INTEGRATING PYROLYSIS INTO SUGARCANE MILLS FOR WASTE VALORIZATION AND ENHANCED SUSTAINABILITY

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ABSTRACT: Sugarcane mills generate vast quantities of bagasse, a fibrous byproduct typically burned for process heat and power. This study investigates the integration of slow pyrolysis into sugar mill operations as a novel strategy to address existing challenges in waste management and energy efficiency. Sugarcane bagasse (≈40% cellulose, 28% hemicellulose, 18% lignin, on dry basis) with high moisture (~45–50% as received) was dried and subjected to slow pyrolysis at temperatures up to 400 °C under inert atmosphere. Pyrolysis converted the bagasse into roughly one-third solid char, one-third bio-oil condensates, and one-third non-condensable syngas. The char product had a higher heating value ~21 MJ/kg and a BET surface area ~318 m²/g, indicating its potential as a solid fuel or activated carbon precursor. The bio-oil condensed into an oxygen-rich aqueous fraction (high in acetic acid and furfural) and a viscous tar fraction rich in phenolics, with total liquid yield ~33 wt%. The syngas (~35 vol% CO_2, 19% CO, ~2.4% CH_4, balance N_2 and trace H_2) can be used on-site for heat and power. Notably, trace amounts of valuable furanic compounds (e.g. furfural and 2,5-dimethylfuran) were identified in the pyrolysis vapors. Embedding a pyrolysis unit within the mill infrastructure enables waste valorization: the energy-dense biochar can be used as a renewable boiler fuel or soil amendment, and the bio-oil chemicals (like furfural) can be extracted as value-added products. Operational and economic advantages of integration include improved energy efficiency, reduced waste volume, and new revenue streams from biochar and bio-oil. By leveraging existing utilities (e.g. waste heat for drying) and eliminating biomass transport costs, an integrated pyrolysis system can enhance the commercial viability of sugar mills. These findings demonstrate that retrofitting sugar mills with pyrolysis technology transforms them into biorefineries that not only produce sugar but also renewable energy and bioproducts. The study concludes that integrating pyrolysis addresses key challenges in sugarcane mills – improving waste management, energy self-sufficiency, and profitability – thereby advancing the sustainable development of the sugar industry.
Keywords: biochar, fertilization, pyrolysis, pyrolysis oil

1 INTRODUCTION

Sugarcane processing results in large quantities of lignocellulosic residues, primarily bagasse – the fibrous sugarcane stalk material remaining after juice extraction. Bagasse typically constitutes about 30% of the harvested cane by mass (Hiranobe et al., 2024). In traditional mill practice, around 70% of this biomass is directly burned in boilers to generate steam and electricity for the mill (Hiranobe et al., 2024). This cogeneration helps mills meet their energy needs and sometimes export surplus power to the grid. However, simple combustion of bagasse presents several challenges. First, raw bagasse has high moisture content (40–50%), requiring drying or inefficient burning if used wet. Second, the energy recovery efficiency in older boiler systems can be limited, and significant energy potential may remain untapped in the biomass. Third, ash from bagasse combustion (rich in silica) can cause fouling in boilers and are often discarded or used in low-value applications (Hiranobe et al., 2024). Finally, any excess bagasse beyond the boilers' capacity is sometimes stockpiled or even treated as waste, especially in peak harvest seasons or at mills without optimized cogeneration, leading to disposal problems (Sugar Alliance, 2025). These issues highlight a need for improved waste valorization strategies in sugar mills to fully exploit bagasse's potential as a resource.

Pyrolysis is a thermochemical process that can play a key role in advancing sugar mill sustainability by converting biomass into multiple useful products. In pyrolysis, biomass is heated in the absence of oxygen to produce a solid biochar, liquid bio-oil, and combustible gases. Unlike combustion, which emits all carbon as CO_2, pyrolysis traps a portion of carbon in solid char and provides liquid/gaseous fuels, thereby enabling carbon management and product diversification (Hiranobe et al., 2024). For sugarcane bagasse, pyrolysis is particularly attractive: it can efficiently produce bio-oil and char from the cellulose, hemicellulose, and lignin fractions (Hiranobe et al., 2024). Recent reviews have noted that pyrolysis offers unparalleled versatility in the range of products obtained and can reduce unwanted residues (like ash) compared to direct burning (Hiranobe et al., 2024). By embedding pyrolysis units into existing mills, the traditionally single-output process (sugar with energy co-generation) transforms into a biorefinery capable of generating renewable fuels, chemicals, and materials on-site (Hiranobe et al., 2024). Such integration could address the operational issues mentioned: for example, biochar production on-site would reduce waste volume and create a stable, energy-dense fuel that is easier to store or transport than raw bagasse (Sugar Alliance, 2025). The extraction of chemicals like furfural from bio-oil provides new revenue streams, and the syngas can supplement process energy, potentially increasing overall mill efficiency.

The concept of integrating thermochemical conversion in agro-industrial facilities is not without precedent. Rice mills, for instance, have explored using rice husk (another biomass residue) in advanced gasification or pyrolysis systems. A recent review by Dafiqurrohman et al. (2022) concluded that combining a rice mill with a rice husk gasification plant is economically optimal, as it harnesses waste husks for energy and yields a high economic performance (Dafiqurrohman et al., 2022). This underscores the economic appeal of on-site biomass conversion in agricultural industries. Similarly, in the oil palm industry, empty fruit bunches (EFB) are abundant wastes. Studies have shown that installing a fast pyrolysis unit at a palm oil mill (using EFB as feedstock) is financially promising; by eliminating feedstock transport costs and utilizing the residue at its source, the bio-oil production cost becomes competitive (Peryoga et al., 2014). Peryoga and colleagues reported that the best scenario was to integrate the bio-oil plant within the palm mill itself, ensuring a free feedstock supply and insulation from market price fluctuations of the biomass. These examples from rice and palm industries highlight a key point: embedding conversion technologies on-site can drastically improve the viability of biofuel and bio-product projects in agro-industries.

For the sugarcane sector, research into integrated pyrolysis is now emerging. Salina et al. (2021) modeled the integration of a fast pyrolysis process for sugarcane straw into a sugar/ethanol plant. By using excess cane straw (formerly a field waste) as feedstock and applying pinch analysis for heat integration, they achieved significant improvements in energy efficiency. In their simulation, surplus electricity output from the plant increased by 30–46% when pyrolysis and proper heat integration were implemented, compared to the base case with no pyrolysis (Salina et al., 2021). This result illustrates how product diversification and heat integration via pyrolysis can enhance the overall performance of sugarcane biorefineries. Another recent study by Martins et al. (2024) experimentally pyrolyzed sugarcane bagasse and straw, demonstrating the production of energy-dense char and bio-oil from these residues. Their work, titled “Sugarcane biorefinery: Unlocking the potential of the pyrolytic process…”, emphasized that thermal conversion of sugarcane wastes could yield value-added products and improve the sustainability of sugar mills. Building on such insights, the present study aims to experimentally evaluate bagasse slow pyrolysis under conditions relevant to mill operation and to discuss the practical integration of this process into sugar mill infrastructure. As well as give keen insights into the economics thereof.

In summary, this work addresses the gap between bench-scale biomass pyrolysis results and their application in a real sugar mill context. By characterizing the yields and properties of bagasse-derived char, oils, and gases, we provide data crucial for designing an integrated pyrolysis system. It is then analyzed how these pyrolysis products can be utilized or marketed in the framework of a working sugar mill to tackle current challenges: waste surplus, energy efficiency, and economic diversification. The overarching goal is to demonstrate that integrating pyrolysis into sugar mills can convert an environmental liability (excess bagasse) into multiple assets, thereby enhancing both operational sustainability and commercial viability of sugar production.

This study was conducted at a working sugar mill in South Africa, where operational realities heavily influence technology adoption. The mill's primary motivation was to avoid additional energy costs and logistical burdens associated with waste disposal. In this context, the complex reactor designs and catalytic upgrading steps seen in modern pyrolysis research were not practical. Instead, the focus was on developing a low-cost, robust, and simple pyrolysis system that could process bagasse in its natural setting. By prioritizing integration with existing infrastructure—such as using waste steam for drying and repurposing existing handling systems—the project demonstrates that even basic pyrolysis technology, when strategically embedded in mill operations, can yield significant economic and environmental benefits.

2 MATERIALS AND METHODS

2.1 Feedstock and Pyrolysis

Sugarcane bagasse was obtained from a local sugar mill immediately after the juice extraction process. The as-received bagasse had a high moisture content (~45–50% by weight) and notable mineral ash content (~8% on dry basis). Its composition (on a dry basis) was approximately 40% cellulose, 28% hemicellulose, and 18% lignin (with the remainder being ash and minor extractives), consistent with typical literature values for sugarcane bagasse. Prior to pyrolysis, the bagasse was air-dried and oven-dried to reduce moisture to below 10%. This step is critical because high moisture in bagasse can hinder pyrolysis by consuming heat for water evaporation and can lead to poor bio-oil quality. In an integrated mill setup, low-grade waste heat (for example, flue gas from the boiler or exhaust steam) could be utilized for such drying, minimizing energy penalties. The dried bagasse was milled to a particle size of roughly 1–5 cm fiber lengths, a size easily handled by both the existing mill conveying systems and the pyrolysis reactor feeding system.
The ultimate analysis of the dried bagasse showed: C ~45.2 wt%, H ~5.8%, O ~44% (by difference), N ~0.3%, S <0.1%, and ash ~4–5 wt%. The high oxygen content reflects the fibrous carbohydrate nature of bagasse. Proximate analysis (dry basis) indicated ~75–80% volatile matter, ~15–20% fixed carbon, and ~5–8% ash, depending on the batch. The heating value (gross HHV) of the dry bagasse was measured at ~17 MJ/kg. These characteristics made bagasse a suitable candidate for pyrolysis: high volatile matter content favors the generation of liquids and gases, whereas the moderate fixed carbon will contribute to char formation. However, the ash (rich in silica and alkali metals) can act as a catalyst or heat sink during pyrolysis, potentially influencing product yields and char properties. In this study, some additional experiments were conducted with special pretreatment (such as acid washing to remove ash, and densification), to reflect real mill conditions and to evaluate the economic benefit for a more realistic implication versus the gain of feedstock optimization.

2.2 Pyrolysis Reactor and Procedure

Slow pyrolysis experiments were carried out in a laboratory-scale fixed-bed batch reactor made of stainless steel. Approximately 200 g of dried bagasse was loaded per batch. The reactor was equipped with an electric heating jacket and a programmable temperature controller. The bagasse was heated at a rate of ~10 °C/min from ambient to a final set-point of 400 °C. The temperature was held at 150°C, 250°C and 380°C, and the vapor was alllowed out of the reactor. This gives an insight into unique pyrolysis kinetics and in-situ fractionation at the different temperatures. Each vapour stream condensed was analyszed. The final temperature for 1 hour to ensure complete devolatilization. These conditions (moderate temperature, long residence time) characterize slow pyrolysis, which is known to maximize char yields (Hiranobe et al., 2024). The chosen final temperature of 400 °C is somewhat lower than the maximum decomposition temperature of lignin, to avoid excessive secondary reactions; this reflects a trade-off favoring char production and simplicity (since higher temperatures would yield more gas at the expense of char and require more energy input).

The vapor stream exiting the reactor passed through a condensing train. The char yield was determined by weighing the residual solids. The liquid yield was found by combining the mass of condensates from both collectors. Gas yield was calculated by difference (and also cross-checked by gas volume measurements).

3 PRODUCT ANALYSIS

A suite of analyses was conducted on each fraction to characterize its properties and potential uses:

- Biochar Analysis: The char was analyzed for proximate and ultimate composition using standard methods (ASTM D3172 for proximate, CHNS analyzer for ultimate). The heating value of char was measured with a bomb calorimeter. A notable analysis was the measurement of surface area and porosity by N_2 BET adsorption isotherms. Surface morphology and ash content in char were observed via scanning electron microscopy (SEM) coupled with EDX (energy dispersive X-ray) for elemental analysis of ash. These char properties indicate its suitability for applications such as solid fuel, activated carbon production, or soil amendment.
- Bio-Oil Analysis: The collected liquid was often biphasic, separating into an aqueous layer (rich in lighter oxygenates) and a viscous hydrophobic layer (heavy tars). The overall water content of the bio-oil was measured by Karl Fischer titration. Each phase was analyzed by gas chromatography–mass spectrometry (GC–MS) to identify major compounds. Known pyrolysis products of carbohydrates (like acetic acid, furfural, hydroxyacetone) were expected in the aqueous fraction, while phenolic compounds (guaiacol, syringol, etc.) from lignin were expected in the tarry fraction. We also screened for any furanic biofuel compounds such as 5-hydroxymethylfurfural (HMF) or 2,5-dimethylfuran (DMF) given literature reports that certain conditions can produce these from biomass. The pH, density, and elemental composition (CHNO) of the bulk bio-oil were measured to gauge its quality as a fuel.
- Pyrolysis Gas Analysis: The non-condensable gas was directed to a gas chromatograph equipped with a thermal conductivity detector (GC-TCD) to determine permanent gas composition (CO_2, CO, H_2, O_2, CH_4, and C_2–C3 hydrocarbons). A small fraction of higher hydrocarbons was also checked with a flame ionization detector (FID). This analysis reveals the fuel value of the syngas and whether it contains any corrosive or problematic components. The gas calorific value was estimated from its composition.

These analyses collectively inform how each product stream might be utilized within a sugar mill. For instance, knowing the char's heating value and ash content tells us its suitability as a boiler fuel (or whether it could be briquetted and sold), while the identification of specific chemicals in the bio-oil highlights opportunities for chemical recovery (e.g., furfural extraction) as part of an integrated biorefinery.

4 RESULTS

4.1 Pyrolysis Product Yields

Slow pyrolysis of sugarcane bagasse at 400 °C produced three main product fractions with roughly comparable yields. On a dry feed basis, the biochar yield was in the range of 30–35 wt% of the bagasse. The liquid (bio-oil) yield was approximately 32–35 wt%, and the non-condensable gas yield was about 30–33 wt%. These yield distributions (char: ~1/3, liquids: ~1/3, gas: ~1/3) are in line with expectations for lignocellulosic biomass pyrolysis in this temperature regime. Only a minor fraction (<5 wt%) of the input mass was unaccounted (attributed to light gases like H_2 or undetected losses), indicating good closure of the mass balance. The results confirm that a significant portion of bagasse can be converted into solid char, which is substantially higher than the fixed carbon content (~11%) of the raw bagasse, demonstrating that pyrolysis effectively concentrates carbon into char.

It was observed that the moisture content of the feed had a noticeable impact on the liquid yield: runs with insufficiently dried bagasse resulted in more water in the condensate and slightly lower organic liquid yield. This reinforces the importance of proper drying (or utilizing the mill's low-pressure steam for drying) in any integrated system.

4.2 Biochar Characteristics

The char is a friable black solid, retaining the fibrous morphology of bagasse to some degree but significantly more brittle. Proximate analysis of the char showed ~65–70% fixed carbon, ~25–30% ash, and <5% volatiles (dry basis), reflecting that most volatiles were driven off during pyrolysis. The relatively high ash content in char (originating from the original biomass minerals concentrated in the residue) suggests that if the char is used as a fuel, it will produce ash enriched in silica and potassium. This ash could potentially be collected and sold (e.g., as a cement additive or fertilizer ingredient), rather than fouling the mill boilers Ultimate analysis of char found ~75–78% C, 3–4% H, O (by difference) ~14–15%, N ~0.5%, S <0.1%. The higher heating value (HHV) of the char was measured to be ~21 MJ/kg. This is about 20–25% higher than the HHV of the original bagasse (~17 MJ/kg), confirming an energy densification in the char. While 21 MJ/kg is slightly lower than typical coal (~24–30 MJ/kg), it indicates that bagasse char could serve as a reasonable solid fuel for co-firing or for standalone char burners, with the advantage of being carbon-neutral.

One of the most remarkable properties of the bagasse char was its surface area. N_2-BET analysis yielded a surface area of approximately 318 m²/g. Such a high surface area (achieved without any activation other than the pyrolysis process itself) suggests that the char is somewhat activated – likely due to the silica templating and micropore formation from devolatilization. This makes the char immediately interesting for use in adsorption applications (e.g., for water treatment or as a catalyst support) if further activated or even as-is. In the context of a sugar mill, this char could be used to adsorb impurities from process liquids or effluents, effectively finding an internal use beyond combustion. Additionally, if the char were to be sold as biochar for soil amendment, its porous nature is beneficial for soil aeration and water retention, and its high carbon content means it can sequester carbon in soils for long periods.

4.3 Bio-Oil Composition

The pyrolysis liquids (bio-oil) collected amounted to roughly one-third of the bagasse input by mass. Visually, the bio-oil separated into two layers upon standing. The top layer was a brown, aqueous phase (often called pyroligneous acid or wood vinegar in biomass pyrolysis contexts) and comprised about 60–70% of the total liquid mass. This fraction had a water content of ~50% and a pH around 2.8–3.0, indicating high acidity. GC–MS analysis of the aqueous phase revealed a suite of light oxygenated organic compounds: acetic acid was a major component (consistent with the deacetylation of hemicellulose), along with acetol (hydroxyacetone), formic acid, furfural, and smaller amounts of methanol and lactic acid. Furfural ($C_5H_4O_2$), derived from hemicellulose pentoses, was present at several weight percent of the aqueous bio-oil. Furfural is notable as a platform chemical that can be refined to fuels or resins; its presence here suggests that an integrated mill could potentially recover furfural from the pyrolysis condensate as a value-added product (furfural is traditionally produced in dedicated plants by acid hydrolysis of bagasse or other residues).

The bottom layer of the bio-oil was a much more viscous, tarry phase – dark brown/black in color. This heavy fraction is rich in phenolic compounds and other high-boiling organics predominantly originating from lignin breakdown. GC–MS of the tar identified compounds such as phenol, guaiacol (2-methoxyphenol), syringol (2,6-dimethoxyphenol), 4-methylguaiacol, and other alkyl-phenolics. These phenolic tar compounds give the bio-oil its smokey odor and are potential precursors for phenolic resins or could be combusted as a burner fuel. The overall elemental analysis of the combined bio-oil was around 55–60% C, 6–8% H, 30–35% O, with negligible sulfur and ~0.5% nitrogen – reflecting an oxygen-rich liquid that would typically require upgrading (through hydrodeoxygenation or emulsification with conventional fuels) to be used as a transport biofuel. The gross calorific value of the raw bio-oil was measured ~16 MJ/kg, which is lower than petroleum fuels due to the high oxygen and water content.

One intriguing finding was the detection of furanic compounds beyond furfural. Trace quantities of 5-hydroxymethylfurfural (HMF) and 2,5-dimethylfuran (DMF) were identified in the GC–MS spectra of the bio-oil. DMF, in particular, is a high-energy density biofuel molecule (with research octane ~119 and energy content comparable to gasoline)

Its presence in the pyrolysis vapors (even at trace levels) is scientifically interesting because DMF is usually produced via catalytic routes from sugars; here it appears as a minor product of pure thermal decomposition. While the yield of DMF in the experiments was very low (estimated <0.1% of total products), its detection opens the question of whether certain catalysts or reaction conditions could be employed in an integrated process to boost the yield of premium fuels directly from bagasse pyrolysis vapors. However, for the scope of the present study, the key takeaway is that the pyrolysis bio-oil contains identifiable chemical families (acids, furans, phenolics) that have potential market value if separated. In an integrated mill setting, one could envision a small fractionation unit recovering furfural or acetic acid from the aqueous stream, for example, adding an extra revenue stream to the mill.

4.4 Pyrolysis Gas Composition

The non-condensable pyrolysis gas (often termed "syngas" in this context, though it is a low-H_2 syngas) accounted for roughly one-third of the biomass carbon and energy. The gas volume production was on the order of 0.3–0.4 m³ (STP) per kg of dry bagasse. The composition (by volume) averaged about 35% CO_2, 19% CO, 2–3% CH_4, 1–2% light hydrocarbons (C_2–C_3), and the balance being mostly N_2 (from purge gas) with only trace H_2 (<1%) detected. The low hydrogen content is typical for pyrolysis gases produced without steam or catalysts; most of the hydrogen in the biomass ends up in the biochar (as surface functional groups) or in the bio-oil (as part of water or organics), rather than as H_2 gas. The calorific value of the dry pyrolysis gas was estimated around 5–6 MJ/m³. This is lower than natural gas (≈35 MJ/m³) but comparable to low-BTU fuel gases from biomass gasifiers. In a sugar mill, this gas could be directly combusted in the boilers or in a furnace to provide heat for the pyrolysis itself or other processes. Indeed, using the pyrolysis gas to fire the pyrolysis reactor (making the system autothermal after startup) is a strategy for integration. Alternatively, if cleaned of tars, the gas could fuel gas engines or turbines to generate electricity.

An important observation is that by not venting this gas but rather utilizing it, the integrated process ensures that no flammable or greenhouse gases are released untreated. All the carbon either goes into char (sequestered or used as solid fuel) or is converted to CO/CO_2 which can be captured in flue gas if needed. In essence, the pyrolysis gas provides an energy feedback loop: its combustion can supply part of the energy required for drying the bagasse or heating the pyrolysis reactor, improving the energy efficiency of the overall system. Calculations shows that there is enough thermal heat available to sustain the pyrolysis reaction and export heat into the mill.

5 TECHNO-ECONOMIC ANALYSIS

The pyrolysis data obtained from the testing was used to perform a techno-economic assessment of a commercial-scale system using sugar mill bagasse as input. The study was conducted with the specific goal of understanding the economic viability of integrating such a system into an existing sugar mill, especially in a South African context where energy cost sensitivity and operational simplicity are critical. Pyrolysis remains an underutilized technology in this market, and large-scale adoption is hindered by unfamiliarity and limited product offtake agreements. However, this study shows that even a modestly configured pyrolysis system, based on low-complexity technology and conservative revenue assumptions, can deliver high financial returns.

The analysis began by determining the energy required to dry and heat bagasse up to 400°C. The system assumed included a rotary dryer and rotary pyrolysis chamber. The mill processes around 20 tons of wet bagasse per day during a 9-month milling season (~244 days), factoring in 90% plant availability. Three heating options were assessed: high-pressure (HP) steam supplied from the mill's own boiler, liquefied petroleum gas (LPG), and electricity. The energy cost and integration feasibility were compared and HP Steam was found to be the most feasible medium for integration. Other cost is explained as per below:

Table I: Drying Medium Sensitivity

Parameter	HP Steam	LP Gas	Electricity
Source Availability	High (on-site)	Medium	High (grid)
Thermal Energy Required/day	32.3 GJ	32.3 GJ	32.3 GJ
Energy Cost (USD/GJ)	**$1.21**	**$11.28**	**$16.33**
Daily Drying Cost (USD)	**$39.27**	**$364.76**	**$528.92**
Annual Drying Cost (USD)	**$8,637**	**$80,128**	**$116,610**
Integration Feasibility	Excellent	Moderate	Poor (high cost)
Sustainability (GHG)	Low	Medium	High (fossil)

The yields from testing indicated that one operational season would result in the following product outputs:

Table II: Annual Product Yields

Product	Yield (wt%)	Mass (tons/season)	Mass Flow (kg/s)
Dried Bagasse	–	2,580.06	0.14
Pyroligneous Acid	32.89%	848.58	0.04
Biochar	32.49%	838.26	0.08
Syngas	33.94%	875.67	0.09

Heating costs were likewise calculated using standard thermophysical assumptions:

Table III: Heating Energy Cost (Converted to USD)

Parameter	HP Steam	LP Gas	Electric Heating
Required Heat Input (MW)	0.0777	Same	Same
Cost per kg Feedstock	**$0.00091**	**$0.01011**	**$0.00590**
Annual Heating Cost	**$2,357**	**$26,092**	**$15,222**

Using previously benchmarked operating and capital costs, the annualized expenditure and investment are as follows:

Table IV: Operating and Capital Expenditure (Converted to USD)

Category	Cost (USD/year)
Staff Costs	**$76,865**
General Utilities & Maintenance	**$239,081**
Shipping and Marketing	**$606,350**
Admin & Consumables	Included
Total OPEX	**$922,296**
CAPEX (one-time)	**$2.54 million**

Revenue was estimated based on conservative pricing below typical market rates, to account for local uptake barriers.

Table V: Annual Revenue (Converted to USD)

Product	Selling Price	Output (tons)	Revenue (USD/year)
Biochar	$0.81/kg ($810/t)	838.26	**$679,991**
Pyroligneous Acid	$1.19/kg ($1,190/t)	848.58	**$1,009,291**
Total Turnover	—	—	**$1,689,282**

Table VI: Estimated Profit & ROI by Heating Source (USD)

Scenario	Heating Source	Turnover (USD)	Annual Profit (USD)	ROI (%)
Base Case	HP Steam	$1.69 million	**$610,000**	**24 %**
Moderate Case	LP Gas	$1.69 million	**$335,000**	13%
Worst Case (High OPEX)	Electricity	$1.69 million	**$114,000**	4.5 %

Even with conservative product pricing and no revenue assumed from syngas, the base-case scenario—using existing HP steam from the mill—demonstrates an impressive 24% ROI. This outcome is particularly notable considering that no carbon credits, fertilizer offsets, or advanced chemical extraction are included in the current model. The use of on-site steam makes the system nearly self-sufficient in energy, further improving sustainability and reducing dependency on fossil fuels.
This high ROI under basic assumptions underscores that simplicity, integration, and realism are key success factors. Rather than pursuing technologically intensive solutions, the approach proves that a practical, modular pyrolysis system embedded within existing mill infrastructure can achieve substantial returns and long-term value—with minimal risk and complexity.

6 DISCUSSION

The experimental results demonstrate that slow pyrolysis can effectively convert sugarcane bagasse into a portfolio of useful products. The discussion now turns to the implications of integrating this process into an operating sugar mill, focusing on how it addresses current challenges and improves the mill's waste management and economics. Several key aspects emerge: waste reduction and valorization, energy efficiency and process integration, new product streams and revenues, and commercial viability.

6.1 Waste Reduction and Valorization

Integrating pyrolysis directly tackles the issue of excess bagasse and other residues by converting waste into value. In a conventional mill, any bagasse that exceeds the boiler's demand must be stockpiled or disposed of. This can be problematic, as wet bagasse ferments, attracts pests, and can even catch fire spontaneously. Pyrolysis provides a means to continuously consume surplus bagasse during the crushing season, reducing piles of waste fiber. The output is biochar, which is far more compact and stable than raw bagasse. In this study, ~1 ton of dry bagasse yields ~0.3 tons of char. This represents a significant mass and volume reduction. The char, being energy-dense and hydrophobic, can be stored easily (outdoors or in silos) without decomposing, and used months later as fuel or soil amendment. This is a crucial advantage in seasonal industries like sugar milling: pyrolysis enables off-season energy use of bagasse via char. Instead of trying to preserve wet bagasse for boiler fuel beyond the harvest (which is technically difficult), mills could stockpile biochar and use it to maintain power generation or export in the off-season. Thus, the integration smooths out the resource utilization across the year.

Moreover, by converting a large fraction of bagasse into char and oil, the amount of boiler ash generated is potentially reduced. Currently, burning bagasse yields ash that contains most of the biomass minerals (silica, calcium, etc.). This ash often has to be hauled and can pose disposal issues, although it has some uses (e.g., as a cement additive or soil liming agent). In an integrated pyrolysis scenario, a significant portion of minerals report to the char. If that char is not all burned but partly used in materials (like as biochar in soil or activated carbon), then those minerals are effectively removed from the boiler circuit and put to productive use (such as improving soil nutrient content if returned to fields). This not only reduces the strain on the boiler (less slagging/fouling from silica) but also recycles nutrients. The circular economy aspect is noteworthy: biochar applied to cane fields returns minerals and carbon to the soil, improving soil health and potentially cane yields, which in turn benefits the mill's core business.

6.2 Energy Efficiency and Process Integration

The addition of pyrolysis can improve a mill's overall energy efficiency through cogeneration synergy and heat integration. In our results, the pyrolysis gas contains about 20% of the initial energy of the biomass (with char retaining ~45% and bio-oil ~35% of the energy). If this gas is captured and burned in optimized equipment (like a burner or gas engine), it can produce additional power or heat. For instance, the syngas could supplement boiler fuel, allowing the boiler to produce more steam for electricity generation without consuming extra bagasse.

Alternatively, if run through a gas engine, it could generate electricity at potentially higher efficiency than the Rankine steam cycle used in traditional mills. Heat integration is also critical: the substantial waste heat from the exothermic char combustion or syngas combustion can be recovered. As demonstrated by Salina *et al*. (2021), careful heat integration (using pyrolysis heat in the ethanol fermentation or distillation sections of a biorefinery) led to a 30–46% increase in surplus electricity (Salima *et al.*, 2021). In a sugar mill context, one could integrate heat by, for example, using the hot pyrolysis gases (~400 °C) to pre-dry incoming bagasse or generate steam. The pinch analysis concept would identify how waste heat from pyrolysis can reduce steam demand in cane juice evaporation or crystallization processes, thereby freeing up more bagasse to either pyrolyze or sell/export as electricity.

It is also noteworthy that autothermal operation is feasible. The char can be partially combusted to provide the heat for pyrolysis, or the syngas can be recycled to fire the reactor. This means that after startup, the process will not need significant external fuel. Many modern designs of pyrolyzers use a portion of the produced gas/char to sustain the reaction. In an integrated mill, one could envision diverting a controlled fraction of biochar to a combustor that heats the pyrolysis reactor, while the rest of the char is preserved for sale or other uses. This ensures that the pyrolysis process does not detract from the mill's energy output; instead, it would ideally power itself and contribute excess energy to the mill.

Another efficiency aspect is the avoidance of dry fuel shortages. During peak crop, mills sometimes have more bagasse than needed, and in off-crop, they have none (often switching to auxiliary fuels if they continue running). By converting bagasse to char in-season, mills can create a fuel reserve. Char, being dry (~1–3% moisture) and high-carbon, burns more efficiently than raw bagasse in a boiler (which often has 50% moisture). If an integrated system produces char and stores it, the mill could burn char in the off-season at higher combustion efficiency and with lower flue gas losses (since no moisture to evaporate). This means the same boiler could produce more heat from a ton of stored char than from a ton of fresh bagasse, improving off-season energy generation potential.

6.3 New Product Streams and Economic Opportunities

Perhaps the most transformative impact of integration is the creation of new product streams and revenue sources beyond sugar and electricity. The pyrolysis of bagasse yielded two such streams: biochar and bio-oil (which itself contains multiple sub-streams of chemicals).

The biochar stands out as a versatile product. In many regions, agricultural biochar is gaining attention as a soil amendment that can improve soil quality and sequester carbon. Sugarcane cultivation could benefit from biochar incorporation: studies have shown that adding bagasse-derived biochar to soil can increase water retention and nutrient availability, potentially improving cane yields over time (this is an area of ongoing research). If a sugar mill produces biochar, it can either apply it to its supplied farms (closing the nutrient loop and potentially qualifying for carbon credits under climate initiatives) or sell it into the growing biochar market (e.g., for gardening, landscaping, or environmental remediation purposes). Additionally, bagasse biochar can be a precursor to activated carbon. With its high surface area (~318 m^2/g from the results of this study), minimal further activation (e.g., steam or chemical activation) could create a high-grade activated carbon. This could be used for the mill's own wastewater treatment or sold to industries for purification processes. There is a known demand for activated carbons, and producing it from a waste biomaterial could be economically attractive if quality standards are met.

The bio-oil fraction, while more challenging to handle due to its complexity, also offers opportunities. One immediate application is as a liquid fuel for burners or boilers on-site. Instead of using fuel oil or diesel in lime kilns or other supplementary fired equipment, the mill could burn the bio-oil (after modest filtering) to offset fossil fuel use. Beyond burning, specific components of the bio-oil are valuable: for example, the furfural content could justify installing a small separation unit. Furfural sells globally as a solvent and chemical intermediate (for resin manufacture, furfuryl alcohol, etc.), and bagasse has historically been used to produce furfural in some countries. Pyrolysis-derived furfural recovery could piggyback on that knowledge. Acetic acid is another potential product, though likely present in lower concentrations. The heavy phenolic fraction of the tar could be used as a binding material (some researchers have explored using pyrolysis tar as a substitute for phenol in phenol-formaldehyde resins). In essence, a sugar mill could evolve into a biorefinery where sugar is one of many outputs, alongside energy, solid biofuels, and organic chemicals.

From an economic perspective, integrating pyrolysis could improve the mill's bottom line. By generating additional saleable products (biochar, chemicals) and potentially increasing power export (through better energy use), the mill diversifies its income. This diversification is crucial in times when sugar prices are volatile; alternative revenues can buffer the business. A techno-economic assessment by Peryoga et al. (2014) on palm empty fruit bunch pyrolysis is enlightening in this regard: they found that locating the pyrolysis plant on-site (thus avoiding feedstock purchase costs) made the bio-oil production cost competitive, and they recommended integration as the best option for economic viability. For sugar mills, bagasse is essentially a free byproduct, so any valorization of it is nearly pure profit after processing costs. One can draw a parallel with integrated rice mill gasification: Dafiqurrohman et al. noted that using what was once waste (rice husk) to generate electricity and possibly products like silica (from ash) yielded the highest economic performance for the mill. Likewise, a sugar mill that uses pyrolysis to turn bagasse into electricity and biochar could see significant economic gains, especially if carbon credits for biochar or renewable power incentives are available.

A real-world example underlining commercial potential is the American BioCarbon project at a Louisiana sugar mill (Cora-Texas factory). In their pilot, bagasse is being converted on-site into fuel pellets and biochar, which are sold globally as renewable fuel and soil additives. The company reports that doing this "right at the mill where the feedstock is generated" increases efficiency and lowers the carbon footprint of the products. This demonstrates that the concept is not just theoretical – it can be implemented in practice. Their biochar is marketed as a soil enhancer for local cane fields and their pellets as a coal-replacement fuel. This kind of venture indicates that mills can become hubs of sustainable product manufacturing, not just sugar production.

6.4 Considerations for Implementation and Viability

While the prospects are attractive, integrating pyrolysis into existing sugar mills does come with technical and economic considerations. Capital cost is one hurdle – pyrolysis reactors, condensers, and upgrading units require upfront investment. However, these costs must be weighed against the savings from waste reduction and the profits from new products. As technology matures and if carbon pricing becomes stricter, the economics will tilt more favorably. Our findings contribute to this by providing data for scale-up calculations (e.g., knowing yields and energy contents helps in sizing equipment and estimating returns).

Another consideration is operational integration. Sugar mills operate continuously during the crushing season; any pyrolysis unit must be able to handle a continuous flow of bagasse or have buffering systems. This might entail a shift from batch to continuous pyrolysis reactors for industrial scale. Technologies such as belt dryers, screw pyrolyzers, or fluidized bed pyrolyzers could be more suitable at large throughput. The pyrolysis conditions might also be tuned for desired outcomes: a mill prioritizing maximum char for fuel might operate at lower temperatures (~350 °C) to boost char yield, whereas one targeting more bio-oil for chemical extraction might go to higher temperatures or use catalysts. Flexibility is key – indeed, being able to adjust the pyrolysis severity gives a mill the agility to produce more of what is needed (energy vs. chemicals) depending on market conditions.

Environmental and regulatory aspects also come into play. Pyrolysis, when integrated properly, can reduce overall emissions (for instance, by curtailing open-air burning of field residues or by stabilizing carbon in char). Nonetheless, the process itself must be monitored for any emissions of volatiles or waste effluents from bio-oil handling. Fortunately, most emissions can be controlled: the syngas is burned (no release of unburned hydrocarbons), and the bio-oil can be fully contained and processed. If biochar is applied to fields, guidelines must ensure it is free of harmful contaminants (our analysis shows primarily carbon and ash, with no detected heavy metals, since bagasse is a clean biomass). Achieving certifications for biochar (e.g., for carbon sequestration credits) could further enhance economic viability.

In terms of comparison with other thermochemical options, one might ask: why pyrolysis and not gasification or direct combustion upgrade? Gasification is indeed another integration pathway (as evidenced by the rice mill example and various studies). Pyrolysis provides a nice balance by giving a solid product and a fuel gas, whereas gasification gives only gas (and minor char/ash). A hybrid approach could even be envisaged: a two-stage process where bagasse is first pyrolyzed to get char and liquids, and then the char (or the heavy tar) is gasified to syngas in a second stage (such integrated schemes have been researched for EFB). Such complexity may be beyond near-term deployment, but it highlights that pyrolysis integration is a stepping stone toward more advanced biorefinery schemes.

Ultimately, the viability of embedding pyrolysis in mills will depend on detailed techno-economic analysis and pilot demonstrations. Our experimental results serve as a foundation: for example, knowing that ~0.33 kg char, ~0.33 kg oil, and ~0.33 kg gas come from 1 kg bagasse, and the char has ~21 MJ/kg, a mill processing, say, 1000 tonnes of bagasse per day could produce about 300 tonnes of char per day with an energy content equivalent to ~6,300 GJ. If that char were sold at even a modest price (or used to offset coal at $89 per GJ), one can estimate annual revenue. The furfural in the oil might be a few weight percent of 330 tonnes (maybe ~10 tonnes furfural per day if extracted), which at market price ~$1000/ton could add several million dollars per year of revenue. These back-of-envelope figures suggest the stakes are significant enough to pursue integration, especially in large sugar factories.

7 CONCLUSION

This study has demonstrated the technical feasibility and potential benefits of integrating a pyrolysis process into sugarcane mill operations. Slow pyrolysis of sugarcane bagasse produces a carbon-rich biochar, an energy-containing bio-oil, and a combustible syngas – each of which can be harnessed to improve the sustainability and profitability of a sugar mill. The char, with its high heating value and adsorptive surface area, can be used as a renewable solid fuel or functional material, turning what was once a low-value boiler byproduct into a marketable commodity. The bio-oil contains platform chemicals like furfural and phenolics, pointing to opportunities for the mill to expand into biochemical production. Meanwhile, the syngas can provide process energy, reducing reliance on conventional fuels.

By embedding pyrolysis within the existing mill infrastructure, several operational challenges are addressed. Waste biomass that might otherwise accumulate is continuously converted into storable products, mitigating disposal issues and fire hazards. Energy efficiency is enhanced through additional power generation and heat integration, as evidenced by analogies from other industries and our analysis. The mill effectively becomes a biorefinery, capable of producing food (sugar), energy (electricity/steam, biofuels), and materials (biochar, chemicals) from the same feedstock, thus exemplifying circular economy principles. This integration also improves the mill's carbon footprint – biochar can sequester carbon in soils and displace fossil fuels, and more complete utilization of biomass means fewer emissions per unit of product.

The findings align with observations in similar agro-industrial integrations: rice mills with gasifiers achieve superior economics (Dafiqurrohman et al., 2022), palm oil mills with pyrolysis units minimize waste and add profit (Peryoga et al., 2014), and sugarcane ethanol plants with integrated pyrolysis yield more energy and diversified outputs (Salina et al., 2021). This work extends this knowledge by providing specific data for sugarcane bagasse and articulating how a conventional sugar mill could transition to a multi-output biorefinery.

In conclusion, integrating pyrolysis into sugar mill operations offers a compelling pathway to valorize biomass waste, improve energy self-sufficiency, and create new revenue streams, all while advancing environmental sustainability. The novel contribution of this integration lies in addressing the dual mandate of waste management and economic viability in the sugar industry: it turns an abundant residue into a resource and does so in a way that leverages the mill's existing strengths (feedstock supply, utilities, expertise in handling bulk biomass). For commercial realization, further pilot projects and economic analyses are recommended, but the evidence strongly suggests that such integrated projects can be commercially viable. As the sugar industry faces growing pressure to improve its environmental profile and profitability, pyrolysis integration provides a timely and practical solution, transforming sugar mills into hubs for renewable energy and bioproduct generation.

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