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### Combustion profiles: A means to characterize the Cretaceous-Cenozoic coals in the Benue Trough, Nigeria: An insight for Electricity Power Generation.

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#### Abstract

This study presents an integrated geochemical, petrographic, and thermogravimetric assessment of Cretaceous-Cenozoic coal deposits from the Benue Trough, Nigeria, with the objective of characterizing their combustion behavior and evaluating their suitability for thermal power generation. The Benue Trough is a major NE-SW trending intracontinental rift basin extending from the Gulf of Guinea to the Chad Basin and hosts significant coal-bearing successions of economic importance. Despite the global transition toward low-carbon energy systems, coal remains a strategic component of the global energy mix, particularly in developing economies where energy demand continues to increase and infrastructure for renewables remains limited. Twenty-nine representative coal samples collected from multiple sub-basins within the trough were subjected to proximate analysis, total sulfur determination, bomb calorimetry, reflected-light petrography (maceral quantification), and thermogravimetric analysis (TGA). Proximate data indicate generally high volatile matter contents and low ash yields, consistent with sub-bituminous to high-volatile bituminous rank. The average gross calorific value is 24.82 MJ/kg, suggesting moderate-to-high energy potential. Total sulfur contents are generally low to moderate, supporting their potential for relatively cleaner combustion compared to high-sulfur coals. Petrographic examination reveals that the organic fraction is dominated by vitrinite (mean 59.3 vol.% on a mineral-matter-free basis), indicating significant contribution from woody precursor material deposited under predominantly reducing conditions. Inertinite contents show marked variability across the Upper, Middle, and Lower Benue sub-regions, reflecting spatial differences in paleofire intensity, oxidation conditions, and depositional regimes. Liptinite macerals are sparse and notably absent in samples from the Middle Benue Trough, suggesting limited preservation of hydrogen-rich algal or resinous components. Thermogravimetric profiles demonstrate characteristic devolatilization and combustion stages consistent with vitrinite-rich coals. Except for samples O1 and 17, which exhibit anomalously high ash yields (73.03 wt.% and 81.57 wt.%, respectively) and are thus unsuitable for efficient combustion, the majority of the samples meet fundamental criteria for coal-fired power applications. Overall, the results establish that most Benue Trough coals possess favorable combustion characteristics and calorific properties, supporting their strategic potential for domestic power generation and energy security in Nigeria.

#### Keywords

Coal Combustion;  
Mamu Formation;  
Awgu Formation;  
Macerals;  
Proximate Analysis.

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## 1. Introduction

This study presents the combustion characteristics and petrographic composition of Cretaceous-Cenozoic coal deposits in the Benue Trough, Nigeria, to evaluate their potential for power generation. The petrographic composition of coal samples reveals the complexity of coal in terms of its discrete microscopic organic (maceral) and inorganic (mineral) components and their relationships. Coal is a highly versatile fossil fuel used primarily for electricity generation in industrialized nations, thanks to its reliability and affordability [1]. Despite Nigeria's substantial coal reserves, which are estimated at 639 million tonnes of proven and 2.75 billion tonnes of inferred, the country has not fully harnessed this resource due to misplaced priorities and a lack of technological expertise [2, 3, 4, 5, 6].

In 2014, the Nigerian government set a target for 30% of the country's electricity to be generated from coal, highlighting the need for a strategic shift towards coal utilization [3, 4, 5, 6]. This study aims to characterize coal samples from the three sub-regions of the Benue Trough - the Lower Benue Trough (LBT), Middle Benue Trough (MBT), and Upper Benue Trough (UBT) - based on their combustion reactivity profiles. These profiles are crucial for assessing coal quality and predicting combustion behavior, which can inform the development of coal-fired power stations and contribute to Nigeria's energy mix [1]. While the country currently does not utilize coal for electricity generation, coal's potential extends beyond power, encompassing metallurgical processes and other industrial applications [1].

The petrographic composition of the Benue Trough's coal deposits, marked by moderate levels of vitrinite macerals and varying proportions of inertinite, liptinite, and mineral

matter, is a key factor in understanding coal behavior [7, 8]. This study's findings on coal quality and combustion characteristics can provide valuable insights for the optimization of coal utilization in Nigeria, ultimately supporting the country's efforts to secure a stable and sustainable energy supply [2].

Proximate analysis and regional variability show the LBT samples are characterized by high fixed carbon, rich volatile matter, and consistently low ash content (ash yield typically <17.6 wt.%), making them premium quality for energy application [1, 2]. MBT samples exhibit high fixed carbon and volatile matter but elevated ash content in samples 01 (73.03 wt.%) and 06 due to mineral impurities like kaolinite and quartz [12]. UBT samples show high fixed carbon and volatile matter are offset by very high ash in samples 11 and 17 (81.57 wt.%) alongside elevated moisture, impairing combustion efficiency [1, 2]. Sulfur content universally shows low sulfur levels (<0.85% dry ash-free) across all samples, reducing environmental concerns [9, 10].

### Petrographic composition and implications

**Maceral distribution:** Vitrinite dominates at 59.3% (mineral-matter-free avg.), enhancing reactivity during combustion [10]. Inertinite and liptinite show significant variability. Inertinite prolongs burnout time, while liptinite (absent in MBT) aids devolatilization [10]. Mineral matter (e. g kaolinite, quartz) constitutes 3.2-79.0 wt.%, directly correlating with ash content [10].

**Spontaneous combustion risk:** Vitrinite-rich samples increase proneness to spontaneous ignition, while inertinite slows but extends combustion, raising storage/transport risks [10]

## 2. The geology of the study area.

The Benue Trough is characterized by a thick sedimentary deposit that unconformably overlies the Precambrian Basement rocks [10, 11, 12, 13, 14, 15, 16, 17]. This sedimentary deposit is part of a Rift System that has undergone several tectonic events, resulting in episodes of subsidence which eventually led to its opening into the South Atlantic Ocean [18, 19, 20]. The basin's thickness varies between 4,000 and 6,000 meters [21, 22, 23, 24].

Many modern analytical and sampling techniques have greatly contributed to our understanding of the Benue Trough's geology [25]. It primarily consists of organic matter, and coal seams are hosted by three distinct geological units: The Mamu Formation of the Campanian-Maastrichtian age in the Lower Benue Trough (LBT), the Awgu Formation of the Turonian-Santonian depositional cycle in the Middle Benue Trough (MBT), and the Gombe Sandstone, Numanha Shale, and Lamja Sandstone Formation of the Upper Cenomanian-Turonian-Santonian ages in the Upper Benue Trough (UBT) [10]. Over the years, extensive research has been conducted on the Benue Trough by various geologists and researchers, and their findings continue to provide valuable insights into the geology of this extensive Rift System [24, 25, 26, 27, 28, 29, 30, 31].

## 3. Materials and Methods.

### 3.1. Sampling

In the Benue Trough, a total of 29 grab samples of coal were acquired from 18 coal locations (7 samples from UBT, 9 from MBT and 13 from the LBT). The samples were labelled and kept in zip lock sample bags [10, 23, 23, 24].

### 3. 2. Sample Preparation

All obtained coal samples were representative of their parent sources and were stored appropriately before analysis to prevent oxidation and uncontrolled physical changes. The samples were combined with epoxy resin and hardener, formed into blocks with a 30mm diameter, and left overnight in a vacuum to eliminate air bubbles. The blocks were then prepared for petrographic analysis through a process that produced a clean, uniformly flat, pit-free, and scratch-free surface of the embedded coal particles. This preparation involved several stages [10, 23, 23, 24].

1. **Initial Grinding:** The blocks were ground using an MD Largo 9 (Allergro) diamond suspension.
2. **Secondary Grinding:** Further grinding was done using an MD DAC Dia-Pro 3 diamond suspension.
3. **Final Polishing:** The blocks were ultimately polished with an MD Chem OP-S non-dry colloidal silica suspension. The entire procedure adhered to the standards set in SANS 7404-3:1994 / ISO 7404-3 [10, 22, 23, 24].

### 3. 3. Sample Analyses

Approximately 1g of sample (212 $\mu$ m) of coal was placed in the TGA under air at a capacity flow of 3.5L min<sup>-1</sup> with about 80 mg of fuel used for each experiment. Working process involved heating the samples at a continuous rate of 10°C min<sup>-1</sup> until equilibrium in weight loss was observed [10, 22, 23, 24].

## 4. Result Presentation.

### 4.1 Chemical Analyses

The chemical analyses of the 29 coal samples present the chemical composition for each of the analyzed samples (Table 1).

Table 1. Proximate, GCV, and Ultimate data [10, 22, 23, 24]

Proximate Analysis (Wt. %)						Gross Calorific Value (CV)	Ultimate Analysis (%) (Daf)				
Sample	I. D	V M	F C	Ash	Moist	(MJ/Kg)	S	C	H	N	O <sup>a</sup>
UBT	11	24.0	39.4	31.0	5.6	20.28	0.79	76.40	5.98	2.05	14.78
	12	29.8	58.8	6.8	4.6	28.70	0.81	75.13	5.42	1.94	16.69
	13	27.7	47.8	21.8	5.6	24.55	0.51	78.50	6.40	1.58	13.00
	14	25.1	51.5	18.3	5.1	24.64	0.48	76.67	5.56	1.62	15.66
	15	31.1	52.1	6.8	10.0	26.19	0.32	73.47	5.82	1.48	18.91
	16	28.7	40.6	21.1	9.6	20.27	7.34	65.64	6.07	1.24	19.70
	17	14.0	3.8	79.0	3.2	1.90	2.19	39.75	7.68	1.63	48.76
Areal											
Ave.	27.7	48.4	17.6	6.8	24.11	0.85	74.30	5.88	1.72	16.46	
MBT	01	16.0	9.5	69.2	5.2	4.07	0.74	54.76	7.39	1.99	35.11
	02	23.4	57.4	15.7	3.4	28.49	0.78	83.25	5.33	2.18	8.46
	03	24.6	55.7	12.3	7.5	24.16	0.97	73.75	4.85	1.94	18.49
	04	22.3	43.0	25.1	9.6	18.21	1.03	70.62	4.90	1.99	21.46
	05	23.4	48.3	17.9	10.4	20.61	0.92	70.72	4.81	1.97	21.58
	06	19.9	33.3	37.2	9.7	12.68	0.88	63.07	5.21	1.83	29.01
	07	24.6	39.0	24.3	12.1	15.02	0.64	60.72	5.24	1.82	31.57
	08	20.5	60.0	18.3	1.2	27.85	1.27	81.12	5.12	2.09	10.41
	09	40.8	45.6	3.7	10.0	28.73	2.08	70.98	6.96	1.57	18.40
Areal											
Ave.	24.9	47.8	19.3	8.0	21.97	0.90	71.78	5.30	1.92	19.92	
LBT	10	42.9	44.0	3.2	9.8	30.02	0.61	73.86	7.02	1.94	16.57
	18	33.7	51.8	11.0	3.5	29.36	4.02	80.00	5.84	1.71	8.43
	19	31.7	52.0	12.6	3.6	28.39	0.84	78.20	6.36	2.13	12.47
	20	37.0	47.7	11.5	3.7	28.93	2.03	78.33	6.32	1.76	11.55
	21	30.6	50.8	12.8	5.8	26.11	0.66	72.26	5.97	1.93	19.17
	22	33.4	48.3	10.5	7.9	28.63	0.71	78.64	6.27	1.97	12.40
	23	30.0	50.5	15.2	4.3	28.52	0.86	80.09	6.80	2.17	10.08
	24	39.4	39.5	16.6	4.4	26.11	0.77	72.19	7.80	1.52	17.71
	25	32.8	48.9	13.4	7.9	26.85	0.79	74.33	6.86	1.83	16.19
	26	36.6	48.9	5.8	8.7	28.58	0.61	73.79	6.19	1.64	17.78
	27	36.5	44.0	6.5	13.0	29.42	0.70	74.23	7.46	1.66	15.95
	28	35.3	46.8	7.3	10.6	27.79	0.74	71.59	6.49	1.64	19.54
29	30.9	47.4	5.9	15.8	30.33	0.73	74.97	8.47	1.95	13.88	
Areal											
Ave.	34.7	47.7	10.2	7.6	28.39	1.08	75.58	6.76	1.83	14.75	
Areal											
Total Ave	29.1	48.0	15.7	7.45	24.82	0.94	73.89	5.98	1.82	17.04	

## 4.2 Combustion Test (TGA)

The twenty-nine (29) coal samples combustion profiles results were generated by the thermogravimetric analyzer (Figures 1-3). The combustion profiles provide some understanding on each sample combustibility and is not an in-depth study, rather indicative of potential use.

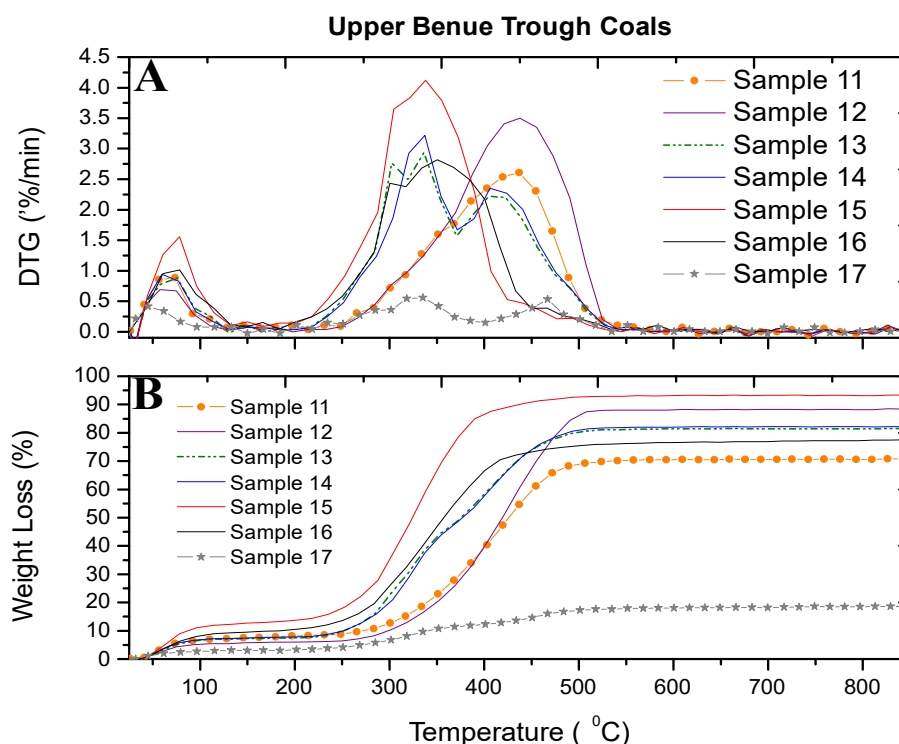


Figure 1. Combustion reactivity curves for the coal (UBT) [10, 22, 23, 24]

### Subplot A. DTG (%/min) VS Temperature (°C)

DTG (Derivative Thermogravimetry) measures the rate of weight loss per minute as a function of temperature. This plot helps identify the stages of combustion and the intensity of reactions occurring at different temperatures [32, 33, 34]. All samples exhibit similar trends, with peaks indicating significant weight loss rates during specific temperature ranges. The primary peak around 300-400°C corresponds to the devolatilization stage, where volatile organic compounds are released. Secondary peaks at higher temperatures (around 500-600°C) likely represent the char combustion stage [24]. Sample 17 shows a lower peak intensity compared

to other samples, suggesting less efficient combustion due to its high ash content. [10]

### Subplot B: Weight Loss (%) VS. Temperature (°C)

Weight Loss (%) indicates the cumulative mass reduction of the sample as it undergoes heating [32, 33, 34]. This plot reflects the overall extent of decomposition and combustion. All samples experience initial weight loss starting around 100°C, which increases sharply between 200-400°C, corresponding to the devolatilization stage. By 600°C, most samples reach a plateau, indicating the completion of major combustion processes [35]. Sample 17 shows significantly less weight loss compared to others, consistent with

its high ash content and reduced combustibility [10].

The TGA results confirm that most samples exhibit good combustion characteristics, with high volatile matter and low ash content contributing to efficient weight loss during heating. Sample 17 stands out due to its poor

combustion performance, aligning with the earlier finding of extremely high ash content. These findings support the conclusion that most Benue Trough coals are suitable for power generation, except for those with high ash content requiring beneficiation.

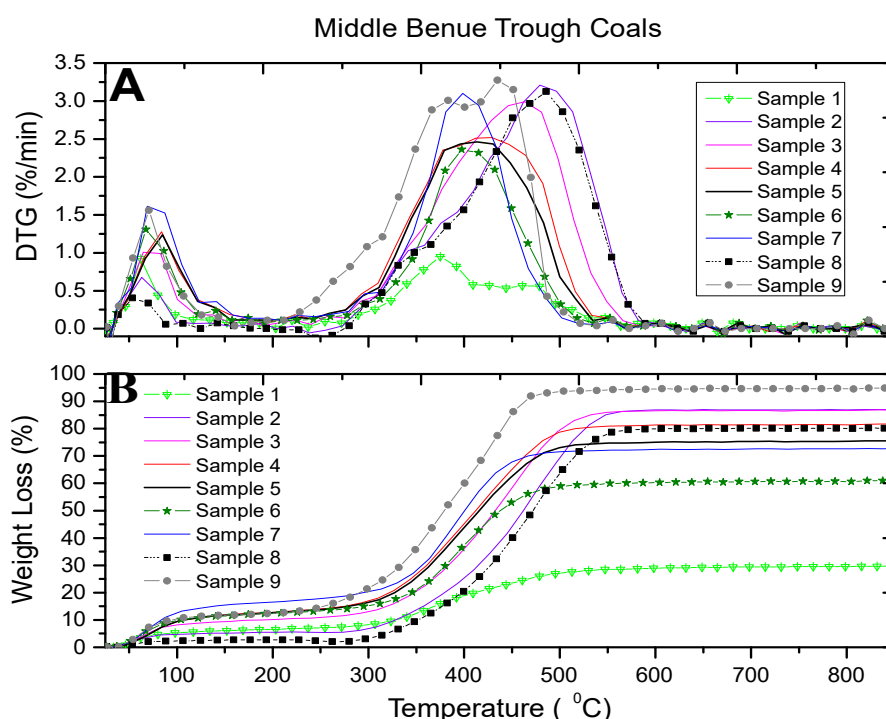


Figure 2. Combustion reactivity curves for the coal (MBT) [10, 22, 23, 24]

#### Subplot A: DTG (%/min) vs. Temperature (°C)

**DTG (Derivative Thermogravimetry)** measures the rate of weight loss per minute as a function of temperature. This plot highlights the stages of combustion and the intensity of reactions at different temperatures. All samples exhibit similar trends, with peaks indicating significant weight loss rates during specific temperature ranges. The primary peak around 300–400°C corresponds to the devolatilization stage, where volatile organic compounds are released. Secondary peaks at higher temperatures (around 500–600°C) likely represent the char combustion stage. Samples 1 and 8 shows a lower peak intensity compared to other samples, suggesting

less efficient combustion due to their high ash content.

#### Subplot B: Weight Loss (%) vs. Temperature (°C)

**Weight Loss (%)** indicates the cumulative mass reduction of the sample as it undergoes heating. This plot reflects the overall extent of decomposition and combustion. All samples experience initial weight loss starting around 100°C, which increases sharply between 200–400°C, corresponding to the devolatilization stage. By 600°C, most samples reach a plateau, indicating the completion of major combustion processes. Samples 1 and 8 shows significantly less weight loss compared to others, consistent

with its high ash content and reduced combustibility.

The TGA results confirm that most samples exhibit good combustion characteristics, with high volatile matter and low ash content contributing to efficient weight loss during heating. Samples 1 and 8 stands out due to their

poor combustion performance, aligning with the earlier finding of extremely high ash content.

These findings support the conclusion that most Benue Trough coals are suitable for power generation, except for those with high ash content requiring beneficiation.

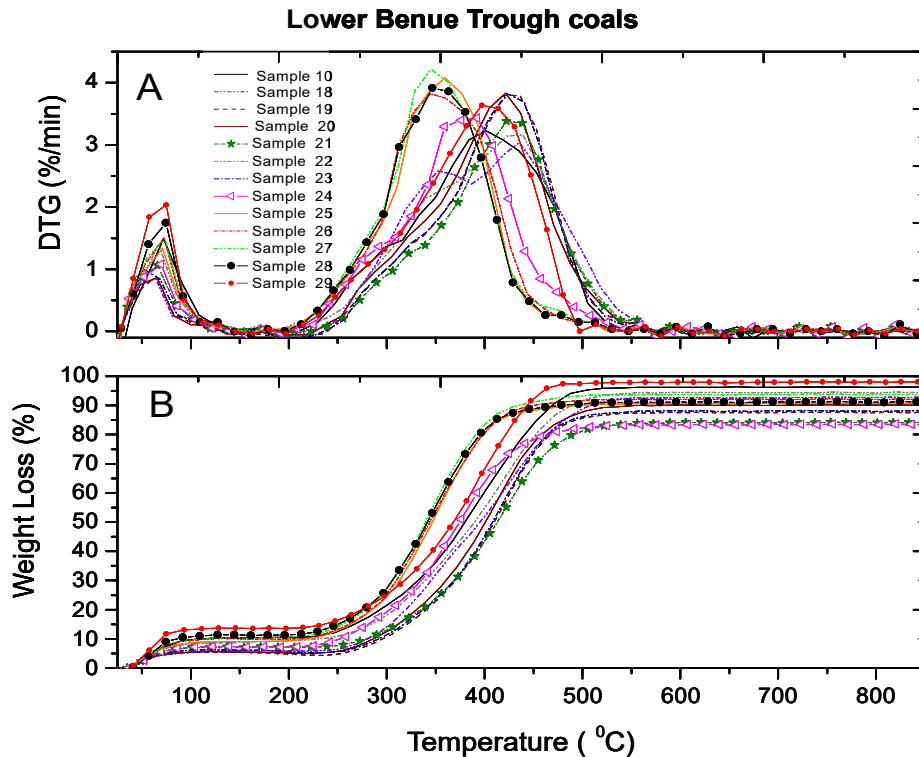


Figure 3. Combustion reactivity curves for the coal (LBT) [23]

#### Subplot A: DTG Curves

##### Three Stages of Combustion

**Devolatilization Stage (Below 300°C):** All samples exhibit a sharp peak in the DTG curve around 100°C, indicating the release of moisture and volatile organic compounds. This stage is characterized by rapid weight loss.

**Volatile Burning Stage (300-500°C):** A second, broader peak appears in this range, representing the combustion of volatiles released during devolatilization. The intensity and position of this

peak vary among samples, reflecting differences in their volatile matter content.

**Char Combustion Stage (Above 500°C):** The DTG curves gradually decline after 500°C, indicating the slower oxidation of residual carbon (char). Some samples show a slight increase in DTG at higher temperatures, possibly due to the presence of reactive minerals.

### Sample-Specific Variations

Samples like Sample 10, Sample 18, and Sample 20 display relatively high DTG peaks during the volatile burning stage, suggesting a higher volatile matter content compared to other samples.

Sample 28 and Sample 29 show lower DTG peaks, indicating less volatile matter and potentially poorer combustion reactivity.

### Temperature Dependence

The onset temperature for significant weight loss varies slightly among samples, ranging from approximately 100°C to 150°C. This variation could be attributed to differences in moisture content and the nature of volatile compounds present in each sample.

### Sub plot B: Cumulative Weight Loss Curves

The weight loss curves show a gradual increase up to about 90% weight loss, with most samples reaching this level by 600°C. Beyond this point, the weight loss plateaus, indicating the completion of major combustion processes.

Samples with higher volatile matter content (e.g., Sample 10, Sample 18) achieve greater weight loss at lower temperatures compared to samples with lower volatile matter content (e.g., Sample 28, Sample 29).

### Residual Ash Content:

The final weight loss percentages suggest that some samples leave behind a significant amount of ash, particularly those with lower overall weight loss. For example, Sample 28 and Sample 29 retain more weight at higher temperatures, indicating higher ash content.

### Combustion Efficiency

Samples with steeper weight loss curves (e.g., Sample 10 and Sample 18) demonstrate higher combustion efficiency, as they achieve greater weight loss within a shorter temperature range. In contrast, samples with flatter curves (e.g. Sample 28 and Sample 29) exhibit lower combustion efficiency [10].

### Implications for Coal Quality and Power Generation

The combustion reactivity curves provide valuable insights into the suitability of these coal samples for power generation:

**High Volatile Matter and Low Ash Content:** Most samples exhibit favorable combustion characteristics, with high volatile matter content and low ash content, making them suitable for use in power plants. These properties contribute to efficient and clean combustion, reducing the formation of harmful emissions.

**Regional Variation:** The observed differences in combustion behavior among samples highlight regional variations in coal quality within the Lower Benue Trough. Understanding these variations is crucial for optimizing coal utilization and minimizing environmental impacts.

**Poor Combustion Performance:** Sample 1 shows poor combustion performance, likely due to its high ash content. Such samples may require additional processing or blending with higher-quality coals to improve their combustion efficiency and reduce ash-related issues.

Table 2. Temperature characteristics (as indicative), proximate, ultimate, CV, and petrographic data of the coal deposits within the Benue Trough [10, 24].

TGA (TEMPERATURES °C)		CV MJ/kg			PROXIMATE /ULTIMATE (Wt. %)				PETROGRAPHY (Vol%)					
Sub / Basin	S/ ID	T <sub>I</sub>	T <sub>P</sub>	S/ T <sub>B</sub>	ID CV	Moist	Ash	VM	Carbon (daf)	RoV	Rank (ISO 11790)	Vit. mmf	Inert mmf	Lip mmf
UBT	11	230	437.0	557.8	19.14	5.6	31.0	24.0	76.40	0.64	Med..R. C	64.2	27.6	8.2
	12	230	437.8	542.0	27.37	4.6	6.8	29.8	75.13	0.71	Med..R. C	70.2	20.4	9.4
	13	225	336.2	543.0	23.17	5.6	21.8	27.7	78.50	0.56	Med..R. D	53.4	43.5	3.1
	14	230	337.3	544.4	23.38	5.1	18.3	25.1	76.67	0.64	Med..R. C	48.9	46.6	4.5
	15	220	338.1	528.0	23.57	10.0	6.8	31.1	73.47	0.37	Low R. B	24.8	72.7	2.5
	16	220	350.5	533.7	18.33	9.6	21.1	28.7	65.64	0.38	Low R. B	34.7	57.5	7.8
	17	230	335.2	534.9	1.84	3.2	79.0	14.0	39.75	0.44	Low R. A	68.2	28.2	3.6
MBT	01	230	375.0	563.6	3.86	5.2	69.2	16.0	54.76	0.81	Med..R. C	29.5	70.5	0.0
	02	270	479.3	616.4	27.51	3.4	15.7	23.4	83.25	0.91	Med..R. C	85.7	13.2	1.1
	03	271	463.2	583.7	22.36	7.5	12.3	24.6	73.75	0.85	Med..R. C	89.7	10.1	0.2
	04	272	429.1	567.4	16.46	9.6	25.1	22.3	70.62	0.93	Med..R. C	94.5	5.3	0.2
	05	270	413.5	568.4	18.48	10.4	17.9	23.4	70.72	0.91	Med..R. C	86.4	13.6	0.0
	06	269	397.7	535.8	11.45	9.7	37.2	19.9	63.07	0.62	Med..R. C	75.8	24.2	0.0
	07	270	398.5	519.4	13.19	12.1	24.3	24.6	60.72	0.77	Med..R. C	84.9	14.8	0.3
	08	280	485.8	598.0	27.52	1.2	18.3	20.5	81.12	1.00	Med..R. B	85.1	14.0	0.9
	09	290	434.9	521.3	25.86	10.0	3.7	40.8	70.98	0.35	Low R. B	48.1	16.6	35.3
LBT	10	225	401.3	539.7	27.07	9.8	3.2	42.9	73.86	0.45	Low R. A	59.1	18.0	22.9
	18	226	435.5	569.5	28.34	3.5	11.0	33.7	80.00	0.43	Low R. A	34.8	58.4	6.8
	19	225	420.4	570.4	27.36	3.6	12.6	31.7	78.20	0.46	Low R. A	51.9	31.9	16.2
	20	224	421.2	571.5	27.84	3.7	11.5	37.0	78.33	0.42	Low R. A	36.9	49.5	13.6
	21	220	422.5	572.6	24.58	5.8	12.8	30.6	72.26	0.52	Med..R.D	33.8	58.9	7.3
	22	220	439.2	573.6	26.38	7.9	10.5	33.4	78.64	0.45	Low R. A	41.3	49.7	9.0
	23	219	423.9	574.3	27.31	4.3	15.2	30.0	80.09	0.53	Med..R.D	55.6	35.0	9.4
	24	227	392.5	575.2	24.95	4.4	16.6	39.4	72.19	0.49	Low R. A	59.0	15.0	26.0
	25	220	359.6	526.3	24.72	7.9	13.4	32.8	74.33	0.43	Low R. A	54.2	43.1	2.7
	26	221	344.7	527.6	26.10	8.7	5.8	36.6	73.79	0.42	Low R. A	29.3	63.0	7.7
	27	220	345.4	528.7	25.61	13.0	6.5	36.5	74.23	0.45	Low R. A	57.5	34.9	7.6
28	200	346.8	529.9	24.85	10.6	7.3	35.3	71.59	0.39	Low R. B	49.5	43.1	7.4	
29	200	397.3	497.1	25.53	15.8	5.9	30.9	74.97	0.37	Low R. B	71.7	8.1	20.2	

## 5. Discussion.

According to the document, the most preliminary investigations that determine the coal chain value are gross calorific value, proximate and ultimate analyses. Other analyses, such as petrography (maceral groups) and rank determination (mean vitrinite reflectance), are considered secondary.

The volcanic matter, hydrogen, and oxygen content of coal samples decreases as carbon content increases, resulting in higher thermal properties. Additionally, the ash content of coal ranges from 3.2 to 79.0 wt.%, mainly due to the presence of kaolinite and quartz minerals.

### Petrographic Composition (Vol%)

**Rank (ISO 11790):** Coal rank based on international standards. Ranges from Low Rank Anthracite (Low R. A) to Medium Rank Coking Coal (Med. R. C), indicating varying degrees of coal maturity.

**Vitrinite Macerals (Vit. mmf):** The percentage of vitrinite macerals, which are derived from woody plant material. Values range from 24.8% to 94.5%, with higher vitrinite content generally associated with better combustion properties.

**Inertinite Macerals (Inert mmf):** The percentage of inertinite macerals, which are derived from non-woody plant material and are less reactive. Values range from 0.0% to 72.7%, with higher inertinite content potentially reducing combustion efficiency.

**Liptinite Macerals (Lip mmf):** The percentage of liptinite macerals, which are derived from algal and spore material. Values range from

0.0% to 35.3%, with liptinite being relatively rare in these samples.

The UBT samples are marked by high mineral matter and moisture content, which has a negative impact on their combustion profile. On the other hand, the MBT samples' high ash content is attributed to their high mineral content. Among these, sample 09 stands out as the best combusting sample due to its high moisture and low ash content, along with its high liptinite composition, which positively influences the devolatilization processes.

Lastly, the LBT samples exhibit the best combustion profiles with prolonged burning, which can be attributed to their low mineral and moisture content, as well as their moderate distribution of maceral groups.

As depicted in Figures 1-3, coal samples' combustion performance can be characterized by parameters from their burning profiles. One sample, in particular, showcased the best combustion profile due to its low ash and high calorific value (CV) content.

### Thermogravimetric Analysis (TGA)

**T<sub>I</sub> (Initial Decomposition Temperature):** The temperature at which decomposition begins. Values range from 220°C to 290°C, indicating the onset of volatilization.

**T<sub>P</sub> (Peak Decomposition Temperature):** The temperature at which the maximum rate of decomposition occurs. Values range from 335.2°C to 485.8°C, reflecting the peak activity of volatilization.

**T<sub>B</sub> (Burnout Temperature):** The temperature at which decomposition ends. Values range from 519.4°C to 616.4°C, indicating the completion of combustion.

#### Combustion behaviour and thermal performance:

Optimal Samples: LBT coals show **prolonged combustion temperatures (344–439°C)** and peak performance due to low ash/moisture.

Sample 09 (MBT) excels despite high moisture, aided by liptinite [24].

**Sub-optimal Samples:** High-ash samples (01, 17) exhibit **minimal weight loss** during combustion due to inert mineral matter, reducing calorific value and efficiency [10, 22, 23, 24].

#### Temperature Ranges for Boiler Design

UBT: 336–438°C

MBT: 398–486°C

LBT: 345–439°C [24].

Table 3. Critical Coal Quality Indicators by sub-region [24]

Parameter	LBT	MBT	UBT
Avg. Ash (wt.%)	Low (<17.6)	Variable (High: 01/06)	Very High (11/17: >73%)
Calorific Value	High (≥24.11 MJ/kg)	Moderate	Low (Sample 17)
Key Maceral	Vitrinite-dominant	Vitrinite; no liptinite	Vitrinite + inertinite
Suitability for Power	Excellent	Moderate (excl. 01/06)	Poor (excl. 11/17)

#### Quality Assessment for Power Generation

All Benue Trough coals are **generally suitable for power generation**, except: **Sample 01 (MBT)**: 73.03 wt.% ash, low CV, poor maceral distribution [24]. **Sample 17 (UBT)**: 81.57 wt.% ash, negligible weight loss during combustion (Table 3) [24]. Optimal feed stocks include LBT samples (e.g. 12 and, 15) due to **high CV, low ash, and balanced macerals** ensuring efficient energy output [24].

#### Observations and Interpretations

**High-Quality Samples:** Samples with high CV, low ash yield, and high volatile matter (e.g. Samples 08, 18, and 19) are likely to be suitable for power generation due to their efficient combustion properties.

**Low-Quality Samples:** Samples with high ash yield and low CV (e.g. Samples 01 and 17) may require beneficiation or processing to improve their usability for power generation [10].

**Regional Variations:** Samples from different sub-basins (UBT, MBT, LBT) exhibit varying properties, reflecting geological and

depositional differences. For example, LBT samples generally have lower ash yields and higher CVs compared to UBT samples [10].

## 6. Conclusion

The 29 grab coal samples from the Benue Trough exhibit a highly complex and heterogeneous composition, making it essential to employ a comprehensive and integrated approach to fully understand their coal quality. This thorough analysis is crucial for a suitable characterization and utilization of the coal samples.

In terms of electricity generation, coal remains a vital energy resource, especially for developing countries, offering a stable and affordable source of power in the short term. The proximate analysis of the samples reveals that most of them have a high volatile matter and fixed carbon content, which are desirable characteristics for coal as they contribute to heat generation. Notably, only two samples, 01 and 17, have high ash content.

With the exception of samples 01 and 17, which are not suitable for power generation due to their high mineral matter content (inorganic) and lack of weight loss, the majority of the coal samples have a high calorific value, making them suitable for electricity generation. The combustion profile curve for the Upper Benue Trough (UBT) indicates a range of peak temperatures from 336.219 to 437.79 °C, which are essential parameters for designing power station boilers.

Among the different maceral groups present in the coal samples, huminite (exinite)

exhibited the highest reactivity, followed by vitrinite, and then inertinite. This ranking was confirmed through a complementary study on chars derived from maceral concentrates, where inertinite chars burned more slowly compared to vitrinite and exinite-rich chars. The DTG and weight loss curves reveal important details about the devolatilization, volatile burning, and char combustion stages, as well as the influence of volatile matter and ash content on combustion efficiency. These findings are essential for assessing the suitability of these coals for power generation and guiding future exploration and utilization efforts in the region.

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## 8. Declarations

Conflict of interest, the authors declare that no conflict of interest.

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