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A Comparative Investigation of Heat Release Patterns During Combustion of Date Seed, Coconut Shell and Sugarcane Bagasse Via Thermogravimetric Analysis

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ABSTRACT
This study presents a comparative investigation of the thermal degradation behavior and heat release patterns of three agricultural biomass residues date seed, coconut shell, and sugarcane bagasse using thermogravimetric analysis (TGA). Proximate analysis revealed low moisture contents ranging from 3.40% to 4.85%, ash contents between 1.99% and 3.00%, and remarkably high volatile matter exceeding 90% across all samples. Calorific values ranged from 14.69 MJ/kg for date seed to 18.42 MJ/kg for coconut shell. Ultimate analysis showed carbon contents between 47.28% and 52.60%, with coconut shell exhibiting the highest carbon fraction. TGA results demonstrated multi-stage thermal degradation, with active decomposition occurring primarily between 200 to 400 °C. Coconut shell displayed greater thermal stability and higher residual mass due to its lignin-rich composition, while sugarcane bagasse showed faster devolatilization. The DTGA curves revealed distinct peaks corresponding to hemicellulose and cellulose decomposition, with coconut shell exhibiting broader peaks indicative of slower degradation. The findings confirm that these locally available agro-wastes possess sufficient energy potential and favorable combustion characteristics, making them viable alternatives for sustainable heat generation and bioenergy applications.

INTRODUCTION

The rapid increase in global energy demand, alongside the environmental consequences associated with fossil fuel utilization, has intensified the search for cleaner and more sustainable energy alternatives. Conventional fuels such as coal, petroleum, and natural gas have long dominated the global energy mix due to their high calorific values and established infrastructure. However, their continued use contributes significantly to environmental degradation, including greenhouse gas emissions, air pollution, and climate change. These concerns have driven growing interest in renewable energy sources, particularly biomass, as viable substitutes (Vassilev *et al*., 2012a).

Biomass materials derived from agricultural residues have emerged as promising alternatives due to their renewability, availability, and relatively low environmental impact. Among these, date seeds, coconut shells, and sugarcane bagasse are abundant agro-wastes in many regions and are often underutilized or improperly disposed (Aliyu *et al*., 2017)

Thermogravimetric Analysis (TGA) is a widely used analytical technique for studying the thermal decomposition and combustion characteristics of materials. It provides valuable insights into mass loss behavior, thermal stability, and heat release patterns under controlled heating conditions. By analyzing TGA and derivative thermogravimetric (DTG) curves, it is possible to identify distinct stages of combustion and evaluate the energy potential of different biomass materials.

This study focuses on a comparative investigation of heat release patterns during the combustion of date seeds, coconut shells, and sugarcane bagasse using TGA. By examining their thermal degradation behavior and combustion characteristics.

MATERIALS AND METHODS

Sample Collection and Preparation

All collected biomass materials was thoroughly cleaned to remove impurities such as dust and stones. The samples were then be dried either under sunlight or in an oven at approximately 105°C until a constant weight is achieved. This reduces moisture content and ensures uniformity during thermal analysis.

Proximate Analysis of Biomass Samples

Proximate analysis of the biomass samples (date seed, coconut shell, and sugarcane bagasse) was carried out using an automatic proximate analyzer in accordance with ASTM standards: ASTM E871 for moisture content, ASTM E872 for volatile matter, and ASTM D1102 for ash content, while fixed carbon will be determined by difference. The analysis provided information on the fuel quality and combustion characteristics of the selected biomass samples.

Ultimate Analysis of Biomass Samples

Ultimate analysis of date seed biomass was conducted using an elemental analyzer to determine carbon, hydrogen, nitrogen, sulfur, and oxygen contents in accordance with ASTM D5373 and ASTM D4239 standards. This analysis provides insight into fuel quality, combustion behavior, and emission characteristics.

Calorific Value Determination

The higher heating value (HHV) of each biomass sample was determined using an isoperibol bomb calorimeter (Parr 6200) following ASTM D5865 / ISO 1928 standards. Each sample was pressed into pellets of approximately 0.5–1.0 g to ensure uniform and complete combustion in the bomb vessel. Benzoic acid (certified standard, 26.454 MJ/kg) was used for calorimeter calibration. Three independent replicates were performed for each sample and the mean value reported. The lower heating value (LHV) was subsequently calculated from the HHV using the hydrogen content from ultimate analysis via: $LHV = HHV - 2.442 \times (9H/100)$, where H is the hydrogen mass fraction on a dry basis.

Thermogravimetric Analysis

Thermogravimetric analysis was performed using a simultaneous TGA/DSC analyzer at Bayero University Kano. Approximately 5–10 mg of each finely ground, sieved sample was placed in an alumina (α-Al_2O_3) crucible. The temperature was ramped from 30 °C to 900 °C at a constant heating rate of 10 °C/min under two atmospheric conditions: (1) Inert atmosphere — high-purity nitrogen (N_2, 99.99%) at a flow rate of 50 mL/min to simulate pyrolysis conditions; and (2) Oxidative atmosphere — synthetic air (21% O_2/79% N_2) at a flow rate of 50 mL/min to simulate combustion conditions. The TGA curve (normalized mass % versus temperature) and the first derivative DTG curve (rate of mass loss, %/°C, versus temperature) were recorded and analyzed using instrument software. Key parameters extracted from the DTG profiles include: onset temperature of Stage II (T_onset, defined at 2% mass loss rate), peak decomposition temperature (T_peak), end temperature of active decomposition (T_end), and residual mass at 900 °C. Burnout temperature under air atmosphere was defined as the temperature at which mass loss rate falls below 1% of peak rate.

RESULTS AND DISCUSSIONS

Proximate Analysis and Calorific Value

The proximate analysis is conducted to determine the percentage composition.

Table 1: Proximate Analysis and Calorific Value of the Raw Samples

S/N	Samples	Moisture content (%)	Ash content (%)	Volatile matter (%)	Fixed carbon (%)	Calorific Value (MJ/Kg)
1.	sugarcane	4.85	1.99	90.71	2.45	18.17
2.	coconut shell	3.40	1.99	92.18	2.43	18.42
3.	date seed	3.70	3.00	92.10	1.20	14.69

The proximate analysis reveals that all three raw biomass samples possess low moisture content, ranging from 3.40% for coconut shell to 4.85% for sugarcane. This is highly advantageous for thermochemical conversion because high moisture content demands significant thermal energy for water vaporization, which lowers the overall efficiency of the pyrolysis reactor. Furthermore, the ash content representing the non-combustible inorganic residue is exceptionally low for sugarcane and coconut shell (1.99%), and only slightly higher for date seed (3.00%). In thermochemical systems, minimizing ash is critical because high inorganic concentrations trigger reactor fouling, slagging, and accelerated catalytic cracking of volatile vapors, meaning these specific feedstock's will minimize operational challenges while producing cleaner products.

A defining characteristic of this feedstock is their extremely high volatile matter, which exceeds 90% across all samples, peaking at 92.18% in the coconut shell. This indicates that the biomass structures are highly reactive and will readily decompose into condensable vapors and non-condensable syngas when subjected to thermal degradation in an oxygen-free environment. Conversely, the fixed carbon contents are inherently low (1.20% to 2.45 %) because the majority of the organic matrix is bound within these volatile fractions. Consequently, while these raw feedstocks are naturally skewed toward maximizing liquid bio-oil and syngas yields during fast pyrolysis, they require careful control of process parameters, such as heating rate and residence time, if the objective is to optimize solid briquette production.

The calorific value measures the chemically bound energy density of the biomass, with coconut shell exhibiting the highest heating value at 18.42MJ/kg , followed by sugarcane at 18.17MJ/kg, and date seed at 14.6MJ/kg. The superior energy density of the coconut shell and sugarcane correlates with their lower ash content and typically higher proportions of lignin, a complex polymer that inherently stores more energy than cellulose or hemicellulose. Ranging from 14.69 To 18.42 MJ/kg, these energy profiles are highly competitive with standard agricultural residues used globally in bioenergy conversion. This confirms that these local feedstocks possess sufficient thermal energy potential to serve as viable alternatives for clean fuel generation and sustainable bio-char synthesis.

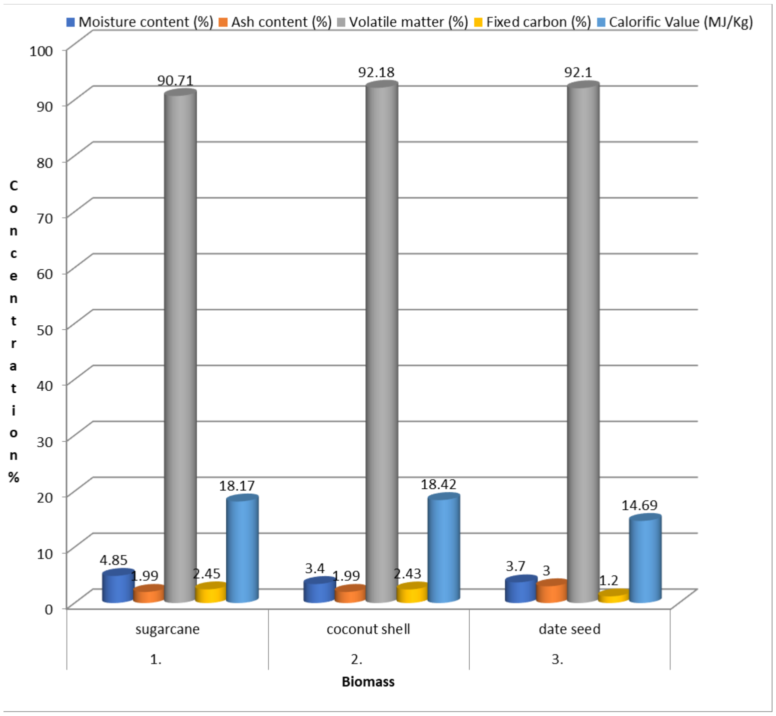

Figure 1: Chart Showing Variations in Physical Parameters

Table 2: Ultimate Analysis of the Raw Samples

S/N	SAMPLE ID	CARBON (%)	HYDROGEN (%)	NITROGEN	SULPHUR (%)	OXYGEN (%)
1	Sugarcane	47.28	5.40	0.19	0.030	47.1
2	Coconut Shell	52.60	5.26	0.12	0.031	41.98
3	Date Seed	49.41	6.52	0.58	0.061	43.42

Figure 1 the expected variations in moisture content, Ash content, Volatile matter content and fixed carbon content for Samples.

Ultimate Analysis of the Raw Samples

The ultimate analysis provides the definitive elemental composition specifically Carbon (C), Hydrogen (H), Nitrogen (N), Sulphur (S), and Oxygen (O) of the raw sugarcane, coconut shell, and date seed samples. Evaluating these basic chemical building blocks is essential for understanding the fuel structure, expected volatile interactions, and environmental implications of the feedstock's during thermochemical processing. Carbon and hydrogen serve as the principal oxidizable elements in biomass, where the cleavage of C–H and C–C bonds during pyrolysis or combustion releases thermal energy.

Coconut shell exhibits the highest elemental carbon fraction at 52.60%, followed by date seed at 49.41%, and sugarcane at 47.28%. Conversely, date seed displays the highest hydrogen concentration at 6.52%, while sugarcane (5.40%) and coconut shell (5.26%) show slightly lower, comparable values. The high concentration of carbon in the coconut shell directly accounts for its superior calorific value (18.42MJ/kg) recorded in the proximate analysis. High proportions of carbon and hydrogen relative to oxygen are structurally desirable in solid fuels because they elevate the higher heating value (HHV), confirming that coconut shell and date seed possess excellent for high-energy content. Oxygen in biomass typically resides within cellulose, hemicellulose, and lignin polymers. According to the updated data, sugarcane contains the highest oxygen content at 47.1%, followed by date seed (43.42%) and coconut shell (41.98%).

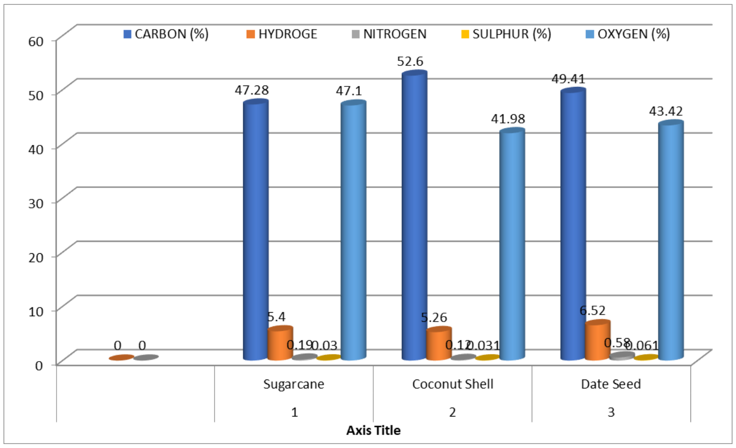

Figure 2: Elemental Analysis Chart

The figure 2 shows variations in the compositional values of carbon, Hydrogen, Nitrogen, Oxygen and Sulphur in both sugarcane, coconut shell and date seed. Carbon content of the materials ranges from 47.28% to 49.56 %. Theses are typical values within the range of biomass which is between 30% to 50% (Dermibas, 2004). Hydrogen content of the sample ranges between 5.30% to 6.22% . The ranges of these values matched with the range typically obtained for biomass that is between 5% and 7%. (Kumar et al., 2018).

Nitrogen content of the samples ranges from 0.12% to 0.58%. These are values needed for every biomass 10% and 20% (Kumar et al., 2019). Oxygen content of the sample ranges from 41.98% down to 47.10% it is within 10% and 15% obtainable as reported by (Dermibas, 2004). Sulphur the 0.030% to 0.080% obtained lies within typical range observed by (Singh et al., 2017).

Thermogravimetric Curve

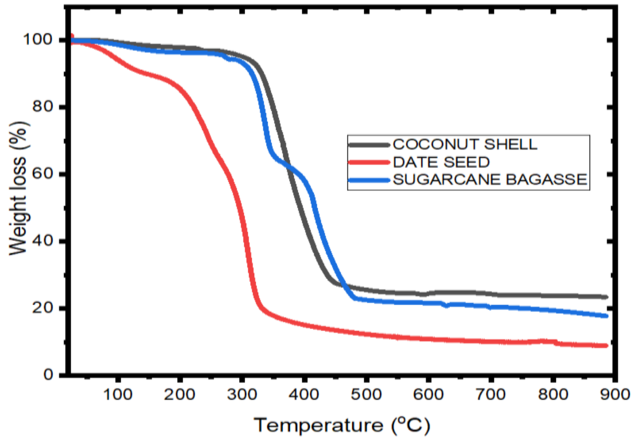

Figure 3: TGA Curve of Coconut Shell, Date Seed and Sugarcane Bagasse

The thermogravimetric analysis (TGA) revealed that coconut shell and sugarcane bagasse undergo thermal degradation in several distinct stages corresponding to moisture evaporation, active devolatilization, and char formation. The initial weight loss observed below approximately 100–150 °C is attributed to the removal of physically absorbed moisture from the biomass materials. Similar observations have been reported by Yang et al. (2007), who stated that moisture evaporation occurs at low temperatures before the decomposition of the major lignocellulosic components.

The major weight loss occurred within the temperature range of approximately 200–400 °C, representing the active pyrolysis zone. This stage is associated with the decomposition of hemicellulose and cellulose, which release volatile compounds and contribute significantly to mass reduction. Hemicellulose generally decomposes between 200 and 315 °C, while cellulose decomposes rapidly between 315 and 400 °C (Yang et al., 2007). The gradual mass loss observed above 400 °C is attributed to lignin decomposition, which occurs over a wider temperature range because of its complex aromatic structure.

Coconut shell exhibited greater thermal stability and retained more residual mass compared to sugarcane bagasse. This behavior can be attributed to its higher lignin content, which enhances resistance to thermal degradation and promotes greater char formation. Similar findings were reported by Tsai et al. (2006), who observed higher char yields from coconut shell due to its lignin-rich composition. Conversely, sugarcane bagasse showed faster decomposition because of its higher cellulose and hemicellulose contents, which are more readily volatilized during process.

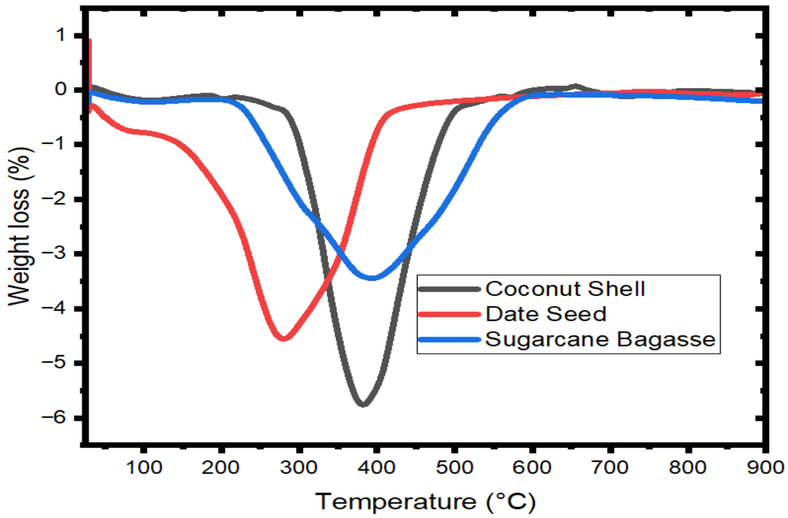

Figure 4: D TGA Curve of Coconut Shell, Date Seed and Sugarcane Bagasse

The derivative thermogravimetric analysis (DTGA) provided further insight into the decomposition behavior of the biomass samples by indicating the rate of weight loss with temperature. The DTGA curves generally exhibited distinct peaks corresponding to the decomposition of hemicellulose and cellulose. The first peak at lower temperatures is associated with hemicellulose degradation, while the major peak corresponds to cellulose decomposition.

The broader DTGA peak observed for coconut shell suggests a slower and more gradual decomposition process, indicating higher thermal stability. In contrast, sugarcane bagasse displayed a sharper peak, reflecting rapid devolatilization and faster thermal degradation. Similar DTGA patterns have been reported by many researchers studying lignocellulosic biomass, confirming that the thermal behavior of biomass is strongly influenced by the proportions of cellulose, hemicellulose, and lignin present in the material (Yang et al., 2007).

The higher thermal stability of coconut shell suggests that it may be more suitable for biochar production due to its greater residual carbon content, while sugarcane bagasse may be more appropriate for processes aimed at producing higher volatile yields, such as bio-oil and syngas production.

The thermogravimetric analysis (TGA) of coconut shell and sugarcane bagasse revealed a multi-stage thermal degradation process characteristic of lignocellulosic biomass materials. The initial weight loss observed at temperatures below approximately 150 °C is attributed to the evaporation of moisture and other light volatile compounds present in the biomass. This stage generally involves the removal of physically absorbed water and occurs with minimal structural decomposition.

The major weight loss occurred within the temperature range of approximately 200–400 °C, corresponding to the active pyrolysis region. During this stage, hemicellulose decomposes first because of its lower thermal stability, followed by cellulose degradation at higher temperatures. The rapid decrease in mass observed in this temperature range indicates extensive devolatilization and the release of gaseous products. Similar findings were reported by

Yang et al. (2007), who observed that hemicellulose decomposes between 220–315 °C, cellulose between 315–400 °C, while lignin decomposes slowly over a broad temperature range.

Coconut shell exhibited higher thermal stability than sugarcane bagasse, as indicated by its slower rate of decomposition and greater residual mass after pyrolysis. This behaviour can be attributed to the higher lignin content of coconut shell, since lignin possesses a complex aromatic structure that resists thermal degradation and promotes char formation. In contrast, sugarcane bagasse contains higher cellulose and hemicellulose contents, leading to faster decomposition and lower char yield. Tsai et al. (2006) similarly reported that coconut shell produced a greater amount of solid residue due to its higher lignin concentration.

CONCLUSION

After successful hybridization of the three different biomass samples, findings revealed possibility in exchanging core qualities for achieving sustainable fuel that could serve the energy solution. An alternative heat source has been unveiled based on the scientific analysis conducted where a modest combustible with reasonable calorific value and other necessary qualities such as moisture, ash, Volatile, fixed carbon, nitrogen, sulfur, hydrogen oxygen and thermogravimeric analysis.

It clearly shows how Sugarcane, coconut shell and date seed can be considered as a source of heat that can replace hazardous conventional firewood used globally having lower than 50% of carbon content and Nitrogen far lower to about 5%. Availability, affordability, cleanliness, recycling ability, and calorific value are the qualities to consider as advantages.

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