Life Cycle Assessment of a Lab-Scale Anaerobic Digestion-Advanced Oxidation System for Wastewater Treatment

Thashrik Pirthiraj*, Emmanuel Kweinor Tetteh, Nhlanhla Phillipa Nkosi, Sudesh Rathilal

***Abstract*— This study explored the environmental impact of a wastewater treatment system that combines anaerobic digestion with an advanced oxidation process (AD-AOP) for sustainable wastewater treatment and methane-rich biogas production. A life cycle assessment (LCA) was used to quantify and evaluate the system's environmental footprint and treated water using a local sugar refinery effluent (SRE) feedstock. Results of the LCA demonstrated that the SRE contributed most to ecological impacts, including global warming (50.3%) and ecotoxicity (60.2%). The electricity demand was also found to have a significant effect, provided the system can generate energy for its reusability. The AD-AOP system has the potential to address multiple developmental challenges by converting wastewater to safe, usable water, generating clean energy, and supporting climate goals.**

***Keywords*—Biogas production, Climate change, Environmental impact, Life cycle assessments, Wastewater treatment**

I. Introduction

South Africa is facing an extreme energy and water crisis, made worse by the lack of adequate existing infrastructure and climate change. Due to the increase in population with agricultural and industrial activity, wastewater treatment plants (WWTPs) are unable to meet with the rising demand, meaning that they would need to evolve to keep up with this increase and meet environmental standards [1]. A direct consequence of this is poorly treated water that can affect nearby water and bring harm to the environment and people within the area. The World Health Organization (WHO) stated that over 2.4 billion people do not have access to adequate water and sanitation facilities, further showing the importance of establishing efficient wastewater collection and treatment systems [2]. Anaerobic digestion (AD) is a possible solution, providing biogas while treating wastewater. This biogas can be used as a clean-burn alternative energy source, which may relieve pressure on more traditional sources, such as coal or oil. These systems are required to ensure the health and safety of people and the environment, but they are lacking in rural and township areas where they are needed the most.

South Africa's energy mix mainly consists of coal and oil, both known to be high-emission fossil fuels that add to global warming, justifying the need to shift towards cleaner, more environmentally sustainable sources of energy [3]. Biogas obtained from the anaerobic digestion of organic matter within wastewater may act as a substitute in maintaining the balance of both current and future energy systems as a nearly carbon-neutral energy source [4, 5]. The global population is expected to reach 9.7 billion by 2050, raising concerns about water scarcity and energy depletion worldwide. These issues are already widespread in developing and underdeveloped nations, such as South Africa [6]. By 2050, more than 6 billion people worldwide will face some form of water scarcity, underscoring the need for sustainable wastewater treatment plants (WWTPs). WWTPs can address both water scarcity and waste management issues by providing water for industrial processes and irrigation, thereby diverting freshwater to sanitation and drinking needs. This also protects the environment by reducing pollutants that could enter water systems [7].

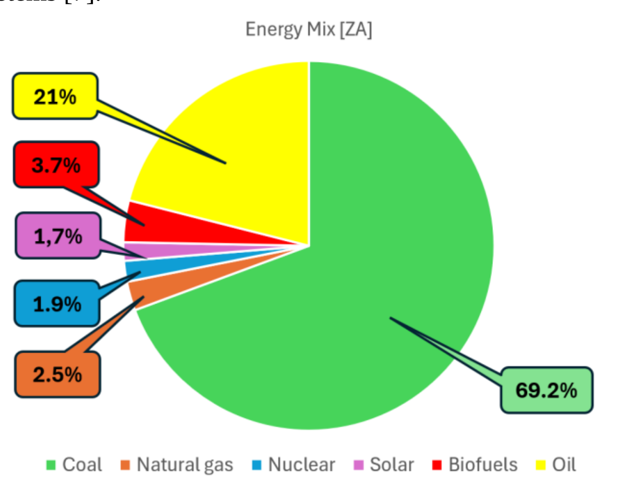

Fig. 1: Total energy supply (TES) for South Africa in 2023

A life cycle assessment (LCA) is a tool used to analyze the potential environmental impacts of a process or product throughout its life cycle. The concept of the LCA was introduced in the late 1960s to measure the energy consumption and needs of industrial processes, which eventually changed to involve waste production, water use, and a variety of environmental impacts [8]. The modern version of the LCA was proposed by the Society of Environmental Toxicology and

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Chemistry and included in the ISO 14000 Environmental Management Standards. The current ISO 14040 and 14044 standards define an LCA as a method for compiling and analyzing the inputs, outputs, and potential impact of a product throughout its lifetime [9]. LCAs provide comprehensive analyses of the environmental impacts of processes by measuring the effects across all stages of a system's life cycle. While laboratory studies provide an understanding of different treatment methods, they may not fully consider variables involved with real-life implementation, especially in regions like South Africa, which has limited infrastructure [10]. Performing an LCA is crucial for highlighting the region's specific environmental impacts, given its socioeconomic and ecological setting.

Anaerobic digestion (AD) is defined as the decomposition of organic waste material in the absence of oxygen. The process converts the organic waste into biogas, mainly consisting of methane and carbon dioxide [11]. It is a slow conversion consisting of four phases: hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

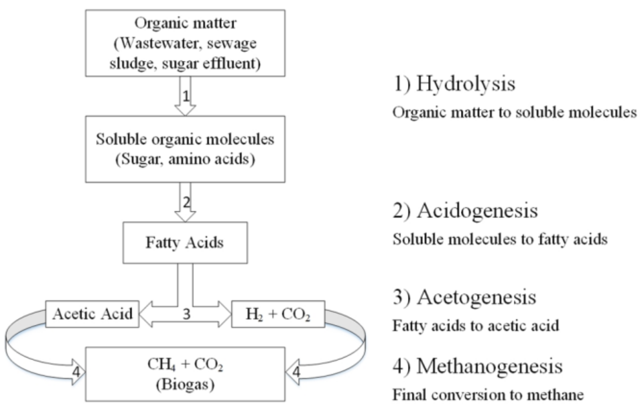

Fig. 2: Anaerobic digestion mechanism

Advanced oxidation process (AOP) is a chemical treatment that uses oxidation to break down recalcitrant contaminants in wastewater. AOPs generate highly reactive hydroxyl radicals that break down organic matter into more biodegradable components that have a lower potential for adverse environmental effects.

The foundation of the AD-AOP system involves both anaerobic digestion and advanced oxidation processes. Anaerobic digestion is a biological process that decomposes organic material in an oxygen-free environment, yielding biogas (primarily methane) and a digestate by-product. The biogas production rate depends on COD levels in the feedstock, as organic content directly influences microbial activity and biogas output. [12]. COD, measured in mg/L, serves as an indicator for the availability of organic matter. AOPs, on the other hand, involve oxidation to degrade pollutants that are resistant to biological breakdown. In AD-AOP systems, AOP typically follows anaerobic digestion to target any remaining contaminants. This step improves water quality by breaking down recalcitrant molecules that anaerobic digestion may not entirely remove, enhancing the final effluent's usability for non-potable purposes [13]. In terms of LCA, several studies have detailed environmental assessment methodologies for wastewater systems. The standardized phases include the goal and scope definition, inventory analysis, impact assessment, and interpretation [14]. This systematic approach ensures a thorough evaluation of environmental impacts, from raw materials to post-treatment stages.

II. Methodology

A. Goal and scope

The main goal of this study is to analyze the environmental effects of feedstock, sugar effluent, sewage sludge, and wastewater, and the biogas produced within the AD-AOP system. The functional unit was defined as 0.1887 kg of biogas produced per 10 kg of feedstock. This study takes a cradle-to-gate approach, beginning with analyzing the collection of feedstocks as they are created and ending after biogas production. This study aligns with several United Nations Sustainable Development Goals (SDGs), such as SDG 6 (clean water and sanitation) through wastewater treatment, SDG 7 (affordable and clean energy) through biogas production, and SDG 12 (responsible consumption and production) by reducing greenhouse gas emissions compared to conventional treatment methods and its stand-alone feedstock.

B. Inventory analysis

The inventory analysis was conducted using data from previous studies on the AD-AOP system, which were then imported into SimaPro. Each input and output is selected from the Ecoinvent 3.0 database.

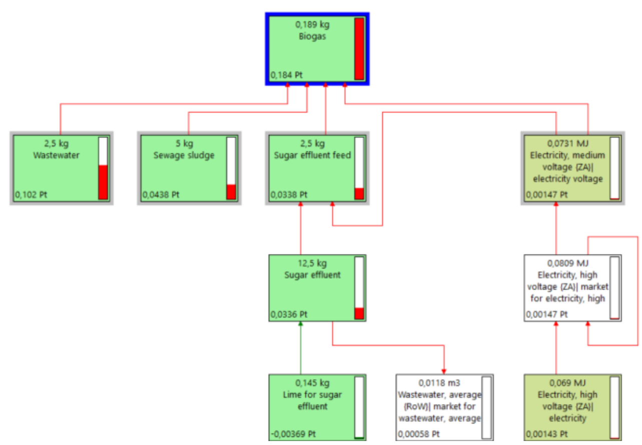

Fig. 3: Network diagram listing the inputs for the AD-AOP system

C. Impact assessment

The LCA was performed in SimaPro software, version 9.6.0.1. This assessment allowed for the analysis of the AD-AOP system, and in the determination of the various environmental impacts. For the impact assessment, the ReCiPe Endpoint method was used to determine the environmental impacts of the system. The Hierarchist perspective was used to gauge the environmental impact of the AD-AOP system over a mid- to long-term period, ranging from 100 to 1000 years in SimaPro. The perspective assumes that any environmental damage can be reversed with effective policy management.

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TABLE I: SCOPE OF ENDPOINT IMPACT CATEGORIES FOR LIFE CYCLE ASSESSMENT

Impact category	Impact category	Units (endpoint)
Ecosystems	Stratospheric ozone depletion	species.yr
	Ozone formation	species.yr
	Terrestrial acidification	species.yr
	Freshwater eutrophication	species.yr
	Marine eutrophication	species.yr
	Terrestrial ecotoxicity	species.yr
	Freshwater ecotoxicity	species.yr
	Marine ecotoxicity	species.yr
Human Health	Global warming	DALY
	Water consumption	DALY
	Resource scarcity	DALY
Resources	Mineral resource scarcity	USD2013
	Fossil resource scarcity	USD2013

D. *Interpretation*

The interpretation of the results was intended to identify the effects of the sugar effluent, wastewater, and sewage sludge feedstock, as well as the produced biogas, on the impact categories shown in Table 1.

III. Results and Discussion

A. *Results*

TABLE II: QUANTIFIED ENDPOINT IMPACT ASSESSMENT OF AD-AOP SYSTEM

Impact category	Unit	Biogas	Sugar effluent feed	Carbon dioxide
Global warming	DALY	0,0000928	0,000200795	-4,52841E-08
Stratospheric ozone depletion	DALY	0	3,10694E-06	-4,34712E-12
Ozone formation	DALY	0	6,14495E-08	-5,93144E-11
Fine particulate matter formation	DALY	0	5,11484E-05	-3,27847E-08
Terrestrial acidification	species.yr	0	1,37508E-07	-2,1395E-11
Freshwater eutrophication	species.yr	0	1,37218E-08	-9,567E-12
Marine eutrophication	species.yr	0	7,10197E-11	-4,33657E-15
Terrestrial ecotoxicity	species.yr	0	1,08202E-09	-5,07652E-12
Freshwater ecotoxicity	species.yr	0	5,00876E-10	-1,53812E-12
Marine ecotoxicity	species.yr	0	1,0613E-10	-3,19089E-13
Human carcinogenic toxicity	DALY	0	0,00000506	-2,28958E-08
Human non-carcinogenic toxicity	DALY	0	7,50156E-06	-1,00369E-08
Mineral resource scarcity	USD2013	0,635970058	2,266093164	-3,55113E-05
Fossil resource scarcity	USD2013	0	0,713511307	-0,002082453
Water consumption	DALY	0	0,000145997	-3,24373E-10

Table 2 shows the quantified impacts of each of the components within the AD-AOP system. The positive values show the environmental impact of the components within the scope, while the negative values show the impact of the avoided products, such as the digestate and carbon dioxide emissions.

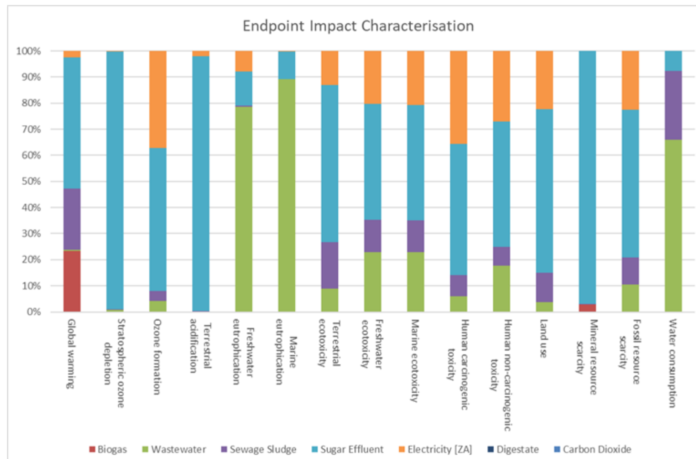

Fig. 4: Characterization of endpoint impact categories

B. *Discussion of results*

Global Warming—Figure 3 shows the impact of global warming on human health, with the major contributors being sugar effluent feed, sewage sludge, and biogas, accounting for 50.3%, 23.4%, and 23.3%, respectively. Sugar effluent, which is rich in organic materials, is the main driver for the production of biogas, and thus has the highest GWP. The significance of the global warming impact result in figure 3 highlights the relative contributions of the different inputs to greenhouse gas emissions.

Stratospheric Ozone Depletion—Figure 3 shows that sugar effluent feed accounts for almost all (98.9%) stratospheric ozone depletion. This is due to the characteristics and processing steps associated with sugar byproducts, such as sugar effluent. The biogas generated has a minimal impact on stratospheric ozone depletion compared to sugar effluent, as it is commonly used as a clean, sustainable energy source with low emissions. Sewage sludge has a minimal impact on ozone depletion because it is stable and partially decomposed before entering the biogas process.

Terrestrial Acidification—The terrestrial acidification impact category refers to substances that may be released into the environment to acidify soil. Acidifying compounds, such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia

(NH_3), can deposit onto soil through processes like rainfall or direct deposition. Sugar effluent had the most tremendous impact in this category, accounting for 54.9% of the terrestrial acidification potential. Electricity from the South African grid is the second-largest contributor, accounting for 37.1% of the impact. The other feeds, biogas, wastewater feed, and sewage sludge feed, contribute much less to terrestrial acidification due to their lower content of nitrogen and sulphur compounds relative to sugar effluent feed.

Eutrophication (freshwater and marine)—The freshwater and marine eutrophication impact categories assess the potential of nutrient-rich compounds, particularly nitrogen and phosphorus, to cause nutrient enrichment in aquatic ecosystems. Wastewater contributes the most to both freshwater (78.5%) and marine eutrophication (89.1%) because it typically contains high concentrations of nitrogen and phosphorus compounds from organic matter, fertilizers, and industrial chemicals. Other feeds, such as sugar effluent, biogas, and sewage sludge, contribute far less to eutrophication due to their lower concentrations of bioavailable nitrogen and phosphorus.

Ecotoxicity (terrestrial, freshwater and marine)—The Terrestrial, Freshwater, and Marine Ecotoxicity impact categories evaluate the potential of toxic substances to harm various ecosystems. Grid electricity contributed 13.2% to the ecotoxicity impact for the same reasons discussed previously. The sugar effluent feed contributes the highest share to terrestrial ecotoxicity, at 60.2%, due to its high organic content and residual chemicals from sugar processing. Sewage sludge feed contributes 17.8% to terrestrial ecotoxicity. Sewage sludge contains various contaminants, including heavy metals such as cadmium, chromium, and zinc, as well as pharmaceuticals from human waste streams. Wastewater feed, which contributes 18.87% to terrestrial ecotoxicity, is another significant contributor and can contain industrial chemicals, detergents, and heavy metals, depending on its source. Biogas does not affect terrestrial ecotoxicity because it consists of methane (CH_4) and carbon dioxide (CO_2), which are non-toxic to soil ecosystems. Freshwater and marine ecotoxicity measures the effect of pollutants on freshwater and marine environments. The freshwater and marine ecotoxicity impacts in the biogas production process are primarily driven by grid electricity (20.3%), sugar effluent feed (44.4%), sewage sludge feed (12.4%), and wastewater feed (23%). Electricity contributed more to marine/freshwater ecotoxicity (20.3%) than to terrestrial ecotoxicity (13.2%). The sugar effluent feed remains the most significant contributor to both freshwater and terrestrial ecotoxicity, but its impact is lower in freshwater ecotoxicity (44.4%) than in terrestrial ecotoxicity (60.2%). Sewage sludge feed has a similar effect on both marine/freshwater (12.4%) and terrestrial ecotoxicity (17.8%), although its contribution to freshwater ecotoxicity is somewhat reduced. Wastewater feed contributes more heavily to freshwater ecotoxicity (23%) than terrestrial ecotoxicity (18.87%).

IV. Conclusion

The study underscores the significant impact of wastewater management and biogas production on global health, environmental sustainability, and resource management. The LCA highlights that the sugar effluent feed had the most important ecological impact across most of the impact categories, especially with respect to GWP, ozone depletion, acidification, and ecotoxicity. Its high organic content and processing byproducts introduce significant greenhouse gases, ozone-depleting substances, and acidifying compounds into the biogas production process. The effluent's nutrient-rich nature further contributes to eutrophication and ecotoxicity, underscoring its role as the primary driver of overall environmental impacts in biogas production.

Recommendations include implementing targeted measures to reduce the environmental impact of sugar effluent feed. Improved treatment of the effluent before it is introduced into the system could help mitigate specific ecological effects. Additionally, optimizing biogas production systems to handle sugar effluent more effectively could lower emissions and pollutant discharge, aligning the process with environmental sustainability goals.

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References

[1] Aziz, N.I.H.A. and M.M. Hanafiah, *Life cycle analysis of biogas production from anaerobic digestion of palm oil mill effluent.* Renewable Energy, 2020. 145: p. 847–857. https://doi.org/10.1016/j.renene.2019.06.084

[2] Adhikari, S. and R.U. Halden, *Opportunities and limits of wastewater-based epidemiology for tracking global health and attainment of UN sustainable development goals.* Environment international, 2022. 163: p. 107217. https://doi.org/10.1016/j.envint.2022.107217

[3] Obaideen, K., et al., *Biogas role in achievement of the sustainable development goals: Evaluation, Challenges, and Guidelines.* Journal of the Taiwan Institute of Chemical Engineers, 2022. 131: p. 104207. https://doi.org/10.1016/j.jtice.2022.104207

[4] Rafiee, A., et al., *Biogas as an energy vector.* Biomass and Bioenergy, 2021. 144: p. 105935. https://doi.org/10.1016/j.biombioe.2020.105935

[5] Mutezo, G. and J. Mulopo, *A review of Africa's transition from fossil fuels to renewable energy using circular economy principles.* Renewable and Sustainable Energy Reviews, 2021. 137: p. 110609. https://doi.org/10.1016/j.rser.2020.110609

[6] Tetteh, E.K., *Wastewater treatment and photo-reduction of CO2 using an integrated magnetized TiO2 anaerobic- photocatalytic system*. 2022. p. 313.

[7] Balboa, S., et al., *The fate of SARS-COV-2 in WWTPS points out the sludge line as a suitable spot for detection of COVID-19.* Science of The Total Environment, 2021. 772(12): p. 145–268. https://doi.org/10.1016/j.scitotenv.2021.145268

[8] Liu, M., G. Zhu, and Y. Tian, *The historical evolution and research trends of life cycle assessment.* Green Carbon, 2024.

[9] Amahmoud, A., M.M. El Attar, and A. Meleishy. *The evolution of life cycle assessment approach: a review of past and future prospects*. in

IOP Conference Series: Earth and Environmental Science. 2022. IOP Publishing. https://doi.org/10.1088/1755-1315/992/1/012002

[10] Ragazzo, P., et al., *Wastewater disinfection: long-term laboratory and full-scale studies on performic acid in comparison with peracetic acid and chlorine.* Water Research, 2020. 184: p. 116169. https://doi.org/10.1016/j.watres.2020.116169

[11] Uddin, M.M. and M.M. Wright, *Anaerobic digestion fundamentals, challenges, and technological advances.* Physical Sciences Reviews, 2023. 8(9): p. 2819–2837. https://doi.org/10.1515/psr-2021-0068

[12] Patel, R.K., et al., *Treatment of sugar processing industry wastewater using copper electrode by electrocoagulation: Performance and economic study.* Journal of the Indian Chemical Society, 2022. 99(8): p. 100563. https://doi.org/10.1016/j.jics.2022.100563

[13] Silva, F.B., et al., *Primary data priorities for the life cycle inventory of construction products: focus on foreground processes.* The International Journal of Life Cycle Assessment, 2020. 25(6): p. 980–997. https://doi.org/10.1007/s11367-020-01762-4

[14] Bishop, G., D. Styles, and P.N.L. Lens, *Environmental performance comparison of bioplastics and petrochemical plastics: A review of life cycle assessment (LCA) methodological decisions.* Resources, Conservation and Recycling, 2021. 168: p. 105451. https://doi.org/10.1016/j.resconrec.2021.105451

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