Techno-Economic Analysis on the Lab-scale Integrated Anaerobic Photomagnetic System

Sydney Mandla Khanyile, Emmanuel Kweinor Tetteh and Sudesh Rathilal

***Abstract*— This study presents a techno-economic analysis (TEA) of an innovative 5L lab-scale Integrated Anaerobic Photomagnetic System (IAPMS), which integrates anaerobic digestion (AD) and advanced oxidation processes for wastewater treatment and biogas production. Key economic indicators, such as Net Present Value (NPV) and Simple Payback Period (SPP), were used to assess technological viability. Simulated performance showed that IAPMS significantly outperformed the lab-scale system, achieving 94.74% chemical oxygen demand (COD) removal and a biogas yield of 710.53 mL/(gCOD), compared with 75% COD removal and 51 mL/(gCOD) in the lab-scale system. The optimised system also operated with a longer hydraulic retention time (21 days vs. 10 days) and enhanced its energy potential. Environmentally, the optimised IAPMS demonstrated an energy efficiency ratio of 2.15, which was higher than that of a standalone AD system (1.32). Economically, the AD system showed a negative NPV (-R9 903.53), while the optimised system indicated strong viability with a positive NPV (R145 548.56) and a payback period of less than 5 years. These findings support IAPMS as a promising waste-to-energy solution that can foster sustainability, environmental stewardship, and innovation. The system has strong potential for scale-up, integration with other green technologies, and application in the decentralised, resource-limited water sector.**

***Keywords*—Anaerobic Digestion, Biogas Production, Optimisation, Techno-Economic Analysis, Wastewater.**

I. Introduction

Access to safe drinking water has become a pressing global issue, with over 40% of the world's population affected and approximately 700 million people lacking access to clean water [1]. This challenge is primarily attributed to climate change, increasing living standards, and rapid population growth. The growing global population has placed a significant strain on municipalities, making it increasingly challenging to meet the rising demand for freshwater, surpassing the available supply [2].The surge in population and industrialisation has also contributed to the depletion of energy resources, freshwater scarcity, and increased anthropogenic CO_2 emissions [3, 4]. A study by Hube, Eskafi [5] reported that the world population stood at 7.7 billion in 2019 and is projected to grow to approximately 9.7 billion by 2050. Notwithstanding, the global community faces interconnected crises of energy and water scarcity, driven by population growth, urbanisation, and climate change. These pressures have intensified wastewater management challenges while placing urgent demands on the energy sector to shift toward renewable sources. Addressing these dual challenges aligns with several United Nations Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 13 (Climate Action).

Alternative solutions, such as wastewater treatment and seawater desalination, have been explored to address freshwater scarcity [6]. In recent years, researchers have investigated various methods for treating wastewater (WW) to enable its reuse while simultaneously addressing energy consumption challenges[7]. Anaerobic Digestion (AD) has emerged as a widely used process for wastewater treatment, offering the dual benefits of water purification and biogas production. The biogas generated through AD can be used as an energy source, making it a sustainable option for addressing both water scarcity and energy demands [8].

Traditionally, the Anaerobic Digestion (AD) process has been widely used to treat wastewater (WW) and produce biogas. However, with the growing population and advancements in technology, emerging contaminants (ECs) such as hair products, antibiotics, pesticides, and pharmaceutical residues are increasingly being introduced into wastewater streams (WWS) [9]. These contaminants, along with environmental challenges posed by wastewater, have driven global efforts to develop energy-efficient wastewater treatment (WWT) systems capable of addressing these issues [3, 4].

The conventional AD process alone is insufficient for fully treating wastewater containing ECs. Studies by [10] have shown that recalcitrant contaminants, such as antibiotics, can persist in wastewater treatment plant (WWTP) streams even after prolonged treatment. This has prompted the water sector to focus on enhancing WWTP efficiency. To address this limitation, an integrated AD-advanced oxidation process (AOP) photomagnetic system is proposed for wastewater treatment. AOP is a well-established technology recognised for its effectiveness in removing recalcitrant contaminants that conventional methods cannot eliminate [11].

To evaluate the feasibility of this system, a comprehensive techno-economic analysis (TEA) will be conducted. The TEA will involve a comparative assessment of the lab-scale AD-

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AOP photomagnetic system with similar technologies reported in the literature. It will also include a cost-benefit analysis comparing the costs of the lab-scale system to simulated processes using literature data. This approach will provide valuable insights into the economic and technical viability of integrating AOP into advanced wastewater treatment processes.

II. Materials and Methods

The study was carried out using a systematic approach, starting with the design and setup of a lab-scale AD system that treated wastewater under controlled conditions to produce biogas. The effluent from the AD system was further treated using AOP to remove emerging contaminants and enhance water quality. Key performance metrics, including hydraulic retention time (HRT), organic loading rate (OLR), and chemical oxygen demand (COD) removal, were measured in both the AD and AOP systems to assess overall system efficiency. Fig. 1 shows a representation of the AD-AOP simulation system, created using an Excel tool. The input parameter ranges used for the simulation were carefully selected based on a literature study. These ranges were chosen to evaluate the performance of the anaerobic digestion (AD) and advanced oxidation process (AOP) system under realistic operating conditions.

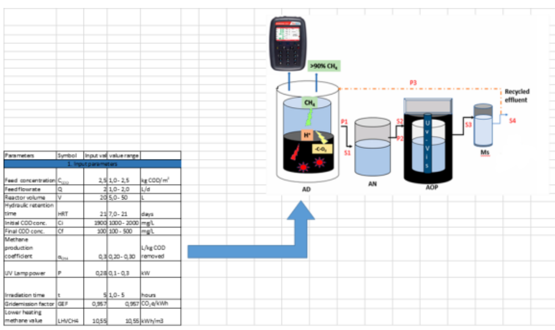

Fig. 1. Optimised AD-AOP Simulation layout and input parameter table

By basing the input ranges on established literature data, the study ensured the simulation and experimental conditions were grounded in validated benchmarks. This approach enabled a comprehensive evaluation of the AD-AOP system's performance, ensuring comparability with existing research findings and thereby enhancing the study's relevance and applicability [2, 12, 13]. This provided a procedure for conducting a cost-benefit analysis, including equations to calculate equipment costs. A statistical tool, such as Excel and ORIGIN, was used to present the results using graphing tools for straightforward interpretation and comparison of the two systems.

III. Results and Discussion

Table I presents a summary of the performance metrics results between a lab-scale system and an optimised simulation in the context of wastewater treatment. The optimised simulation demonstrates a Hydraulic Retention Time (HRT) of 21 days, which is more than twice that of the lab-scale system's 10 days. This results in a substantially higher Organic Loading Rate (OLR) of 0.250 kg COD/L, compared to 0.0025 kg COD/L in the lab-scale system. The increase in HRT and OLR is associated with a marked enhancement in Chemical Oxygen Demand (COD) removal efficiency, achieving 94.74% in the optimised simulation, compared with 75% in the lab-scale system. These results are consistent with recent studies that underscore the significance of extended HRT and optimised OLR in improving COD removal efficiencies in wastewater treatment processes.[14].

Energy recovery parameters demonstrate significant advancements: electrical energy recovery (Ebio) increased to 7.496 kWh/L, while the unit energy use (Euv) decreased to 0.055 kWh/L in the optimised simulation, indicating enhanced energy efficiency. The efficiency ratio (β) exhibits a substantial improvement, increasing from 1.32 to 2.15 in the optimised system.

Biogas production increased significantly, from 51 mL/g COD.d in the laboratory system to 710.526 mL/g COD.d in the optimised scenario. This notable enhancement in biogas yield underscores the potential of optimised systems to enhance resource recovery from wastewater treatment processes, as supported by recent studies on biogas production optimisation [15]. Overall, these findings illustrate the superior performance of the optimised system, highlighting its potential scalability and efficacy for industrial applications.

TABLE I: Summary of results

Description	Units	Lab-scale	Simulation
Hydraulic retention time (HRT)	Days	10	21
Organic loading rate (OLR)	kg COD/L.d	0.0025	0.25
COD removal	%	75	94.74
Electricity per biomass (Ebio)	kWh/kgCOD	0.50	7.50
Energy utilisation (Euv)	kWh/kgCOD	0.15	0.06
Efficiency ratio	β	1.32	2.15
Biogas produced	mL/g COD.d	51	710.53

A. Assessment of capital expenditure and operational costs

Table II below presents the capital and operational expenditures for the lab-scale and up-scale simulated AD systems. The cost includes buying equipment such as AD PVC tanks, a pump, controller components, sensors (pH, ORP, Gas analyser), and chemicals to synthesize the catalyst, as well as installation. The capital for the simulation was based on the upscale factor method for each equipment purchased. The operating costs were calculated based on the system’s monthly electricity usage, using South Africa’s average household electricity tariff of R3.29 per kWh.

TABLE II:

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SUMMARY OF CAPITAL AND OPERATIONAL EXPENDITURE FOR THE LAB-SCALE AND SIMULATION SYSTEM

System description	CAPEX (Rands)	OPEX/yr (Rands)
5L Lab-scale	R260, 869.15	R10, 366.50
20L Simulation	R950, 475.50	R87, 703.21

B. Evaluating the Net present value (NPV) and Cashflow

Table III shows the net present value (NPV) and cash flows for the lab-scale and simulated systems. In investment cycles, NPV is expressed as the sum of the future cash flows. Simultaneously. It is computed to determine the difference between project income and cash inflows or project costs and cash outflows [16]. By evaluating the projected financial returns from the investment and converting these future earnings into present-day currency, one can determine the project's viability and assess whether it justifies the investment. This approach aligns with engineering principles and maintains an academic rigour while ensuring clarity and accessibility [17]. With the system's lifespan set to 30 years and a discount rate of 5%, the lab-scale system demonstrated a negative net present value (NPV) and cash flow, indicating an unfavourable investment. Conversely, the simulated system exhibited positive NPV and cash flow trends, indicating that the project's viability warrants consideration from both engineering and academic perspectives. Equations 1 and 2 were used to calculate the NPV and the cash flow.

$$NPV = \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} - C_o \qquad (1)$$

Cashflow = Annual revenue – Operating cost (2)

TABLE III:
SUMMARY OF THE NET PRESENT VALUE AND ANNUAL CASH FLOW FOR THE LAB-SCALE AND SIMULATION SYSTEM

System description	NPV (Rands)	Cashflow (Rands)
5L Lab-scale	-R9 903.53	-R10 398.71
20L Simulation	R145 548.56	R152 825.98

Table IV presents the annual energy production and revenue generated for both systems, calculated using Equations 3 and 4, considering South Africa's average household electricity tariff of R3.29 per kWh. Using the downward displacement cylinder method, the biogas generated was collected and analysed using a gas analyser for the methane content. The optimised simulation system achieved a high energy output of 19,603.03 kWh, resulting in a higher revenue stream of R240,529.20 than the lab-scale system.

Annual energy production = biogas (m^3) x Net energy value x HRT (3)

Annual revenue = Annual energy production (kWh/yr) x electricity price (R/kWh) (4)

TABLE IV:
SUMMARY OF THE ANNUAL REVENUE AND ENERGY PRODUCTION FOR THE LAB-SCALE AND SIMULATION SYSTEM

System description	Annual Energy Production (kWh)	Annual Revenue (Rands)
5L Lab-scale	15.77	R59.29
20L Simulation	19, 603.03	R240, 529.20

C. Evaluating the Payback period (PBP)

The cost-benefit analysis and payback period for the two scenarios were assessed to determine the time it would take for both systems to start generating revenue exceeding the capital expenditure. Fig. 2 shows the cost-benefit and payback period analyses for the lab-scale AD system with a 30-year project lifespan, highlighting the payback period. The analysis depicted in Fig. 2 shows that the cash flow increases slowly but does not reach the level of operating costs over the 30-year project lifespan. This was due to lower biogas production, which could not be converted into revenue. As a result, the payback period exceeded the project's duration because the break-even point was not reached.

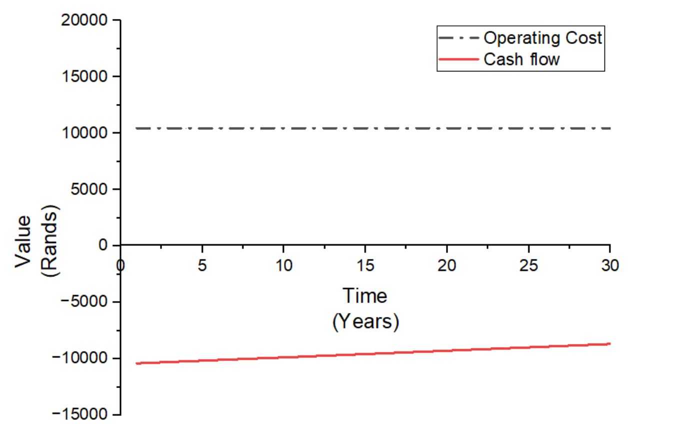

Fig. 2 Cost-benefit and Payback period analysis for the lab-scale AD system

In Fig. 3, the cash flow increases significantly. It reaches break-even in less than 5 years, clearly illustrating the time required for the system to pay back the initial investment in the optimised simulation. Equation 5 is used to calculate the payback period. After year 5, the system starts generating actual profit, which continues until the system's lifespan reaches year 30. This analysis highlights the importance of process optimisation in AD systems. System optimisation ensures higher revenue generation.

Payback period = Initial investment/ Annual revenue (5)

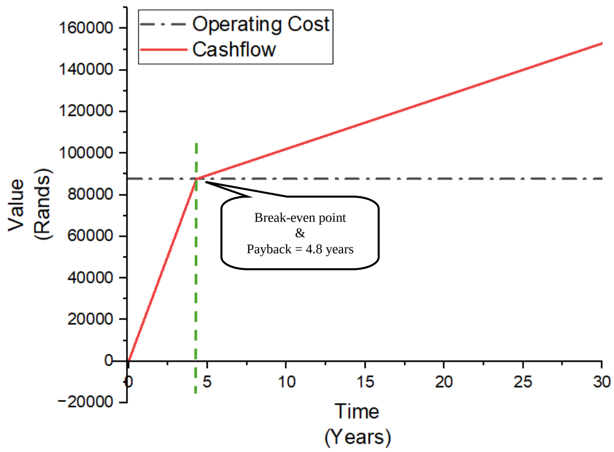

Fig. 3 Cost-benefit and Payback period analysis for the optimised AD Simulation system

IV. Conclusion

This study evaluated the techno-economic feasibility of a lab-scale anaerobic digestion (AD) system integrated with an advanced oxidation process (AOP) for wastewater treatment and energy recovery. The results demonstrated that the lab-scale AD-AOP system achieved a COD removal efficiency of 75%, while the optimised simulation significantly improved this to 94.74%. Biogas production also increased dramatically in the optimised system, with rates improving from 51 mL/gCOD.d to 710,526 mL/gCOD.d, highlighting the system's potential for enhanced energy recovery.

The economic analysis revealed that while the lab-scale system failed to achieve profitability within 30 years, the optimised simulation demonstrated a positive net present value (NPV) and a short payback period of less than five years (n = 4.8 years).

These findings highlight the importance of optimisation in improving both the environmental and economic performance of wastewater treatment systems. This study successfully met its objectives by demonstrating the feasibility of integrating AD and AOP technologies for wastewater treatment, identifying key performance improvements through optimisation, and providing actionable insights for scaling these systems for industrial applications. The results emphasise the potential of such systems to address global water and energy challenges sustainably.

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