Proceedings of the 7th African International Conference on Industrial Engineering and Operations Management
Cape Town, South Africa, May 13-15, 2026

Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/AF07.20260231
Published: May 13, 2026

Comparative Life Cycle Assessment of Bagasse-to-Energy Conversion Pathways for Sustainable Power Generation

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Abstract

Sugar industries generate significant quantities of bagasse as a by-product of sugarcane processing, offering substantial potential for renewable energy generation. However, in many developing countries, including Kenya, bagasse utilization remains largely confined to low-efficiency combustion systems, limiting both energy recovery and environmental performance.This study presents a comparative Life Cycle Assessment (LCA) of four bagasse-to-energy conversion pathways: direct combustion with cogeneration, gasification, pyrolysis, and anaerobic digestion. The analysis is based on a functional unit of 1 MWh of electricity generated and follows ISO 14040/14044 standards within a cradle-to-grave system boundary. Primary operational data were obtained from Kibos Sugar and Allied Industries Ltd, including cane processing capacity, bagasse generation rates, and cogeneration performance, while secondary data for alternative technologies were sourced from peer-reviewed literature.The study integrates factory-level process analysis, defining key inputs, outputs, and environmental impact points across each conversion pathway. Performance evaluation was conducted using key indicators, including energy efficiency, CO_2 emission intensity, and resource utilization. Results indicate that gasification achieves the highest energy efficiency (approximately 55%), while pyrolysis exhibits the lowest CO_2 emissions (0.705 kg CO_2/kWh). Combustion systems show moderate performance but higher emissions, whereas anaerobic digestion demonstrates lower efficiency with favorable environmental outcomes. The findings highlight the mportance of transitioning from conventional combustion to advanced conversion technologies to improve energy recovery and reduce environmental impacts. This study provides a process-based and data-driven framework for sustainable energy planning in biomass-rich sugar industries.

Keywords
Bagasse Energy, Life Cycle Assessment, Biomass Conversion, Renewable Energy, Sustainable Power Generation.

1. Introduction
Global energy demand continues to increase due to industrialization, population growth, and technological advancement, placing pressure on conventional energy systems and accelerating the transition toward sustainable energy sources. In Kenya, electricity demand has grown steadily, with national generation exceeding 14,000 GWh annually, highlighting the need for reliable and locally available energy resources. The sugar industry presents a significant opportunity in this transition due to the large volumes of bagasse generated during sugarcane processing. On average, 1 ton of sugarcane produces approximately 250–300 kg of bagasse, which can be used as a renewable fuel for heat and power generation. In industrial-scale sugar factories operating at capacities of 3,000–10,000 tons of cane

per day, bagasse represents a substantial energy resource capable of supporting cogeneration systems and contributing to grid electricity supply.

Traditionally, bagasse is utilized through direct combustion in boilers to produce steam for electricity generation and process heat. While this approach is widely adopted due to its simplicity and reliability, it is associated with relatively low energy efficiency (20–30%) and significant emissions. Advanced conversion technologies such as gasification, pyrolysis, and anaerobic digestion offer opportunities for improved energy recovery and reduced environmental impacts. These technologies convert bagasse into higher-value energy carriers such as syngas, bio-oil, and biogas, enabling more efficient and cleaner energy production.

1.2 Problem Statement

Despite the growing availability of bagasse within Kenyan sugar industries, its utilization remains largely limited to conventional low-efficiency combustion systems used for steam generation and internal factory operations. Although bagasse possesses significant potential as a renewable biomass resource for sustainable electricity generation, advanced conversion technologies such as gasification, pyrolysis, and anaerobic digestion remain largely underutilized within the Kenyan context.

Conventional combustion systems are associated with relatively low energy conversion efficiencies and increased greenhouse gas and particulate matter emissions. While advanced conversion pathways have demonstrated improved environmental and operational performance in other regions, there is limited comparative information regarding their sustainability performance under conditions relevant to the Kenyan sugar industry.

Additionally, most existing studies focus on individual conversion technologies rather than conducting integrated comparative analyses across multiple pathways using a standardized Life Cycle Assessment (LCA) framework. This limits the ability of policymakers, researchers, and industry stakeholders to identify the most sustainable bagasse-to-energy conversion option for industrial-scale implementation.

Therefore, there is a need for a comprehensive comparative Life Cycle Assessment of bagasse-to-energy conversion pathways to evaluate their environmental performance, energy efficiency, and sustainability potential for application within the Kenyan sugar industry.

1.1 Objectives

The main objective of this study is to comparatively evaluate the sustainability of bagasse-to-energy conversion pathways using a Life Cycle Assessment framework.
The specific objectives are:

2. To assess bagasse generation and energy utilization in a representative sugar industry
3. To define process-level inputs and outputs for selected conversion pathways
4. To evaluate and compare environmental impacts using LCA indicators
5. To analyze performance using key indicators such as efficiency and emissions
6. To identify the most sustainable conversion pathway for industrial application

2. Literature Review

2.1.1 Sugarcane Farming and Milling Performance Indicators

Sugarcane-to-energy systems are strongly influenced by agricultural and milling performance parameters, which determine both the quantity and quality of by-products available for energy conversion. These parameters are critical inputs in Life Cycle Assessment (LCA) as they directly affect resource efficiency, energy potential, and environmental impacts.

2.1.2 Sugarcane Farming Parameters

Key agricultural indicators include:

- Sucrose content (% cane): Typically, 10–16%, determines sugar yield
- Fiber content (% cane): Typically, 12–16%, directly influences bagasse production
- Cane yield (tons/hectare): Affects total biomass availability
- Moisture content: Influences processing efficiency

Higher fiber content increases bagasse availability for energy, while higher sucrose content improves sugar recovery but reduces energy residue (Table 1).

Table 1. Sugarcane Farming Parameters

Parameter	Typical Range	Significance
Sucrose content (% cane)	10–16%	Determines sugar yield; higher sucrose improves sugar recovery but reduces energy residue
Fiber content (% cane)	12–16%	Directly influences bagasse production; higher fibre increases bagasse availability for energy
Cane yield (tons/ha)	Varies by region	Affects total biomass availability for processing and energy generation
Moisture content (%)	Variable	Influences processing efficiency and energy conversion performance

2.1.3 Milling Performance Indicators

During processing, several factory performance indicators determine material flows:

- Bagasse fiber content: Indicates fuel quality
- Bagasse moisture content (typically 45–55%): Affects combustion efficiency
- Bagasse pol: Measures residual sugar in bagasse (energy loss indicator)
- Extraction efficiency: Efficiency of juice removal
- Molasses production: By-product from crystallization

These indicators define how efficiently cane is converted into sugar and how much usable biomass remains for energy generation (Table 2).

Table 2. Milling Performance Indicators

Indicator	Typical Value	Relevance
Bagasse fibre content (%)	Variable	Indicates fuel quality for combustion and energy recovery
Bagasse moisture content (%)	45–55%	Affects combustion efficiency; lower moisture improves energy output
Bagasse pol (%)	Variable	Measures residual sugar in bagasse — acts as an energy loss indicator
Extraction efficiency (%)	Variable	Determines efficiency of juice removal during milling process
Molasses production	By-product	Generated during crystallization; key feedstock for ethanol production

2.1.4 By-Products and Energy Pathways

Sugar processing produces multiple by-products with energy potential (Table 3):

Table 3. By-Products and Energy Pathways

By-Product	Energy Application / Pathway
Bagasse	Combustion, gasification, pyrolysis, anaerobic digestion, briquettes
Molasses	Ethanol production, biogas generation
Filter mud (press mud)	Biogas production, soil amendment

Bagasse is the primary energy source within sugar factories, while molasses plays a key role in bioethanol production. In countries such as Brazil, ethanol derived from molasses is blended with gasoline and regulated by national policy, representing a major alternative energy pathway.

2.2.1 Sugar Production and Bagasse Energy Potential

Sugarcane processing generates significant quantities of bagasse as a by-product during milling. On average, 1 ton of sugarcane produces approximately 250–300 kg of bagasse, depending on extraction efficiency. Bagasse has a lower heating value (LHV) of approximately 7–10 MJ/kg, making it a viable biomass fuel for industrial energy generation.

Industrial sugar factories typically operate at capacities ranging from 3,000 to over 10,000 tons of cane per day (TCD). At these scales, bagasse can support cogeneration systems producing approximately 20–60 kWh of electricity per tonne of cane. In advanced systems, surplus electricity is exported to the national grid. However, in Kenya, most sugar industries rely on conventional low-efficiency combustion systems, limiting energy recovery potential.

Key Calculation:
Bagasse yield = Cane processed (t/day) × Bagasse fraction (0.25–0.30).
Gross thermal potential = Bagasse mass (kg) × LHV (7–10 MJ/kg)
. Electricity output is governed by conversion efficiency of the chosen technology (Table 4).

Table 4. Estimated Bagasse Production and Hourly Feed Rates by Factory Capacity

Cane	Bagasse (kg/ton cane)	Daily Bagasse (tones/day)	Hourly Rate (t/h) 20 h/day	Annual (tones/year) @ 250 days
1,000	250 – 300	250 – 300	12.5 – 15.0	62,500 – 75,000
3,000	250 – 300	750 – 900	37.5 – 45.0	187,500 – 225,000
5,000	250 – 300	1,250 – 1,500	62.5 – 75.0	312,500 – 375,000
10,000	250 – 300	2,500 – 3,000	125 – 150	625,000 – 750,000

Assumptions: 20 operating hours/day; 250 operating days/year; bagasse yield 250–300 kg per tonne of cane crushed (Table 5).

Table 5. Gross Thermal Energy Potential from Bagasse by Factory Scale

TCD	Bagasse (kg/day	Gross Thermal Energy (MJ/day)	Gross Thermal Energy (kWh/day)	Thermal kWh per Tonne Cane
1,000	250,000 – 300,000	1,750,000 – 3,000,000	486,111 – 833,333	486 – 833
3,000	750,000 – 900,000	5,250,000 – 9,000,000	1,458,333 – 2,500,000	486 – 833
5,000	1,250,000 – 1,500,000	8,750,000 – 15,000,000	2,430,556 – 4,166,667	486 – 833
10,000	2,500,000 – 3,000,000	17,500,000 – 30,000,000	4,861,111 – 8,333,333	486 – 833

Energy calculation: E (MJ/day) = Bagasse (kg/day) × LHV (MJ/kg). Conversion: 1 MJ = 0.2778 kWh. LHV range 7–10 MJ/kg.

2.2.2 Sugar Factory Process and Energy Flow

The sugar production process is closely integrated with energy generation. Bagasse produced during milling serves as the primary fuel for energy systems within the factory. The process-based structure below forms the basis for Life Cycle Assessment by defining system boundaries and environmental impact sources.
The general sugar factory process includes the following stages:

- Cane milling — producing juice and bagasse
- Bagasse handling and preparation — conveying and moisture control
- Energy conversion — through one or more of the following pathways:

  - Combustion (steam generation)
  - Gasification (syngas production)
  - Pyrolysis (bio-oil, biochar, syngas)
  - Anaerobic digestion (biogas production)
- Energy utilization - electricity generation and process heat
- By-product management - ash, biochar, and digestate
- Emission release - CO_2 and particulate matter

2.2.3 Inputs and Outputs of Bagasse Conversion Systems

Bagasse-to-energy systems involve distinct inputs and outputs that determine environmental performance. These are essential for Life Cycle Inventory (LCI) development. The table below summarizes the material and energy flows associated with each major conversion pathway (Table 6).

Table 6. Life Cycle Inventory (LCI) Inputs, Outputs, and Environmental Impact by Conversion Pathway

Process	Inputs	Outputs	Environmental Impact
Combustion	Bagasse, air	Steam, CO_2, ash	High emissions; ash disposal required
Gasification	Bagasse, limited O_2	Syngas, tar	Lower emissions; tar management needed
Pyrolysis	Bagasse, heat (N_2 atmosphere)	Bio-oil, biochar, syngas	Low–moderate; biochar sequesters carbon
Anaerobic Digestion	Bagasse, microorganisms, water	Biogas (CH_4 + CO_2), digestate	Low emissions; pretreatment of lignocellulose required

This framework highlights how different technologies influence emissions, energy output, and resource use. Combustion, despite its simplicity, generates the highest CO_2 and particulate emissions. Anaerobic digestion, while biochemically complex, produces the lowest emission intensity. Pyrolysis offers the unique advantage of carbon sequestration through biochar production.

2.2.4 Bagasse-to-Energy Conversion Technologies

Combustion and Cogeneration

Combustion is the most widely used technology in sugar industries globally. It involves complete oxidation of bagasse to generate steam for power production. Conventional systems operate at thermal efficiencies of 20–30%, with higher emission loads depending on boiler performance and fuel moisture content.

In cogeneration configurations, high-pressure steam drives a turbine to produce electricity; exhaust steam is then used for processing heating. Net electricity export to the grid is possible only in high-efficiency plants, which remain rare in Kenya.

Gasification

Gasification converts bagasse into syngas (H_2, CO, CH_4, CO_2) through partial oxidation at temperatures of 700–1,000 °C. It offers higher conversion efficiencies of 40–60% and improved emission performance relative to combustion. However, gasification requires gas cleaning systems to manage tar formation and particulate entrainment.

Pyrolysis

Pyrolysis thermally decomposes bagasse in the absence of oxygen at temperatures of 300–700 °C, producing bio-oil, biochar, and non-condensable syngas. Energy efficiencies range from 35–55%. A notable environmental benefit is the production of biochar, which, when applied to soil, sequesters carbon over decadal timescales and improves soil fertility.

Anaerobic Digestion

Anaerobic digestion is a biochemical process in which microorganisms break down organic matter in the absence of oxygen, producing methane-rich biogas (55–70% CH_4). Due to the recalcitrant lignocellulosic structure of bagasse, mechanical or chemical pretreatment is required to improve digestibility. Conversion efficiencies typically range from 25–45%, with relatively low direct greenhouse gas emissions.

2.2.5 Performance Indicators and Benchmarks

To compare bagasse conversion pathways rigorously, three key performance indicators (KPIs) are employed across the literature: (i) energy conversion efficiency (%), (ii) CO_2 emission intensity (kg CO_2 per kWh of electricity generated), and (iii) resource intensity (kg biomass per kWh). Electricity output per tonne of cane is derived from the product of gross thermal energy and the applicable conversion efficiency (Table 7).

Calculation methodology for electricity output (kWh/t cane):
Step 1 — Bagasse yield: Y = 0.25 to 0.30 t bagasse / t cane.
Step 2 — Thermal energy: Eth = Y × LHV × 1000 / 3.6 (kWh/t cane).
Step 3 — Electrical output: Eel = Eth × η, where η is technology efficiency. Example for Gasification at 3,000 TCD (η = 0.50, LHV = 8.5 MJ/kg, Y = 0.275): Eel = 0.275 × 8.5 × 1000 / 3.6 × 0.50 = 324 kWh/t cane.

Table 7. Technology Performance Benchmark: Efficiency, Electricity Output, and CO_2 Emission Intensity

Technology	Efficiency (%)	Elec. Output (kWh/t cane)	CO_2 Intensity (kg/kWh)	Emission Rating
Combustion	20 – 30	20 – 60	~0.28 – 0.35	High
Gasification	40 – 60	60 – 120	~0.15 – 0.22	Moderate
Pyrolysis	35 – 55	50 – 100	~0.10 – 0.18	Low – Moderate
Anaerobic Digestion	25 – 45	35 – 80	~0.06 – 0.12	Low

These indicators provide a consistent benchmark framework for evaluating the results of this study. Technologies with higher efficiency and lower emission intensity are preferred from both an economic and environmental standpoint. Advanced systems (gasification, pyrolysis) significantly outperform conventional combustion, though at higher capital and operational complexity.

2.2.6 Research Gap

Despite extensive studies on individual technologies, the existing body of literature lacks integration across three critical dimensions: factory-level process data, life cycle inventory inputs and outputs, and comparative analysis across all major conversion pathways within a single analytical framework.

Additionally, Kenya-specific data on advanced bagasse conversion technologies remains scarce. The majority of published LCA studies draw on data from Brazil, India, or European contexts, where feedstock quality, energy infrastructure, and regulatory conditions differ substantially from those in Kenya (Table 8).

Table 8. Research Gap Analysis: Literature Limitations and Study Responses

Gap identified	Limitation in Literature	The study's response
No integrated factory-LCA model	Studies treat technologies in isolation	Combined factory process flow with LCI
Absence of Kenya-specific data	Data from Brazil, India, EU dominate	Primary data from Kenyan sugar mills
No cross-pathway comparative LCA	Individual tech assessments only	Comparative LCA across all 4 pathways
Limited KPI benchmarking	Inconsistent metrics across papers	Unified KPI framework: eff., CO_2, resource intensity

This study addresses these gaps by combining primary industrial data collected from operational Kenyan sugar mills with a comparative Life Cycle Assessment framework spanning all four major bagasse-to-energy conversion pathways. The integrated approach enables direct, like-for-like comparison of technologies under locally relevant conditions.

2.2.7 Conceptual Framework

The conceptual framework of this study is based on the relationship between bagasse generation, conversion technology, environmental performance, and sustainability outcomes. Sugarcane bagasse generated during milling serves as the primary biomass feedstock for the selected conversion pathways, namely combustion, gasification, pyrolysis, and anaerobic digestion.

Each conversion technology utilizes bagasse under different operational conditions, resulting in varying energy outputs, emissions, and by-products. The study evaluates these pathways using Life Cycle Assessment indicators including energy efficiency, CO_2 emission intensity, resource utilization, and environmental impact categories such as global warming potential and particulate matter formation.

The performance results obtained from each pathway are then integrated into a comparative sustainability assessment to determine the most suitable technology for sustainable power generation within the Kenyan sugar industry.

3. Methods

3.1 Research Design

The study adopted a comparative analytical research design based on Life Cycle Assessment (LCA) methodology to evaluate the environmental sustainability of four bagasse-to-energy conversion pathways: direct combustion with cogeneration, gasification, pyrolysis, and anaerobic digestion.
The assessment integrated process-level analysis, environmental impact evaluation, and sustainability performance comparison using operational and literature-based data.

3.2 Functional Unit

The functional unit used in this study was:

1 MWh of electricity generated

The functional unit provided a standardized basis for comparing environmental impacts and energy performance across all conversion pathways.

3.3 System Boundary

The study adopted a cradle-to-grave system boundary in accordance with ISO 14040 and ISO 14044 standards.
The system boundary included:

- Sugarcane processing
- Bagasse generation
- Transportation
- Feedstock preprocessing
- Energy conversion
- Electricity generation
- Emissions and by-product management

The assessment excluded infrastructure construction and end-of-life equipment disposal due to limited data availability.

3.4 Data Collection

The study utilized both primary and secondary sources of data.
Primary operational data were collected from Kibos Sugar and Allied Industries Ltd, including:

- Cane crushing capacity
- Bagasse generation rates
- Boiler performance
- Steam generation
- Electricity production
- Fuel consumption

Secondary data for gasification, pyrolysis, and anaerobic digestion systems were obtained from:

- Peer-reviewed journal articles
- Industrial reports
- Renewable energy databases
- Published Life Cycle Assessment studies

3.5 Life Cycle Inventory (LCI)

Life Cycle Inventory analysis involved quantification of material and energy flows associated with each conversion pathway.

The inventory included:

- Bagasse consumption
- Air and water inputs
- Energy output
- CO_2 emissions
- Ash generation
- Syngas production
- Bio-oil production
- Biogas generation
- Digestate and biochar production

3.6 Environmental Impact Assessment

Environmental impacts were evaluated using selected Life Cycle Assessment indicators including:

- Global Warming Potential (GWP)
- CO_2 emission intensity
- Acidification potential
- Particulate matter formation
- Resource intensity

The impact assessment enabled comparison of environmental burdens associated with each technology.

3.7 Key Performance Indicators (KPIs)

The major performance indicators evaluated in this study included energy efficiency, CO_2 emission intensity, and resource utilization.

Energy Efficiency

$$\eta = \frac{\text{Useful Energy Output}}{\text{Total Fuel Energy Input}} \times 100\%$$

Where:

- η = Energy conversion efficiency (%)

CO_2 Emission Intensity

CO_2 Emission Intensity

$$\boldsymbol{CO_{2\,intensity}} = \frac{\boldsymbol{m_{CO_2}}}{\boldsymbol{E_{electricity}}}$$

Resource Intensity

$$Resource\ Intensity = \frac{\text{Bagasse Consumption}}{\text{Electricity Output}}$$

3.8 Sustainability Index

An integrated sustainability index was used to compare the overall performance of the selected technologies.

$$SI = \sum(w_i X_i)$$

Where:

- SI = Sustainability Index
- wi = weighting factor
- Xi = normalized sustainability parameter

3.9 Data Analysis

The data collected was analyzed using comparative performance analysis and Life Cycle Assessment procedures. Graphical analysis and tabulated comparisons were used to evaluate:

- Energy efficiency
- Emission intensity
- Resource utilization
- Environmental impacts

The results were then used to determine the most sustainable bagasse-to-energy conversion pathway.

4. Data Collection

The study utilizes both primary and secondary sources of data. The researcher will gather primary data within the Kibos Sugar and Allied Industries Ltd in order to obtain data on the operations of the company in relation to bagasse production and energy generation systems. The secondary data will be acquired through peer-reviewed literature, renewable energy databases, and technical reports. The efficiency of the conversion, the emission of greenhouse gases, the emission of particulate matter, and the consumption of resources are considered as the key indicators to be use (Table 9 and Table 10).

5. Results and Discussion

5.1 Numerical Results

Table 9. Numerical Results

Technology	**Efficiency (%)**	**CO_2 (kg/kWh)**	**Resource Intensity**	**Sustainability Score**
Combustion	25	0.90	2.82	0.55
Gasification	55	0.75	1.92	0.82
Pyrolysis	45	0.705	2.35	0.78
Anaerobic Digestion	35	0.60	4.23	0.70

Table 10. Environmental Impact by Technology

Combustion Direct thermal oxidation	high	High	High
Gasification Partial oxidation / syngas	Moderate	Moderate	Low
Pyrolysis Thermal decomposition	Low	Low	Low

Anaerobic Digestion Biological decomposition	Lowest	Low	Very Low

5.2 Graphical Results

Figure 1 illustrates the comparative energy conversion efficiencies of the selected bagasse-to-energy technologies.

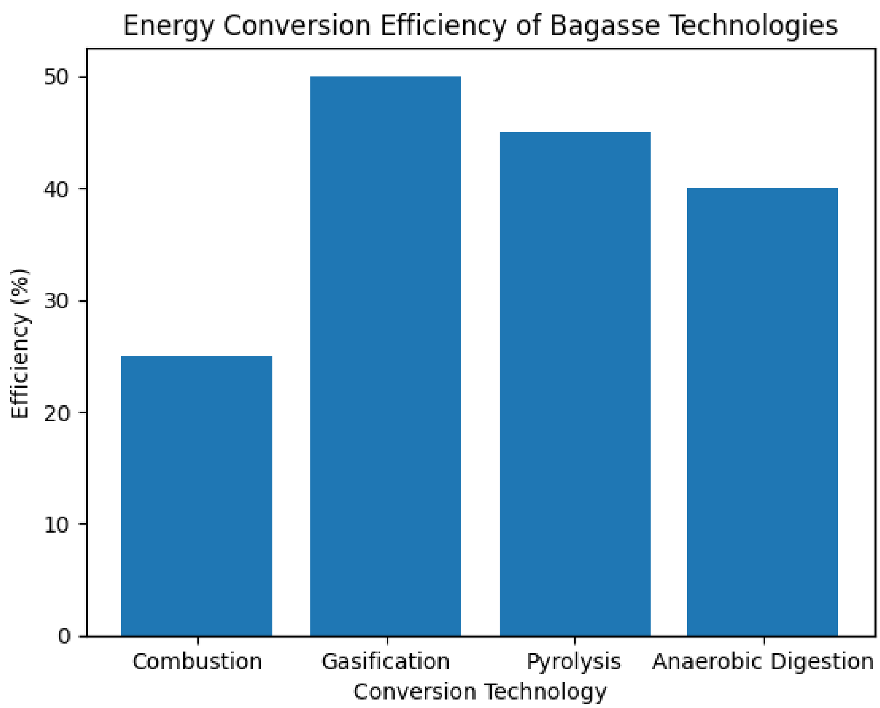

Figure 1. The comparative energy conversion efficiencies of the selected bagasse-to-energy technologies.

The performance of various bagasse-to-energy conversion technologies varies significantly in terms of energy efficiency and environmental impact. Combustion, the traditional method of directly burning bagasse to produce steam, exhibits relatively low efficiency (20–30%) and moderate emissions, reflecting inherent energy losses and pollutant generation. Gasification offers the highest energy efficiency (40–60%) by converting bagasse into syngas through partial oxidation, allowing for more complete and controlled combustion, and producing lower emissions compared to direct combustion. Pyrolysis thermally decomposes bagasse in the absence of oxygen, generating bio-oil, biochar, and syngas, with moderate efficiency (35–55%) and environmental impacts; the use of biochar can partially mitigate carbon emissions. Anaerobic digestion, a biochemical conversion process, produces methane-rich biogas (Li, 2012) with moderate efficiency (30–45%) but the lowest environmental impact, as methane is captured for energy and residual digestate can be used as fertilizer. Overall, the selection of an appropriate technology involves a trade-off between maximizing energy output and minimizing environmental emissions, with gasification favoring efficiency and anaerobic digestion prioritizing sustainability.

5.3 Proposed Improvements

A number of strategies can be made to increase the sustainability of power generation using bagasse. High pressure cogeneration system: it is possible to upgrade old low-pressure boilers to high-pressure systems that can work much better to produce electricity. Particulate emission can be controlled by incorporation of emission control systems like electrostatic precipitators. Combination of thermochemical and biochemical systems can also be translated into hybrid systems that can provide higher energy recovery at minimum waste production.

5.4 Validation

Life Cycle Assessment studies and working data of biomass energy plants are also used to validate the results of the analysis. The sensitivity analysis is done to investigate how the parameters like the moisture content and conversion efficiency affect the results of environmental impact.6. Conclusion.

This study presented a comparative Life Cycle Assessment (LCA) of four bagasse-to-energy conversion pathways—combustion, gasification, pyrolysis, and anaerobic digestion within a system boundary that integrates sugarcane farming, milling, and energy generation processes.

The analysis demonstrated that system performance is not determined by conversion technology alone but is strongly influenced by upstream factors such as cane fibre content, sucrose levels, and bagasse moisture, which affect both energy yield and environmental performance. Milling indicators such as bagasse poll and extraction efficiency further define the quantity and quality of biomass available for energy conversion.

Among the technologies evaluated, gasification exhibited the highest energy efficiency (approximately 55%) and overall sustainability performance, while pyrolysis showed the lowest CO_2 emission intensity (0.705 kg/kWh) due to carbon retention in biochar. Combustion, although widely used, demonstrated lower efficiency and higher emissions, largely influenced by high bagasse moisture content and incomplete energy recovery. Anaerobic digestion showed comparatively lower efficiency but favorable environmental performance.

The results highlight that optimizing bagasse utilization requires a system-level approach that considers agricultural practices, milling efficiency, and appropriate technology selection. While bagasse remains the primary energy source within sugar factories, other by-products such as molasses and press mud offer additional energy pathways, including ethanol and biogas production, which can further enhance sustainability.

This study demonstrates that transitioning from conventional combustion systems to advanced conversion technologies, particularly gasification, can significantly improve energy efficiency and reduce environmental impacts. The findings provide a practical framework for improving energy recovery and supporting sustainable industrial development in biomass-rich sugar industries.

References

Bridgwater, A.V., Review of fast pyrolysis of biomass and product upgrading, Biomass and Bioenergy, 2012.
Cherubini, F., Life cycle assessment of bioenergy systems, Bioresource Technology, 2011.
Demirbas, A., Biofuels: Securing the Planet’s Future Energy Needs, Energy Conversion and Management, 2009.
Goldemberg, J., Ethanol for energy production, Energy Policy, 2008.
Karekezi, S., Renewable energy strategies for Africa, Energy Policy, 2003.
Li, Y., Anaerobic digestion of lignocellulosic biomass, Renewable Energy Reviews, 2012.
Mohan, D., Pyrolysis of wood and biomass: A review, Energy and Fuels, 2006.
Pandey, A., Biotechnological potential of agro-industrial residues, Bioresource Technology, 2000.

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