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| RESEARCH ARTICLE

A Comprehensive Economic Feasibility of Biogas Production from Co-digestion of Sisal Processing Waste and Cow Manure: A Case of Kilifi Sisal Plantation

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| ABSTRACT

This paper evaluates the economic feasibility of biogas production and operational challenges at the Kilifi Sisal Plantation, focusing on substrates such as cow manure, sisal pulp, mango waste, and sisal bole. The research provides a cost-benefit analysis, revealing cow manure, costing KES 258 per ton, as the most cost-effective substrate, followed by Sisal Pulp from KPL at KES 139.8 per ton. Mango waste and sisal bole, with costs of KES 670 per ton and KES 3661 per ton, present higher financial barriers respectively. The Kilifi biogas plant utilizes a fixed-dome system, producing approximately 395 m^3 of biogas daily from cow dung and sisal pulp. While the system generated KES 312,000 over 10 years from energy savings and fertilizer production, the plant faces key challenges, including the inability to meet the 250KW grid connection capacity, which leads to unsold excess electricity, and high operational costs amounting to KES 3,187,254 annually. The small-scale biodigester's Net Present Value (NPV) is KES 2,301.14, and the Payback Period (PBP) is approximately 6.3 years. To enhance profitability, the study recommends optimizing feedstock management, expanding the plant's grid connection capacity to meet national requirements, and investing in technological upgrades, such as automating the feeding system and improving energy efficiency. Additionally, the study recommends regular maintenance and training, implementation of wastewater recycling, and undertaking lifecycle and economic assessment in order to identify cost-saving opportunities and the plant's long-term sustainability.

| KEYWORDS

Agricultural Waste, Biomass, Anaerobic digestion, Renewable energy, Emerging Energy technology, Sustainable Approach

| ARTICLE INFORMATION

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1. Introduction

The economic feasibility of biogas production from agricultural waste has attracted increasing attention in recent years due to its potential to address critical challenges in energy security, environmental sustainability, and waste management (Weiland, 2010; Holm-Nielsen et al., 2009). Among the various biomass sources available, mango waste, cow dung, and sisal residue stand out for their abundance, high methane potential, and compatibility with anaerobic digestion systems. This paper evaluates the economic prospects of biogas production from these three substrates, considering their biochemical properties, availability, and potential contribution to sustainable development goals.

Biogas production offers a promising approach to transforming agricultural residues into renewable energy while mitigating waste disposal issues (Kaparaju et al., 2013). Mango waste, particularly peel and pulp discarded during post-harvest processing, is rich in carbohydrates and organic matter, making it an excellent substrate for anaerobic digestion. Studies have shown that mango waste has a high biochemical methane potential (BMP), attributable to its easily degradable sugars and fiber content (Gunaseelan, 2004; Kumar et al., 2018). Given the seasonal abundance of mangoes in tropical regions and the high volumes of waste generated, this biomass presents an economically viable input for decentralized biogas systems.

Cow dung, on the other hand, is a readily available by-product of livestock farming, especially in rural and peri-urban areas of developing countries. It contains a rich community of microorganisms that play a critical role in enhancing the anaerobic digestion process. When used as a co-substrate, cow dung can significantly improve the stability and efficiency of biogas systems by buffering pH levels and supplying essential microbial populations (Gerben, 2015; Mshandete et al., 2004). In addition to energy production, cow dung has long been recognized for its value as an organic fertilizer, contributing to improved soil fertility and agricultural productivity (Hammond et al., 2018). The integration of cow dung into biogas production thus supports circular economy principles and sustainable farming practices (Daniyan, 2019).

In light of global efforts to reduce greenhouse gas (GHG) emissions, utilizing agricultural waste such as mango residues and cow dung for biogas production aligns with international climate goals. The Intergovernmental Panel on Climate Change (IPCC) has emphasized the need to reduce GHG emissions by more than half to combat climate change and global warming (IPCC, 2012). Furthermore, Sustainable Development Goal (SDG) 7 aims to increase the share of renewable energy in the global energy mix to at least 30% by 2030 (World Bank, 2019). These commitments underscore the urgency of developing decentralized and sustainable energy solutions in agriculture-based economies.

Sisal waste, another underutilized agricultural residue, also offers immense potential for biogas production. Sisal (Agave sisalana), a drought-resistant crop of the Agavaceae family, is cultivated primarily for its strong fiber used in cordage products such as ropes and mats. The global sisal industry, with roots tracing back to its introduction in East Africa in the late 19th century, particularly Tanzania and Kenya, continues to generate significant amounts of lignocellulosic waste during fiber extraction (FAO, 2013; Muthangya et al., 2013). This waste, often discarded or burned, can instead serve as a feedstock for biogas systems when pretreated or co-digested with more readily degradable substrates such as cow dung. Studies have demonstrated that sisal residues can contribute to bioenergy generation and improved waste management when integrated into anaerobic digestion systems (Gosens et al., 2013).

The sisal plant has a lifespan of 7-10 years and produces approximately 200-250 commercially usable leaves. Each leaf contains approximately 1000 fibers. Fibers account for only about 4% of the plant's weight. Sisal is classified as a tropical and subtropical plant because it thrives in temperatures above 25 degrees Celsius and in sunlight. Decortication is a process in which leaves are crushed, beaten, and brushed away by a rotating wheel equipped with blunt knives, leaving only fibers. Alternatively, in East Africa, where production is typically concentrated on large estates, the leaves are transported to an essential decortication plant, where water is utilized to remove the waste parts of the leaf (Bond & Templeton, 2011). The sisal leaf decoration residue is one of the most common agro-industrial residues in East Africa. Only 2.7 - 7.3% of sisal leaf decortications produce hard fiber, which is used for a variety of purposes depending on the age of the plant and the efficiency of the decortication process; the remaining 97.3 - 92.7% consists of solid waste (mucilage) and waste liquid (sisal juice), which are typically discarded (Christiaensen & Heltberg, 2014). These wastes are unattended, disposed of, and, in most cases, burned, dumped in bodies of water, and/or landfilled; such practices are unsustainable and contribute to environmental pollution.

Tanzania was the world's third-largest producer of sisal fiber in 2011, after Brazil and China, with approximately 35,000 tonnes produced (FAO 2012), earning the country foreign exchange through exports. Production is increasing, and in 2016, the country was reported to earn USD 20.6 million from sisal fiber and product imports. Nonetheless, sisal fiber production is a high waste process that currently uses only 2% of the plant, with the remaining 98% biomass being various fractions of wastes. Sisal processing wastes include Sisal Leaf Decortications Wastes (SLDW), which are a combination of pulp and residual fiber, short fibers (flume tow), wastewater, and sisal dust. The industry also produces post-harvest waste (SPHW), which consists of sisal stems comprising of boles and leaf remnant stubs and poles. Therefore, sisal waste is a threat to the environment; previous studies have shown that it can be transformed into high-value commodities and thus should be regarded as a bioresource rather than a waste (Marie et al., 2024; Daher et al, 2023; Amsalu et al., 2024) . Potential high-value commodities from sisal waste include but are not limited to biofuels, foam liquid (cement foaming substance that enlarges sand and cement mixture), organic acids, composite, low-calorie dietary fibers, functional foods, sweeteners, thickeners in ice creams, sandwich spreads, chocolate products, breads pastries, fine and green chemicals (Elisante & Msemwa, 2010; Vijayan et al., 2022).

Sisal is a valuable renewable resource that can contribute to climate change mitigation efforts. Throughout its lifecycle, sisal absorbs more carbon dioxide than it produces. Sisal processing produces bioenergy, animal feed, fertilizer, and ecological housing materials. It is also completely biodegradable at the end of its life cycle (FAO, 2019). Sisal residues have significant energy potential, but are currently underutilized globally (UNEP, 2009). Kenya, as one of the world's largest sisal producers, offers an excellent opportunity to demonstrate the feasibility of generating energy from sisal leftovers. Sisal demand has increased by 3% per year, with current production at around 26,000 tons per year, with 80% coming from big farms in Kenya (Yurtoglu, 2018).

Therefore, the combination of mango waste, cow dung, and sisal residue offers a strategic approach to enhancing biogas production economically and sustainably (Gunaseelan, 2004; Hammond et al., 2018; Mshandete et al., 2004). These feedstocks not only address waste disposal and environmental degradation (Kumar et al., 2018; Gosens et al., 2013), but also provide a decentralized solution to rural energy needs (Amigun, Sigamoney, & Von Blottnitz, 2008). To fully harness the economic and environmental benefits of agricultural waste for biogas production, the adoption of biodigester technology is essential(IPCC, 2012). Biodigesters provide a controlled environment for anaerobic digestion, enabling efficient conversion of organic waste such as mango peels, cow dung, and sisal residue into biogas and nutrient-rich slurry (World Bank, 2019; SNV, 2019). The technology supports decentralized energy solutions, particularly in rural and peri-urban areas, reducing reliance on fossil fuels and enhancing energy access (Amigun, Sigamoney, & Von Blottnitz, 2008). Moreover, modern biodigester designs have evolved to accommodate mixed feedstocks and variable organic loading rates, which enhances process stability and biogas yields (Kossmann et al., 1999). The adoption of biodigesters aligns with national and global strategies promoting clean energy and sustainable waste management. In Kenya, initiatives under the Kenya Biogas Program and similar projects across Sub-Saharan Africa have demonstrated that small- and medium-scale biodigesters are both technically feasible and economically viable for households and institutions (SNV, 2019). Therefore, integrating biodigester technology into agricultural systems that generate substantial organic waste holds great promise for supporting circular economy models and contributing to SDG 7 on affordable and clean energy.

Barriers to biodigester adoption include low awareness and education, high installation and maintenance costs, inconsistent feedstock availability, and limited infrastructure. Moller et al. (2004) and Lantz et al. (2007) found that 2.40 kg of cow dung can produce 0.41-0.82 m3 of biogas per day. Using bovine manure for biogas production instead of direct cooking reduces CO2 emissions from 67.70 kg to 64.08 kg per 1000.0 kg of manure (Saha et al., 2022). Biogas plants save 3.62 kg of CO2 per day by processing 1000.0 kg of dung. According to Bahauddin and Salahuddin (2012), installing biogas facilities could reduce global CO2 emissions by 127,593,150 kg per day. According to a recent report by Ali et al. (2020), livestock and slaughterhouses in Pakistan produce approximately 18,464 kg of dung per day. Despite sisal waste and cow dung availability in Kilifi, biogas production has not been widely explored as a viable economic solution.

1.1 Problem Statement

Research has explored biogas production from agricultural residues and livestock waste, emphasizing its environmental and energy potential. Mburu et al., (2017) and Muthoni et al., (2019) evaluated the potential of sisal waste as a feedstock. While these studies have laid the groundwork for understanding the environmental benefits and technical feasibility of biogas production from these waste materials, special attention to critical economic aspects, such as capital investment, operational costs, and profitability, is yet to be fully explored. Studies rarely provide a comprehensive economic feasibility analysis of combining sisal waste and cow dung for biogas production in a rural Kenyan context, particularly at Kilifi Sisal Plantation. This gap in research limits the practical application of biogas technology in rural communities, where economic sustainability is just as important as environmental benefits. This study plays a key role in filling this gap by focusing on the economic feasibility of combining sisal waste and cow dung for biogas production in Kilifi, providing a comprehensive assessment of the financial viability of this approach for local stakeholders and contributing to the development of sustainable energy solutions in rural Kenya.

1.2 Justification of the Study

Biogas is a clean and sustainable energy source that offers a promising solution to waste management, particularly for agricultural and livestock residues such as sisal waste and cow dung (Ochieng et al., 2018). Production of biogas is gaining traction because it is easy to operate and has a wide feedstock selection. Due to increasing prices of electricity, energy demand, and the evolution of the world economy, biogas production is considered a cost-effective, proven technology, allowing simultaneous waste management and energy production as the fourth largest energy source for the world. Furthermore, these organic materials not only reduce environmental pollution but also provide an alternative energy source, contributing to both energy security and waste management (Wang et al., 2020).

1.3 Objectives

The following objectives guided the study:

i. To evaluate the economic costs associated with biogas production from sisal and cow dung from large and small-scale biodigesters.
ii. To contrast the operational challenges associated with biogas production from co-digestion of sisal processing waste and cow dung from large and small-scale biodigesters.

1.4 Theoretical Framework

The study revolved around the fundamentals of Circular Bio-Economy Theory, outlining the importance of resource efficiency and waste valorization (Stahel, 2016; Ellen MacArthur Foundation, 2015). This theory was introduced by McDonough and Braungart (2002) with their "Cradle to Cradle" concept. This study explores the conversion of sisal waste and cow dung, often seen as agricultural by-products, into biogas for energy and digestate for organic fertilizer. This process mitigates environmental pollution and waste management and boosts productivity (Nzila et al., 2012). The study reinforces this approach, showing that biogas systems in agro-industrial environments enhance energy security and economic benefits. Utilizing the principles of Circular Economy Theory, this study contributes to the fact that biogas production serves as both an environmentally sustainable and economically feasible solution for the Kilifi Sisal Plantation following Kenya's renewable energy goals (Government of Kenya, 2018).

2. Research Methodology

The study employed a mixed-methods approach, using qualitative and quantitative research approaches. The study was conducted at Kilifi Plantation Biogas Plant. The Biogas plant lies at coordinates 3°39'41''S, 39°51'45''E. The amount of feedstock produced is estimated using the Residue-to-Product Ratio (RPR) (Koopmans & Koppejan, 1998). The necessary feedstock production data were derived from the feasibility study. Semi-structured interviews and consultations with key respondents were conducted to gather qualitative information on project context, implementation, results, and impacts. The primary data was collected through Key Informant Interviews (KIIs). Secondary data was obtained by systematically reviewing annual reports and other archival documents at the Kilifi Plantation biogas plant. Environmental and other experts were consulted for more information and guidance. Categories were derived, and the highlighted statements were coded by assigning a category to them. Data analysis was conducted using R statistical software and Microsoft Excel 2019.

3. Study Results

3.1 Availability of substrate for biogas production

Table 1: Availability of biogas substrates and their cost

Substrate	Value cost (KES/t	Collection cost (KES/t)	Transport cost (KES.t)	Pre-Treatment cost (KES/t)	Total Cost (KES.t)
Cow manure	0.00009	258	0	0	258.00009
Sisal Pulp KPL	0	133	6.8	0	139.8
Sisal Pulp rea Vipingo	0	133	93	0	226
Mango Waste	0	67	340	263	670
Sisal Bole KPL	3000	133	34	494	3661
Sisal Bole Rea Vipingo	3000	133	93	494	3720
Molasses	6000	67	3333	231	9631

Findings in Table 1 show that cow manure emerges as the most cost-effective option, with a total cost of 258.00009 KES/t. A collection cost of 258 KES/t primarily drives this, while transport and pre-treatment costs are negligible, making it a highly economical choice. Sisal Pulp from KPL follows closely, with a total cost of 139.8 KES/t. It has a moderate collection cost of 133 KES/t and a low transport cost of 6.8 KES/t, while pre-treatment costs are zero, which makes it affordable. Sisal Pulp from Rea Vipingo is slightly more expensive at 226 KES/t, primarily due to a higher transport cost of 93 KES/t, but the collection cost remains the same at 133 KES/t. Mango Waste incurs significantly higher costs, with a total of 670 KES/t, due to its high transport cost of 340 KES/t and pre-treatment cost of 263 KES/t, making it less cost-effective than Sisal Pulp.

Sisal Bole from KPL and Rea Vipingo are the most expensive substrates, with total costs of 3661 KES/t and 3720 KES/t, respectively. Both have high-value costs of 3000 KES/t, significant pre-treatment costs of 494 KES/t, and transport costs of 34 KES/t for KPL and 93 KES/t for Rea Vipingo. These high costs make them unfeasible for cost-effective biogas production.

Finally, Molasses is the most expensive option, with a total cost of 9631 KES/t. This is due to its high-value cost of 6000 KES/t, a transport cost of 3333 KES/t, and a pre-treatment cost of 231 KES/t, making it the least feasible substrate for biogas production. Subsequently, while substrates like cow manure and Sisal Pulp KPL offer the most affordable options with costs of 258 KES/t and 139.8 KES/t, respectively, others like Sisal Bole and Molasses are less suitable due to their higher costs. Prioritizing cost-effective substrates will maximize biogas production efficiency at the Kilifi Sisal Plantation.

Table 2: Frequency of feeding substrates to the bio-digester

Substrate available at KPL	Amount (t/day)	Frequency of feeding	Volume fed
Cow manure	2	Daily	2
Sisal Pulp KPLS	24	daily	12
Sisal Pulp Rea Vipingo	15		
Mango Waste	7.4	3 times a week	
Sisal Bole KPL	10.36		
Banana Waste	0.26		
water		weekly	8500

Table 2 displays the amount, frequency, and volume of different substrates available at the Kilifi Sisal Plantation (KPL) for biogas production. Cow manure is fed daily, with an amount of 2 tons/day, and the volume fed is 2 tons per day, thus a consistent, daily input of this substrate for biogas production. Sisal Pulp KPLS is the largest volume substrate available, with 24 tons/day fed daily, contributing 12 tons of volume daily. Therefore, the Sisal Pulp from KPL is a highly available substrate for daily feeding, supporting continuous biogas production. Sisal Pulp from Rea Vipingo is fed less frequently, with 15 tons/day. The results further show that mango waste, which is fed 3 times a week, has a feeding volume of 7.4 tons/day, although it is provided less frequently, making it a less constant substrate input compared to daily-fed options. Sisal Bole from KPL is available at 10.36 tons/day, and banana waste is the most minor substrate in terms of volume, with 0.26 tons/day fed regularly. Water is fed weekly with a volume of 8500 liters, supporting the need for hydration in the biogas production to maintain the biogas system's function.

3.2 Large-scale Sisal Waste and Cow-Dug Biogas Cost-Benefit Analysis

Figure 1: Kilifi sisal plantation anaerobic digester

Figure 1 illustrates the fixed-dome biodigester utilized in Kilifi Sisal Production. The anaerobic digester is frequently employed to generate biogas from organic waste. The digester possesses an inner diameter of 15.4 meters, yielding a net volume of 750 cubic meters (m^3) and a gross volume of roughly 850 m^3. It provides a gas storage capacity of 350 cubic meters. The biodigester comprises a tank, typically constructed from concrete or metal, including a stationary, dome-shaped roof intended to retain the biogas generated during the anaerobic breakdown of organic substances, including animal manure, food waste, and agricultural byproducts. This method utilizes microbes to decompose trash in an anaerobic environment, producing biogas, predominantly methane, and carbon dioxide.

The gas is gathered at the apex of the dome and can be utilized for heating purposes, electrical production, or heating. A solid waste outlet at the base expels digested sludge, which may be utilized as fertilizer. The fixed-dome design provides stability, durability, and efficiency, rendering it suitable for large-scale biogas generation and facilitating sustainable waste management while supplying an alternative energy source. The fixed-dome biogas digester contains organic waste combined with water, occupying approximately 80% of its volume, while the remaining 20% is allocated for biogas storage. Biogas collects in the dome-shaped upper part when anaerobic bacteria decompose organic materials. The gas pressure propels the slurry into a compensating chamber. Gas pressure escalates with the volume contained, affecting gas flow and consumption. Therefore, this biogas system exemplifies a practical approach to managing agricultural waste while generating renewable energy, which contributes to environmental sustainability and energy efficiency at the Kilifi Sisal Plantation.

3.2.1 Cost analysis of small-scale biogas

Table 3 contain the results of cost analysis for the biodigester system for several key financial elements required for its operation. The initial investment of KES 98,000,000 is a significant upfront cost for setting up the system. Over the 20-year lifespan, the system is expected to generate annual revenues of KES 23,696,967, with annual maintenance costs of 3,187,254 KES and additional expenses for repairs of KES 1,100,000, replacement of KES 2,053,000 KES, and gas measurement of KES 2,126,850. The total depreciation cost of KES 354,475 KES reflects the decrease in the system's value over time. The biogas unit has been operating for the past 17 years; the system is expected to recoup the initial investment, generating consistent cash flow while covering operating costs. The 9% discount rate was used to calculate the present value of the investment and ensure that future cash flows are adjusted to the present value. Despite the high initial cost, the system appears financially sustainable, offering a return on investment if managed effectively, particularly by addressing ongoing maintenance, repair, and replacement needs.

Table 3: large-scale biogas cost analysis

Item	Cost per unit
Initial investment	98,000,000
Annual maintenance	3,187,254
Total depreciation	354,475
Repair cost	1,100,000
Replacement cost	2,053,000
Gas measurement cost	2,126,850
Cashflow yearly	23,696,967.635
Operation years	17
Discount rate	9%
Lifespan	20

3.2.2 Economic Benefit Analysis of Large-Scale Biogas System

Findings in Table 4 on the economic viability of biogas production at the Kilifi Sisal Plantation show that a Net Present Value (NPV) of KES 27,453,640 is positive, indicating a significant surplus of value over the system's lifespan, thus confirming its financial viability. The Internal Rate of Return (IRR) of 12.05% is higher than the discount rate of 9%, signifying that the project is profitable, though just meeting the required return threshold. The Return on Investment (ROI) of 273.81% indicates that, over the 20-year lifespan, the project will generate returns 2.74 times the initial investment, making it highly profitable. The Payback Period (PBP) is estimated to be 9 years, denoting that the initial investment will be recovered within this time frame, with an additional 11 years of net profit. Finally, the Benefit-Cost Ratio (BCR) of 1.28 shows that the benefits outweigh the costs, making the project financially feasible. Therefore, the biogas production at Kilifi Sisal Plantation is both economically viable and feasible, offering a significant return on investment while providing long-term financial benefits.

Table 4: Large-scale biogas benefit analysis

Economic Metric	Value
Net Present Value (NPV)	27,453,640
Internal rate of return (IRR)	12.05%
Return on Investment (ROI)	273.81
Payback Period (PBP)	9 years
Benefit-Cost Ratio (BCR)	1.28

3.3 Small-scale cow dung biogas cost-benefit Analysis

A comparative analysis of small-scale biogas units was conducted to evaluate their economic viability, facilitating a greater understanding of which unit provides the most cost-effective energy production solution. Elements such as initial investment, maintenance expenses, and prospective returns were assessed for successful comparative analysis. The study findings are presented next.

Figure 2: Small scale- Home-based biogas unit

Figure 2 illustrates a flexible plastic biodigester designed for domestic biogas production. It is frequently selected for its cost-effectiveness and simplicity of installation thus appropriate for rural areas. The biodigester uses organic waste, such as kitchen leftovers, animal waste, and other biodegradable substances. When the waste undergoes anaerobic digestion, it decomposes, generating methane gas and bio-slurry. Methane gas is retained at the up part of the biodigester and can be used for cooking, diminishing reliance on conventional fuel sources such as wood or LPG. The bio-slurry serves as a good organic fertilizer for farming.

3.3.1 Cost analysis of small-scale biogas

Table 5: Small-scale biogas

Item	Cost per Unit
Initial investment	KES 108,000
Initial material cost	KES 6500
Amount of waste and water fed every 2 days	120 kg of cow dung and 50 liters of
Energy saving	Saves KES 400 every week
Produces fertilizer worth	KES 200 every week
Lifespan is 10 years	10 years
Discount rate	9%

Table 5 shows that a small-scale biodigester requires an initial investment of KES 108,000 and material costs of KES 6,500 for setup. It processes 120 kg of cow dung and 50 liters of water every two days, producing biogas for energy use and fertilizer. The system saves KES 400 weekly on energy costs, which translates to KES 20,800 annually. Over its 10-year lifespan, this amounts to KES 208,000 in energy savings. Additionally, the biodigester generates fertilizer worth KES 200 weekly, or KES 10,400 annually, leading to a total of KES 104,000 in fertilizer value over the same period. The energy savings and fertilizer production total KES 312,000 over 10 years, making the biodigester a cost-effective solution, providing both environmental and financial benefits.

3.3.2 Economic Benefits Analysis of Small-Scale Biogas

Results in Table 6 show that the biodigester indicates that it is financially viable but offers a modest return on investment. The Net Present Value (NPV) of KES 2,301.14 is slightly positive, meaning the biodigester generates a small surplus of value over its 10-year lifespan, making it financially viable. The Internal Rate of Return (IRR) is 9.46%, slightly above the discount rate of 9%, indicating that the biodigester barely meets the required return threshold and is marginally profitable. The Energy Return on Investment (EROI) is 58.95%, meaning that over the 10 years, the biodigester returns just under 60% of the initial investment cost, representing a moderate return. The Payback Period (PBP) is 6.3 years, meaning it takes approximately 6.3 years to recover the initial investment, and after that, the system starts generating a net profit, estimated at 3.7 years. The Benefit-Cost Ratio (BCR) is 1.01, which indicates that the benefits slightly outweigh the costs, but the project is essentially breaking even. Therefore, while the biodigester offers a financial return, it is only marginally profitable, with moderate returns and a long payback period.

Table 6: Benefit analysis of Small-scale biogas

Economic Metric	Value
Net present value (NPV)	KES. 2,301.14
Internal rate of return (IRR)	9.46
Energy Return on Investment (EROE)	58.95%
Payback Period (PBP)	6.3 years
Benefit-Cost Ratio (BCR)	1.01

3.4 Challenges facing biogas production

Findings from Key informant interviews show that biogas production faces multiple challenges that affect its efficiency and economic sustainability. A comparative analysis was done to compare the large-scale and small-scale biogas units and results are presented in Table 7.

Table 7: Comparative analysis of challenging facing Small-Scale and Large-Scale biogas production

Challenges	Small Scale	Large Scale	Rank of Impact
Feedstock Availability and Expense	Variable feedstock availability, higher transportation and pre-treatment costs	More consistent feedstock supply, but high cost of transportation and pre-treatment for diverse feedstock	High impact on efficiency and profitability due to inconsistent feedstock and high costs
Grid Connection Capacity	Limited grid connection unlikely to reach high output capacity due to smaller infrastructure	Unable to achieve 250KW capacity, leading to unutilized excess power and lost revenue potential	Moderate impact; small scale may not be as affected by grid capacity issues
Operational Costs	Lower operational costs but higher per-unit feedstock costs due to limited economics of scale	Higher operational costs due to the scale of the operation	Moderate to high impact; higher costs at large scale due to economies of scale but can benefit from higher output
Capital for Enhancements	Minimal capital requirements, but often face difficulty in acquiring resources for upgrades.	Significant capital investment required for upgrades	Moderate impact; large scale needs more capital but has better access to resources and credit
Manual Feeding System	Manual feeding is common, leading to inefficiencies and labor costs	Manual feeding mechanisms lead to inefficiencies, especially for high quantities of feedstock	High impact on operational efficiency due to manual feeding system
Equipment Maintenance and Knowledge	Reliance on basic maintenance skills, often without specialized knowledge of complex systems	Complex equipment requires expert maintenance knowledge; external help is often necessary.	High impact due to the need for specialized skills and external support
Salinity and Proximity to Sea	Less impacted by salinity, as smaller operations are usually not located near the sea	High exposure to saltwater damage from proximity to the sea, leading to higher wear and tear, resulting in increased replacement costs	High impact: salt damage can lead to high costs in both small and large-scale operations

4. Conclusion

The cost-benefit analysis of biogas production shows that substrates like cow manure and sisal pulp from KPL offer cost-effective options; others, such as molasses and sisal bole, are less feasible due to high costs. The availability and cost of feedstock remain challenging, with seasonal materials such as mango waste adding extra expenses due to transport and pre-treatment. The fixed-dome biogas system at the plantation provides a sustainable way to generate renewable energy and manage waste, but it faces operational inefficiencies. These include the inability to meet grid connection requirements, resulting in unsold excess electricity, and high operational costs for substrate handling and maintenance. Moreover, the need for significant upgrades, such as replacing the digester liner and purchasing gas measurement tools, adds to the financial strain. The long payback period of 6.3 years for small-scale biodigesters further emphasizes the need for better management of feedstock and energy consumption. Therefore, this study concludes that despite the challenges, the potential for biogas production remains strong, as it offers significant long-term financial benefits and contributes to sustainable energy solutions. Therefore, overcoming these operational challenges will be crucial for optimizing the economic viability and efficiency of biogas systems in the future.

4.1 Recommendations

Based on the study results, the following recommendations are drawn to enhance the economic feasibility and functional ability of biodigester units:

Table 8: Recommendations for large- and small-scale biogas unit

Small Scale	Large Scale
Diversify feedstock, source locally available materials to reduce costs	Implement large-scale feedstock pre-treatment systems, source diverse feedstocks to ensure consistent supply
Use a small-scale, locally relevant grid connection and focus on energy independence	Upgrade infrastructure to meet national grid capacity, ensuring revenue from surplus electricity
Use cost-effective and simple automated systems, such as DIY kits for small biogas units	Invest in advanced technology like automated feeding systems and real-time monitoring systems
Implement basic energy-saving measures, use biogas for cooking or lighting	Invest in advanced energy management systems to optimize the energy output and reduce waste
Conduct local training programs to empower community members in biogas system maintenance	Provide professional training for maintenance staff, develop partnerships with local technicians for specialized support
Focus on the community aspect, integrate with other sustainable practices like farming	Invest in capital for system upgrades and ensure financial sustainability through government incentives or subsidies

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