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Simulation and Investigation of Factors Affecting the Internal Friction Force of Pneumatic Cylinders

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Extended Abstract

Introduction

The increasing global demand for energy, together with the depletion of fossil fuel resources and growing environmental concerns, has intensified the search for renewable and sustainable energy sources. The extensive consumption of fossil fuels is one of the major contributors to greenhouse gas emissions, particularly carbon dioxide (CO_2), which is directly associated with global warming. Consequently, the development of renewable energy technologies has become an important strategy for simultaneously addressing energy security and environmental challenges. Biomass is among the most promising renewable energy resources because of its widespread availability, energy potential, capability of producing solid, liquid, and gaseous fuels, and potential contribution to reducing dependence on fossil fuels. Biomass accounted for more than 12% of global final energy consumption in 2021 and remains the largest renewable energy source. Agricultural residues represent an important source of biomass energy. In Iran, approximately 70 million tons of agricultural products are produced annually, and a substantial proportion of this production is associated with plant residues that can potentially be utilized for energy generation. Sugarcane bagasse is particularly important because it is an abundant by-product of the sugar and ethanol industries. Its relatively low cost, high availability, appropriate calorific value, and lignocellulosic composition, mainly consisting of cellulose, hemicellulose, and lignin, make it a suitable feedstock for energy conversion processes. In 1402, more than 6.445 million tons of sugarcane were harvested in Khuzestan Province, highlighting the significant regional potential for bagasse-based energy recovery in Iran. Energy recovery from lignocellulosic biomass can generally be achieved through thermochemical, biochemical, and physical-thermochemical conversion pathways. Thermochemical technologies include pyrolysis, hydrothermal liquefaction, gasification, and direct combustion, whereas biochemical conversion mainly involves processes such as enzymatic hydrolysis and fermentation for bioethanol production. Briquetting can also be considered a physical-thermochemical approach that improves the physical and fuel properties of raw bagasse. Each technology has specific advantages, operating requirements, energy efficiencies, and environmental and economic limitations. Therefore, the selection of an appropriate conversion route requires simultaneous consideration of energy yield, feedstock characteristics, process conditions, environmental impacts, and economic feasibility. Accordingly, the objective of this review is to evaluate the principal approaches for recovering useful energy from sugarcane bagasse, with particular emphasis on pyrolysis, hydrothermal liquefaction, gasification, direct combustion, bioethanol production, and briquetting. The study also compares the advantages, limitations, operating conditions, products, and reported performance of these technologies in order to identify promising pathways for sustainable utilization of sugarcane bagasse.

2. Materials and Methods

The present study was conducted as a review of previously published research on energy recovery from sugarcane bagasse. The literature was examined with emphasis on the principal thermochemical, biochemical, and physical-thermochemical conversion technologies applicable to lignocellulosic biomass and specifically to sugarcane bagasse. The reviewed approaches included pyrolysis, hydrothermal liquefaction (HTL), gasification, direct combustion, fermentation for bioethanol production, and briquetting. For each conversion pathway, the reported operating conditions and performance indicators were compared. These parameters included temperature, pressure, heating rate, residence time, feedstock preparation requirements, product distribution, calorific value, conversion efficiency, and major technological limitations. The review also considered the effects of pretreatment, catalysts, gasifying agents, moisture content, and process configuration on energy recovery. The reported results from previous experimental and analytical studies were synthesized to provide a comparative assessment of the technical and environmental potential of the different approaches. The reviewed technologies can be broadly categorized as follows:

1. Thermochemical conversion: pyrolysis, hydrothermal liquefaction, gasification, and direct combustion;
2. Biochemical conversion: pretreatment, enzymatic hydrolysis, and fermentation for bioethanol production;
3. Physical-thermochemical conversion: briquetting and thermal pretreatment for improving the fuel

3. Results and Discussion

3.1. Pyrolysis

Pyrolysis is a thermochemical process in which biomass undergoes thermal decomposition in the absence of oxygen. Depending on the operating conditions, pyrolysis can produce three major product fractions: biochar, bio-oil, and non-condensable gases, mainly including H_2, CO, CO_2, and CH_4. The distribution of these products is strongly affected by temperature, heating rate, residence time, and the physical and chemical characteristics of the feedstock. The review indicates that pyrolysis can be categorized into slow, fast, and ultrafast processes. Slow pyrolysis generally operates at approximately 400–600°C and favors biochar production, with reported yields of approximately 25–35 wt.% biochar and 30–50% liquid products. Fast pyrolysis requires only approximately 2–3 s of heating time and can produce approximately 60–75% bio-oil, 15–25% biochar, and 10–20% synthesis gas. Ultrafast pyrolysis can increase the bio-oil yield to approximately 70–75%. However, fast pyrolysis requires appropriate particle-size reduction to facilitate uniform heat transfer throughout the biomass. Studies on sugarcane bagasse have demonstrated that pyrolysis performance is highly dependent on temperature and heating rate. For slow pyrolysis, one reported study obtained a maximum biochar yield of approximately 28.97% and a pyrolysis-liquid yield of approximately 55.46% at 500°C and a heating rate of 10°C/min. Furthermore, the pyrolysis liquid contained biologically active compounds such as acetic acid, furfural, and phenolic derivatives, indicating that the products may have applications beyond direct energy generation. Overall, pyrolysis offers considerable flexibility because its operating conditions can be selected according to the desired product. Slow pyrolysis is more appropriate when biochar is the primary target, whereas fast and ultrafast pyrolysis are more favorable for bio-oil production.

3.2. Hydrothermal Liquefaction

Hydrothermal liquefaction is a promising technology for converting wet biomass into liquid bio-oil. One of its major advantages over conventional pyrolysis is that complete drying of the feedstock is not required, thereby reducing the energy demand associated with moisture removal. The reviewed studies indicate that HTL generally operates at approximately 250–374°C and 4–22 MPa. The resulting bio-oil can exhibit a significantly higher calorific value than raw bagasse. Whereas raw bagasse has a calorific value of approximately 17 MJ/kg, bio-oils obtained through hydrothermal liquefaction can reach approximately 33–36 MJ/kg. Nevertheless, untreated bio-oil may have relatively high oxygen content, acidity, and viscosity, which can limit its direct use as a transportation fuel. Therefore, catalysts such as NaOH and ZSM-5 can be employed to improve bio-oil quality. A particularly important reported result showed that a maximum bio-oil yield of approximately 46.9% was obtained at 285°C with a reaction time of 30 min. Excessive increases in temperature and reaction time reduced the bio-oil yield because of repolymerization and secondary decomposition reactions leading to gaseous products. The appropriate selection of catalyst concentration and operating conditions was therefore identified as essential for maximizing both bio-oil yield and quality. Another study showed that the choice of solvent strongly affects bio-oil stability. An ethanol/water mixture produced relatively stable bio-oil with thermal properties close to those of diesel, and the resulting product remained suitable for long-term storage, with stability reported for periods of up to approximately 8 years under the studied conditions.

3.3. Gasification

Gasification is a multistage thermochemical process in which biomass is converted into synthesis gas under high-temperature conditions and in the presence of a gasifying agent. The process generally operates within a temperature range of approximately 600–1500°C, producing a gas mainly containing H_2 , CO, CO_2 , and CH_4 . The resulting syngas can be used for heat and electricity generation or as a feedstock for the production of liquid fuels and valuable chemicals. Temperature is one of the most influential operating parameters. Increasing the gasification temperature from approximately 750 to 900°C can substantially increase the concentration of the principal combustible gases, particularly H_2 and CO, while decreasing tar formation. The gasifying agent is also important; replacing air with steam can increase the hydrogen content and calorific value of the produced syngas. Catalysts and reactor design can further improve gasification performance by reducing tar formation. Pretreatment can also significantly influence gasification performance. Hydrothermal carbonization of bagasse under a CO_2 atmosphere increased fixed-carbon content by approximately 5 wt.%, increased the higher heating value by approximately 2 MJ/kg, and reduced ash content by approximately 2 wt.%. The gasification time decreased from approximately 650 s for raw bagasse to 410 s after pretreatment, while H_2 and CO concentrations increased by approximately 5%. These findings demonstrate that suitable pretreatment can improve the reactivity and energy characteristics of bagasse during gasification. However, tar formation remains one of the major limitations of gasification. Tar can condense in gas-transfer lines, causing blockage, corrosion, and performance degradation. Therefore, downstream cleaning, filtration, or catalytic tar reduction may increase the complexity and operating cost of gasification systems.

3.4. Direct Combustion and Co-Combustion

Direct combustion is the simplest and most widely used method for obtaining energy from sugarcane bagasse, particularly in sugar mills where bagasse is burned to generate steam and electricity. However, raw lignocellulosic biomass has relatively low energy density and often contains significant moisture and inorganic components. Consequently, the reported efficiency of direct biomass combustion can be relatively limited, approximately 5–15% under certain operating conditions. The major technical challenges include high moisture content, low calorific value, ash deposition, slag formation, and agglomeration in combustion systems. Pretreatment methods such as drying, granulation, and thermochemical upgrading can improve fuel characteristics. In addition, co-combustion of biomass with coal can provide an effective pathway for reducing emissions while maintaining the energy infrastructure associated with conventional solid fuels. According to the reviewed studies, adding approximately 20% biomass to coal can reduce CO_2 emissions by around 18%, although the actual reduction depends on biomass type and operating conditions. Oxy-fuel combustion is another promising technology because the use of oxygen-rich conditions can increase the CO_2 concentration in the exhaust stream to approximately 95%, thereby facilitating CO_2 separation and potential carbon capture and storage. Nevertheless, the economic and operational feasibility of such technologies must be evaluated for individual systems.

3.5. Bioethanol Production

The biochemical conversion of sugarcane bagasse provides an alternative pathway for producing renewable liquid fuel. Bioethanol derived from lignocellulosic biomass is considered a second-generation biofuel, since it relies on non-food biomass and agricultural residues rather than edible feedstocks.Because bagasse consists primarily of cellulose, hemicellulose, and lignin, pretreatment is necessary to disrupt the lignocellulosic structure, remove lignin and hemicellulose, reduce cellulose crystallinity, and improve enzyme accessibility. The overall bioethanol production pathway includes pretreatment, enzymatic hydrolysis, fermentation, distillation, and dehydration. Several pretreatment technologies, including physical, acidic, alkaline, organosolv, wet oxidation, and steam explosion processes, have been investigated. Alkaline pretreatment is particularly effective for lignin removal, whereas steam explosion provides effective hemicellulose solubilization without requiring highly toxic chemicals. However, high concentrations of alkaline agents may degrade polysaccharides, while high-pressure pretreatment processes can increase safety and economic concerns.

After pretreatment, enzymatic hydrolysis using cellulase enzymes releases fermentable sugars. Saccharomyces cerevisiae is widely used for fermentation because of its relatively high ethanol tolerance and suitable growth characteristics over a broad pH range. The literature reviewed in the article indicates that parameters such as pH, incubation time, and substrate concentration significantly influence ethanol production. Although bioethanol production provides an attractive renewable-fuel pathway, its main limitations include the need for extensive pretreatment, enzymatic hydrolysis, relatively long processing times, possible formation of fermentation inhibitors, and the associated economic challenges of industrial-scale implementation.

3.6. Briquetting

Briquetting is a physical-thermochemical densification process that converts low-density bagasse into a compact solid fuel. This process reduces the volume of raw bagasse, improves its storage and transportation characteristics, and can increase its energy density and combustion performance. Thermal pretreatment, such as calcination at approximately 200°C, can reduce moisture and volatile matter while increasing the relative carbon content. The review reports that calcined bagasse briquettes can achieve an average calorific value of approximately 26.6 MJ/kg, compared with approximately 16.5 MJ/kg for briquettes produced from untreated bagasse. This improvement is attributed mainly to moisture removal and enrichment of the carbon fraction.Experimental investigations have also demonstrated the importance of particle size and binder content. One study reported a maximum briquette density of approximately 0.804 g/cm³, while the optimized conditions included approximately 14.953% combined binder, a particle size of approximately 0.776 mm, density of approximately 0.805 g/cm³, and breaking resistance of approximately 95.811%. Briquettes containing 5% cattle manure achieved a reported calorific value of approximately 39,927 kcal/kg. Compared with conventional coal, briquettes can provide a renewable solid-fuel alternative with lower ash content. The review indicates that briquette ash content may be approximately 2–10%, compared with around 20–40% for coal. Therefore, briquetting is particularly attractive where transportation, storage, and direct combustion of low-density raw bagasse represent major practical limitations.

3.7. Comparative Assessment of Energy-Recovery Routes

The comparison presented in the review demonstrates that no single conversion technology is universally optimal. Direct combustion is the simplest and most established route and is particularly suitable for sugar mills requiring process heat, steam, and electricity. However, its relatively low efficiency and sensitivity to moisture and ash-related problems limit its performance.Gasification provides a more advanced pathway for producing syngas rich in H_2 and CO, with applications in power generation and synthetic-fuel production, although tar formation and gas-cleaning requirements remain significant challenges. Pyrolysis provides greater flexibility in product selection, with slow pyrolysis favoring biochar and fast or ultrafast pyrolysis favoring bio-oil production. HTL is particularly advantageous for wet biomass because it eliminates the need for complete drying. It can convert bagasse into bio-oil with a calorific value of approximately 33–36 MJ/kg, considerably higher than the approximately 17 MJ/kg of raw bagasse. Bioethanol production provides a route toward renewable liquid transportation fuel but requires more complex pretreatment and biochemical processing. Briquetting, in contrast, is relatively simple and inexpensive and primarily improves the physical and fuel characteristics of bagasse rather than fundamentally converting it into another fuel. Therefore, the selection of an appropriate technology should be based on a comprehensive evaluation of technical performance, economic feasibility, environmental impact, available infrastructure, feedstock characteristics, and regional availability. This consideration is particularly relevant for regions such as Khuzestan, where the large quantity of sugarcane production provides an important and locally available source of bagasse.

4. Conclusions

This review evaluated the principal pathways for energy recovery from sugarcane bagasse, including pyrolysis, hydrothermal liquefaction, gasification, direct combustion, bioethanol production, and briquetting. The results demonstrate that sugarcane bagasse is a valuable lignocellulosic resource with significant potential for sustainable energy production and waste valorization. Its relatively high availability, low cost, and suitable chemical composition make it an attractive alternative to fossil-based energy resources. Among the reviewed technologies, hydrothermal liquefaction showed particular potential for converting wet bagasse into high-energy-density bio-oil. The calorific value of the resulting bio-oil can reach approximately 33–36 MJ/kg, compared with approximately 17 MJ/kg for raw

bagasse, while a maximum bio-oil yield of approximately 46.9% was reported at 285°C and 30 min. Pyrolysis provides a flexible platform for producing biochar, bio-oil, and syngas, with fast pyrolysis capable of producing approximately 60–75% bio-oil under appropriate conditions. Gasification can generate syngas rich in H_2 and CO, although tar formation and gas-cleaning requirements remain important challenges. Bioethanol production provides an attractive biochemical route for generating renewable liquid fuel from non-food lignocellulosic resources. However, extensive pretreatment, enzymatic hydrolysis, fermentation, and downstream separation increase the complexity and cost of the process. Briquetting, on the other hand, is a relatively simple and low-cost approach that improves the density, storage, transportation, and combustion characteristics of bagasse. Thermal pretreatment can increase the calorific value of the resulting briquettes to approximately 26.6 MJ/kg. Overall, the reviewed evidence indicates that sugarcane bagasse can play an important role in reducing dependence on fossil fuels, recovering energy from agricultural waste, and supporting circular-economy development. Nevertheless, challenges related to conversion efficiency, industrial-scale economic feasibility, process optimization, emissions control, and infrastructure remain. For regions with substantial sugarcane production, particularly Khuzestan Province in Iran, the development of integrated and multi-product biomass-processing systems could establish an effective link between agricultural production and energy-conversion technologies. Ultimately, the optimal utilization pathway should be selected through an integrated technical, economic, and environmental assessment that considers local feedstock availability and the intended energy or fuel product.

Key words: Sugarcane Bagasse, Biomass Energy, Energy Recovery, Pyrolysis, Hydrothermal liquefaction

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