV is a result of higher capital cost that is required for commissioning of the AD systems. The negative NPV may indicate financial loss based on revenue generated from biogas, however, this AD system comprises of other benefits that can justify the negative NPV. The cost of treating wastewater and discharging sludge can be added to the financial gains for this project. Moreover, the nutrient-rich sludge produced can be sold for use as a bio-fertilizer and generates more revenue. In addition to economic benefits, this technology has significant impact on environmental benefits with a reduction of carbon footprint and replacing chemical synthetic fertilizers with bio-fertilizers and thus preserving the environment.

The payback period and break-even analysis for the two AD systems was conducted to determine how long the project takes to generate cash flow and pay back on the initial investment. In Fig 3, the cash flow equates the annual operating costs after 18 years, indicating that the system will only start generating revenue from the 19th year of the project lifespan. However, the project will take 29 years to pay back the initial investment and can only make profit for only one year before the end of the project lifespan. This is due to low levels of biogas produced based on the AD size, and high operating costs.

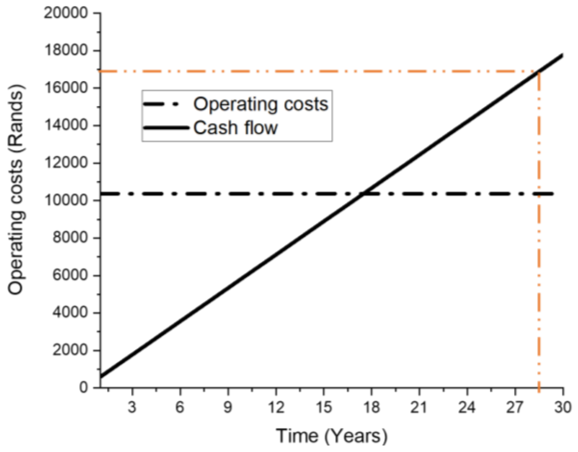

Fig. 3 Payback period and Break-even analysis for the 5 L AD system

In Fig 4, the 50 L AD system starts generating cash flow after 1.5 years, indicating that the amount of biogas generates revenue that will surpass operating costs at a faster rate. The project for the 50 L AD takes only 18 years to pay back the initial investment and therefore can generate profit for the remaining 12 years of the project lifetime. This analysis suggests that the upscaling of a biogas production unit helps with generating more revenue and reducing payback period on the initial investment if the operating cost are kept constant or reducing over time due to improvements and stability in the process.

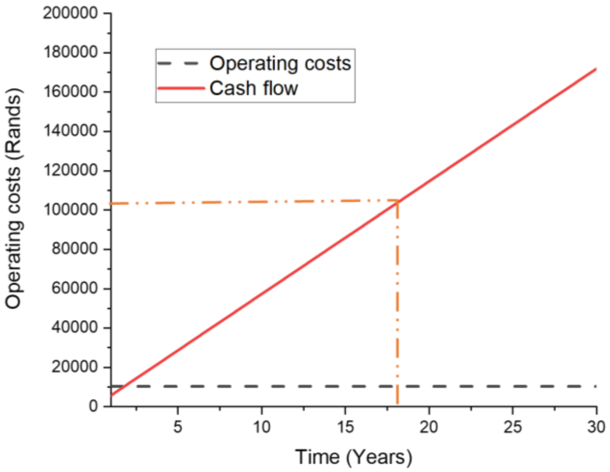

Fig. 4 Payback period and Break-even analysis for the 50 L AD system

IV. CONCLUSION

The need for optimizing up-scale and industrialization of biogas production systems has become an urgency due to an increase in energy demand. In this study, it was evident that upscaling of an AD system and close monitoring increases biogas production and the financial benefits of the project. Up scaling, the AD system from 5 L to 50 L AD reduces the payback period from 29 years to 18.5 years due to increased revenue generation. Both 5 L and 50 L systems have negative NPV values of -R17460 and -R104592.4, suggesting that both systems are not economically viable. However, this technology comprises of other financial gains that can be recovered from the cost of handling and treatment of wastewater and sludge. It also adds value with the reduction of carbon footprint and the use of sustainable bio-fertilizers, thus preventing soil pollution. Upscaling from 5 L to 50 L presents promising results with an increase in the Benefit-cost ratio from 0.06 to 0.55, indicating an improvement in the economic status of the system. Further up-scale to 500 L can be recommended with a pre-treatment stage of the effluent to ensure efficient conversion of organic content into biogas and minimum operating cost.

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