

## Research Article

# Combustion Characteristics of Mui and Taru Basin Coal in a Fluidized Bed Combustor

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Coal reserves at Mui and Taru in Kitui and Kilifi counties in Kenya are estimated to provide over 400 million tons. Being new discoveries, their properties were investigated using the ASTM standards, while the combustion characteristics were studied in a fluidized bed combustor (FBC). Proximate analyses of the Mui1, Mui2, and Taru coal samples were as follows: moisture content 3.75, 5.48, and 3.53%; volatile matter 59.25, 58.05, and 55.10%; ash content 9.25, 11.48, and 24.63%; and fixed carbon 27.80, 25.00, and 16.75%, respectively. Ultimate analysis for Mui1, Mui2, and Taru coal samples is as follows: sulphur wt.% 1.94, 1.89, and 1.07; carbon 65.68, 60.98, and 51.10%; hydrogen 5.97, 5.70, and 5.09%; nitrogen 0.92, 0.94, and 1.00%; and oxygen 11.62, 12.33, and 11.13%, respectively. Temperature–weight loss analysis showed that for Mui and Taru basin coal, devolatilization starts at 200°C and 250°C, and combustion was complete at 750°C and 650°C, respectively. The maximum temperature obtained in FBC was 855°C at 700 mm height, just above the point of fuel feed, while the minimum was 440°C at height of 2230 mm. Maximum pressure drop was 1.02 mbars at 150 mm, while minimum was 0.67 mbars at 700 mm from the base. Gross calorific values were Mui1 coal, 27090 kJ/kg (grade A), Mui2 coal, 25196 kJ/kg (grade B), and the Taru coal, 21016 kJ/kg (grade C). Flue gas analysis for Taru and Mui coal gave hydrogen sulfide as 20 ppm and 6 ppm, maximum carbon monoxide of 2000 ppm at 600°C, and a decrease in oxygen as combustion progressed to a minimum of 15%, followed by an increase to 20.3%, suggesting depletion of coal. Based on the findings, the coal samples were suitable for commercial use.

## 1. Introduction

Energy is one of the key sectors towards the development of any given region [1]. With Kenya's vision 2030 [2], the country has to invest more in energy generation to meet future increase in demand. In recent years, the Government of Kenya has been keen to increase the share of renewable energy sources in the country's generation mix [3]. However, with the discovery of fossil fuels in the country including coal deposits at Mui in Kitui and Taru basin in Kilifi County, oil in Turkana County, and natural gas in Wajir, it is shifting towards a mixed approach encompassing development of both renewable energy plants and fossil fuel generators [4]. As at November 2019, Kenya had 2651 MW grid connection of electricity [5]. Geothermal lead with 44% outdoing hydro-power (33%) and thermal (11%) which had influence from droughts and global fuel prices, respectively [6, 7]. To increase

the number of energy sources, coal is being explored by the government, since it is cheaper than hydro and geothermal despite known negative impacts on the environment such as generation of greenhouse gas, carbon dioxide, and air pollution due to sulphur oxides, nitrogen oxides, coal dust, coal combustion wastes, and coal sludge [8].

Coal is combustible black sedimentary rocks that are formed as a result of continuous exposure to high temperature and high pressure of ancient plants such as trees, fern, and mosses which grew in swamps along the shoreline of the coastal region. The transitional stages to the formation of coal are peat, lignite, subbituminous coal, bituminous coal, and anthracite [9]. Anthracite is the most carbon-rich, moisture-deficient form of coal and has the highest heating value [10]. Coal is the most abundant fossil fuel in the world, and it is widely used in industries making a major contribution to the global economy [11]. It is mined for

commercial purposes in more than 50 countries and used in more than 70 countries. 5800 million tons of coal are consumed annually in the world, out of which about 75% is used for the production of electricity [12]. According to the International Energy Agency, this demand is expected to grow by around 60% in the next 30 years especially in developing countries. In Kenya, coal is mainly used by cement manufacturers to complement heavy fuel oil for processing heat [13]. A total of 537359 tons of coal was imported and consumed in Kenya by 2016 ranking it 81st in the world [14]. Kenya discovered commercial quantities of coal in one of four coal exploration blocks in the Mui basin of Kitui County, located over 200 km northeast of Nairobi, with a reserve estimate of more than 400 million tons [15, 16]. Another major discovery of coal was at the Taru basin in Kilifi and Kwale counties whose resources are expected to be worth over 27 billion US dollars [17]. The coal, therefore, has a role to play towards a sustainable energy in the coming years. As per the 2013 Least Cost Power Development Plan, coal is projected to provide at least 4,500 MW of electricity by 2030 [13]. Characteristics properties (proximate, ultimate, and temperature-weight loss analysis) and fluidized bed combustion characteristics of Mui and Taru basins were studied to assess the commercial viability of the two coals.

## 2. Materials and Methods

For a fluidized bed combustor (FBC), the silica sand was sieve analyzed, and an average particle size of  $325\ \mu\text{m}$  was used as bed material, since sand particle size of 300–3 mm is the best in FBC [18]. For a low pressure drop, bed height was 0.1 m, which is equivalent to  $0.00177\ \text{m}^3$  of sand [19].

Coal was obtained from Mui (Mui1 and Mui2) and Taru in Kitui and Kilifi counties.

Other equipment used in this study included a digital gas analyzer (Altair 5x) to analyse oxygen, carbon monoxide, combustibles, and hydrogen sulfide in the flue gas, the artificial neural network (ANN) model [20] to determine the elemental organic components in the coal samples, the PTC furnace (Carbolite Gero) for proximate and temperature-weight loss analysis.

FBC had a combustion chamber of diameter 0.15 m and height of 2.5 m, fitted with 4 pairs of electrical coil heaters to aid in the combustion. The fuel feed to the combustion chamber is fed in the hopper and flows down to the electric, water cooled, screw feeder. Flue gas passes through course and a fine particle separator before being released to the atmosphere as shown in Figure 1.

**2.1. FBC Calibration.** FBC was calibrated for feed rate, temperature, and pressure along the column length.

For feed rate calibration, screw was disconnected from the FBC and coal input (g/min) was measured at screw revolution per minute (RPM) of 10, 20, 30, and 40, respectively. The results are shown in Figure 2.

Figure 2 shows a linear relationship which is correlated as

$$Y = 115.94x + 118.8, \quad (1)$$

where  $Y$  is the feed rate (g/min.) and  $x$  is the RPM.

During temperature calibration of the FBC, the compressor, fan, and the heaters were switched on with only the bed material in the combustor. The temperatures along the combustor chamber were captured by the sensors:  $T_1$ ,  $T_2$ ,  $T_3$ , and  $T_4$ . The highest temperature was recorded by sensor  $T_4$  and stabilized at around  $700^\circ\text{C}$ ; this was followed by  $T_2$  at  $535^\circ\text{C}$ , then  $T_3$  at around  $500^\circ\text{C}$ , and least was with  $T_4$ , stabilizing at  $346^\circ\text{C}$  as shown in Figure 3.

For pressure measurements, the pressure sensors  $P_1$ ,  $P_2$ ,  $P_3$ , and  $P_4$  gave the pressures.

At  $P_1$ , the lowest point of the four locations, the pressure was the highest pressure, 1.02 mbars. This was attributed by the fact that incoming air from the compressor was first received here. The value is relatively low because of the capacity for the compressor.

The lowest pressure, 0.67–0.68 mbars, was recorded at  $P_2$ , which was the point adjacent to feed; at this point, pressure dropped drastically because it was interfered with by the fuel feed.  $P_3$  and  $P_4$  had pressures 0.97 mbars and 0.81 mbars, respectively.

Agglomeration behavior involved combusting the coal at constant temperature and pressure and then closely examining the drained materials [21], as shown in Figures 4(a) and 4(b). Temperature variation recorded by sensors  $T_1$ ,  $T_2$ ,  $T_3$ , and  $T_4$  obtained from coal combustion are shown in Figures 5 and 6. Results are shown in Figure 7.

**2.2. Proximate, Ultimate, and Temperature-Weight Loss Analysis.** Proximate analysis was done in accordance with the ASTM (D-3172) standards with the use of an oven and a digital weighing balance. In analysis of sulphur, a digital bomb calorimeter (Toshniwal) was used, while for temperature-weight loss analysis, 2 g of coal was combusted in an oven (Carbolite Gero batch) and weight loss expressed as percentage of original weight.

## 3. Results and Discussion

**3.1. Proximate Analysis.** Proximate analysis results consisting of moisture content (MC), volatile matter (VM), ash content (A), and the fixed carbon content (FC) percentage mass of the coal samples are given in Table 1.

Coal with high MC has a longer heating time, consuming more energy and formation of volatiles [22]; this negatively affects GCV [23], while high VM leads to ease ignition, increased reactivity, and spontaneous combustion though it requires a larger combustion chamber in FBC and furnaces [11, 24]. High ash content causes clinkering, declining reaction rate in combustion and environmental pollution [25]; this is likely to be the case with Taru coal. Mui coal is likely to have a higher heating value than Taru coal due to higher FC [26, 27].

**3.2. Ultimate Analysis.** Elemental analysis results consisting of carbon (C), mineral matter (MM), oxygen (O), hydrogen (H), sulphur (S), and nitrogen (N) are given in Table 2.

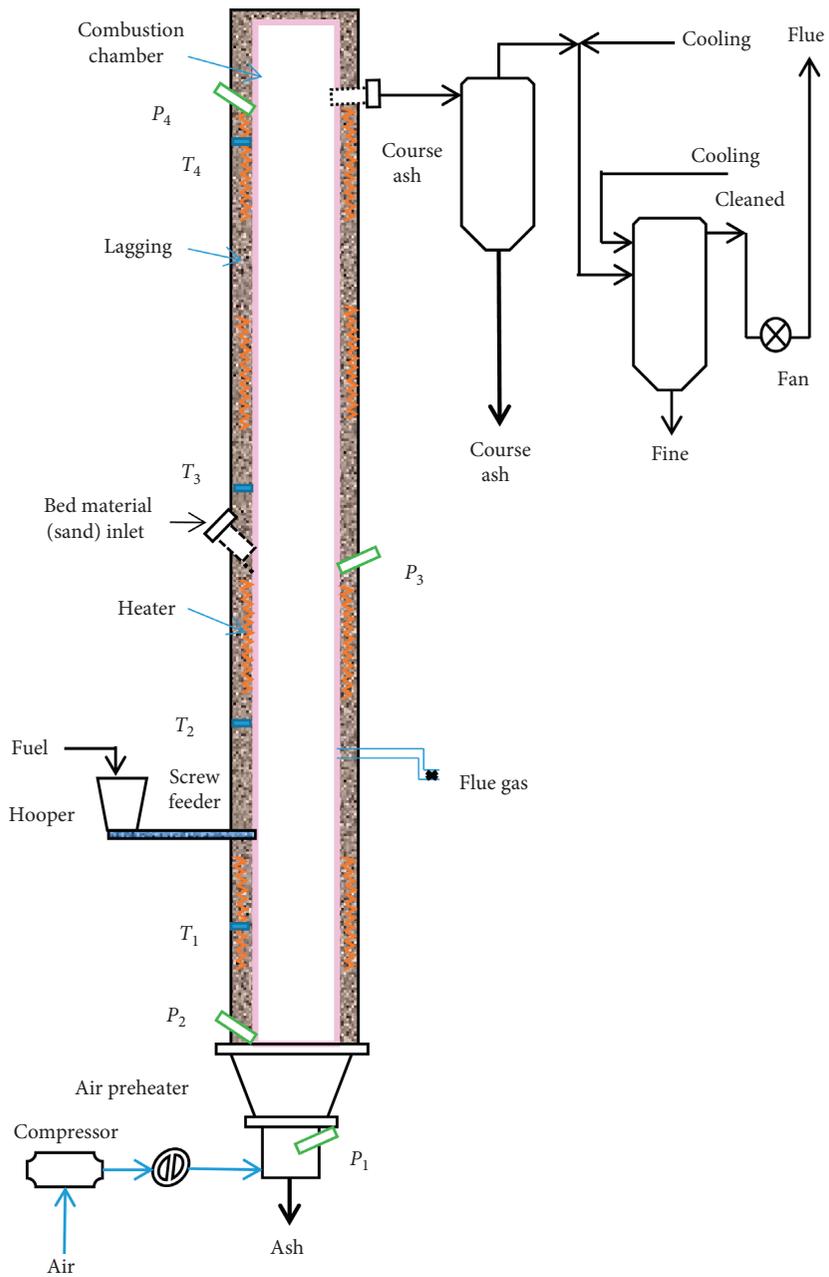


FIGURE 1: Schematic diagram of FBC.

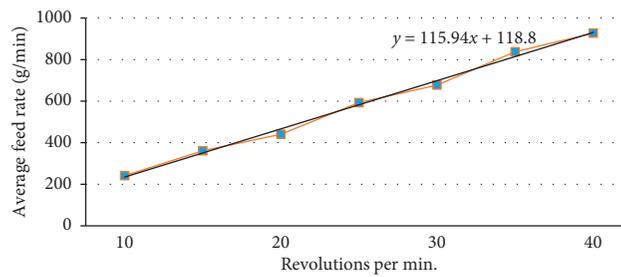


FIGURE 2: Plot of average feed rate against revolution per minute.

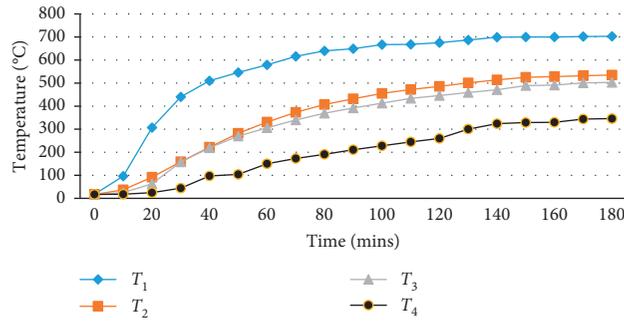


FIGURE 3: Plot of temperature versus time.

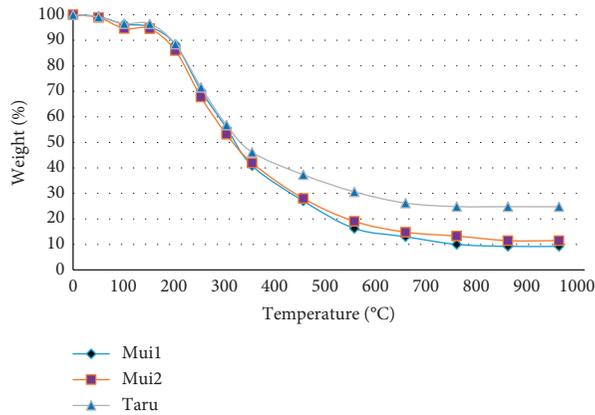


FIGURE 4: Plot of temperature-weight analysis Mui1, Mui2, and Taru coal.

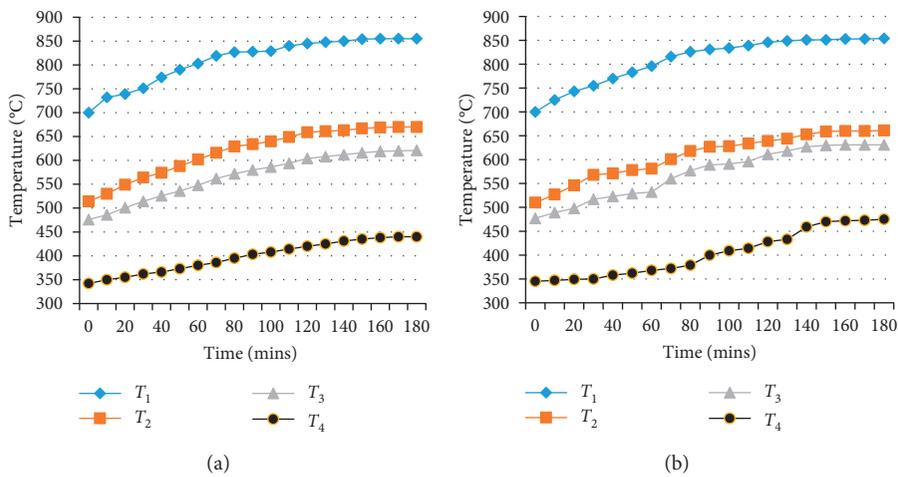


FIGURE 5: Plot of temp against time for (a) Mui and (b) Taru coal.



FIGURE 6: Drained material from FBC after combustion. (a) Mui and (b) Taru coal.

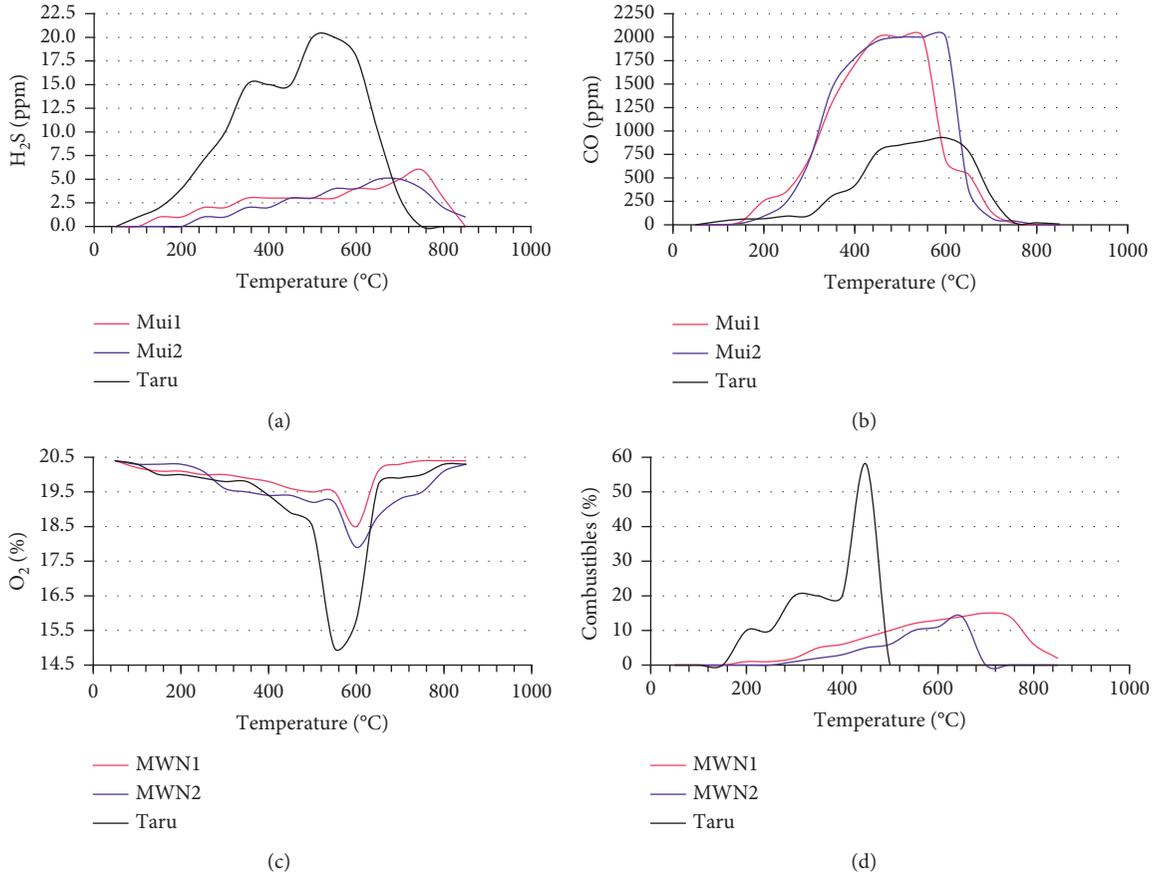


FIGURE 7: Plot of (a) H<sub>2</sub>S in ppm, (b) CO in ppm, (c) O<sub>2</sub>%, and (d) combustibles % against temperature.

TABLE 1: Proximate results.

Coal sample	Mass composition (%)			
	MC	VM	A	FC
Mui1	3.75	59.25	9.25	27.80
Mui2	5.48	58.05	11.48	25.00
Taru	3.53	55.10	24.63	16.75

TABLE 2: Ultimate analysis results for Taru and Mui basins coals.

Coal sample	Mass composition (%)					
	C	MM	O	H	S	N
Mui1	65.68	10.18	11.62	5.97	1.89	0.92
Mui2	60.98	12.63	12.33	5.70	1.94	0.94
Taru	51.10	27.09	11.13	5.09	1.07	1.00

Heating value of S is about a third the heating value of same quantity of carbon per unit [28]. Mui and Taru coal sulphur is in medium sulphur coal [29] and slightly above that of Waterberg and Indian which is 1.49 and 0.6 (wt.%), respectively [22, 29]. Carbon is the chief heat source accounting between 60% and 80% in lignite and anthracite. Hydrogen accounts to approximately 5% of coal elemental composition, and its heating value is slightly above four

times the heating value of same quantity of carbon though part of it combines with oxygen to form water reducing hydrogen utilized for heat generation. The oxygen in coal combines with carbon, partially oxidizing it, hence reducing combustibility [28]. Mineral matter represents the inorganic element combined with organic elements of coal. The origin of such material is the plant materials from which the coal was formed [30]. Normally, nitrogen in coal is 0.5–2%, where it is below 1% for anthracite and 1.5–1.75 for bituminous [31]. As discussed earlier in Material and Methods, the ANN was used as a basis in analysing C, MM, O, H, and N, while S was analyzed by the digital bomb calorimeter.

Firing of coal in power plant station leads to 15–30% of the nitrogen content in it being converted to NO<sub>x</sub> [32]; therefore, having the percentage mass of nitrogen from Table 2, NO<sub>x</sub> can be estimated. Total weight of SO<sub>2</sub> is calculated by multiplying 19 with sulphur content in a given sample of coal and total sample of weight burnt [33]. Having the S in Table 2, hence, SO<sub>2</sub> in any quantity of Mui and Taru coal can be estimated when required.

**3.3. Estimation of Calorific Value of Mui and Taru Basin Coal.** The gross calorific value (GCV) was obtained by multivariable linear regression equation [23]:

$$\text{GCV} = 7115.197 - 23.971 \times \text{MC} - 81.3121 \times \text{A} + 20.7421 \times \text{FC} \quad (2)$$

This resulted in 6474.78 kCal/kg (27090.48 kJ/kg) for Mui1 coal, 6021.95 kCal/kg (25195.84 kJ/kg) for Mui2, and 5022.91 kCal/kg (21015.86 kJ/kg) Taru basin coal. These are given in Table 3.

Grading of this coal therefore gives Mui1 as grade A, Mui2 coal as grade B, while Taru basin coal lies in grade C [34].

**3.4. Temperature–Weight Analysis.** The results from temperature–weight analysis are shown in Figure 7.

From Figure 7, there was insignificant weight loss for the first 50°C. Between 50 and 100°C, there were 2.95, 4.32, and 2.59% loss; this was due to moisture loss and drying before burning starts [21] and a negligible change up to 150°C. This was then followed by devolatilization; here, carbonaceous substances decompose thermally releasing volatiles which are combustible [35]. Organic compounds are broken down resulting in component gases. There was rapid weight loss of 82.24, 79.72, and 70.27% up to 650°C for Mui1, Mui2, and Taru coal, respectively. Coal burns at high temperature, which is due to high density as a result of closely packed particles [36]. Between 650°C and 950°C, there was very minimal weight loss. At this point, char combustion is over; the percentage left was 9.23, 11.48, and 24.77% for Mui1, Mui2, and Taru which were approximately equal to the ash content attained from proximate analysis results.

**3.5. Temperature Variation in a Fluidized Bed Combustor.** During the continuous combustion of the two samples of coal from Mui and Taru basin, the results obtained were recorded and plotted separately as shown in Figure 5.

From Figure 5, the profiles for temperature from the sensors located in different regions showed consistency rise and the plateau after around 150<sup>th</sup> minute for both Mui and Taru coal. The highest temperature was recorded by sensor  $T_1$  855 and 854°C,  $T_2$  670 and 661°C,  $T_3$  621 and 631°C, and  $T_4$  440 and 475°C for Mui and Taru coal, respectively. The temperature change at different bed heights was highest (152°C) at  $T_1$  and least at  $T_4$  (94°C);  $T_2$  and  $T_3$  were 135°C and 118°C, respectively, for Mui coal. A similar trend was observed for Taru coal. This showed that temperature increase was highest at the point of combustion. Volatile combustion takes place at freeboard [21], probably why highest temperature was by  $T_1$  which is slightly above the base holding the burning coal. Note that the electric heaters were switched off once the temperature sensors  $T_1$ ,  $T_2$ ,  $T_3$ , and  $T_4$  were 703, 535, 503, and 346, respectively.

**3.6. Examination of Drained Material after Combustion in the FBC.** The FBC was left to cool for some time after switching off the heaters, the lower valve opens, and the combusted fuel together with the bed material drained and examined, as shown in Figure 4.

TABLE 3: GCV for the Mui and Taru basin coal.

Coal sample	GCV (kJ/kg)
Mui1	27090
Mui2	25196
Taru	21016

Keenly observing the drained material from the FBC after the combusted coal and the bed material, the particles were seen held together by materials in molten state. This was similar in both coal samples. This indicated proof of agglomeration is said to take place when the ash from the coal changes to molten state at very high temperature and holding the bed material together [37].

**3.7. Flue Gases Analysis.** The results obtained from the gas analyzer at different temperature levels are shown in Figure 6. The gas analyzed includes hydrogen sulfide, carbon monoxide, oxygen, and the percentage level of combustibles.

From Figure 6(a),  $\text{H}_2\text{S}$  in Taru coal was maximum (20 ppm) at 500°C, while Mui coal is maximum (6 ppm) at 750°C.  $\text{H}_2\text{S}$  and polysulfide are obtained from S through a chemical conversion by bacteria available in ground water; they are toxic, leads to corrosion of equipment, odors, and emissions, which negatively affect the environment and human beings [38, 39].

For CO as shown in Figure 6(b), a sharp increase was observed between 200°C and 450°C for Mui coal and gradually increases for Taru basin coal for temperatures between 300°C and 600°C. The highest level of 2000 ppm of CO was recorded from the Mui coal, while 687 ppm of CO was observed for the Taru basin sample. During the combustion of coal, an increase in the concentration of flue gases with temperature is noted. Carbon monoxide forms the highest percentage, since it is formed in very large quantities [40]. The concentration of CO above 150–200 ppm may cause unconsciousness and healthy problems, especially for patients with related diseases. When fossil fuels for example coal are combusted, carbon monoxide and carbon dioxide are emitted. These gases cause the greenhouse house effect [41]. They therefore need to be stored or separated to minimize their concentration in the ozone layer. To achieve this, there is need to combust such fuel (coal) in conditions where oxygen is enhanced.

Percentage level of oxygen recorded in the beginning was 20.3% as shown in Figure 6(c). This is approximately the level of oxygen in the atmosphere. This then dropped gradually as combustion continued, with Taru coal recording maximum drop up to 15%. Consumption of oxygen during combustion differ with different coal ranks even at same temperature; however, the change is nonlinear; probably, this is why we have different levels of oxygen at same temperature for different coal samples [42]. In Figures 6(a), 6(b), and 6(d), the number of constituent gases in flue gases was rising. During combustion of coal, a number of reactions tend to take place. These include the physical adsorption of oxygen gas, the chemical adsorption of oxygen gas leading to a complex compound (coal- $\text{O}_2$ ),

and lastly the oxidation process, in which combusted hot coal reacts with oxygen giving rise to flue gases such as carbon dioxide, carbon monoxide, and water vapour [25]. There is always an increased portion of carbon that is combusted when the concentration of oxygen is high in a given mixture of gases [41]. Referring to Figure 6(c), highest combustion of the three samples of coal took place between 500°C and 650°C, Taru coal sample recording more O<sub>2</sub> consumption. This therefore indicates that the portion of Taru coal that is combusted is more than that of Mui coal within the same range of temperatures. The level of oxygen later rose to almost the atmospheric level, implying that coal had been used up; hence, no more oxygen was being used up.

From Figure 6(d), the percentage level of combustibles was observed to rise for all the coal samples. For Taru coal, increase in the percentage level of combustibles was noted to start at 150°C, with a small plateau at 200°C and another at 350°C, after which it sharply rose at 400°C to attain a maximum percentage level of 58% at 450°C and later dropped drastically to zero at 500°C.

During the rise in the percentage level of combustibles, there was noted decrease in the percentage level of O<sub>2</sub>. This means that the O<sub>2</sub> was being utilized in combustion of the combustibles in the coal. The percentage level of O<sub>2</sub> started falling at 350°C and drastically at 450°C where the percentage level of combustibles was highest (58%). Mui1 and Mui2 samples showed their percentage level of combustibles gradually rise starting at temperature 300°C attaining a maximum of 14% at 750°C and 650°C, respectively. The lowest percentage of O<sub>2</sub>, which is 18.5% for Mui1 and 17.9% for Mui2 coals, was attained at 600°C. Like in the case of Taru coal, this showed that oxygen was being used excessively where the combustibles were more. In comparison, the samples from the two regions, that is Mui and Taru, Taru coal has more combustibles, highest at 58% compared to Mui coal samples which attain a maximum of 14% combustibles. Therefore, this means that more oxygen will be required for a complete combustion of Taru coal than required for Mui coal. Data for Figure 6 were continuously taken and recorded as the experiment was being run. This was ideal to detect the change in the flue gases percentages.

#### 4. Conclusion

Newly discovered coal in the Mui and Taru, in Kitui and Kilifi counties in Kenya, has opened new fossil fuel resource for Kenya. Characteristic fuel and FBC combustion properties were studied to establish the commercial potential of the coal. Proximate analysis showed that FC and VM (mass %) varied as Mui1 > Mui2 > Taru and A (mass%) varied as Taru > Mui2 > Mui1. MC for the samples did not follow a trend. Ultimate analysis (mass%) gave the trend for C and H as Mui1 > Mui2 > Taru and for MM and N as Taru > Mui2 > Mui1. Exception was Mui2 with highest O and S. Caloric values followed the expected order: Mui1 > Mui2 > Taru. The study of weight loss upon heating showed a close behavior for all samples for up to 350°C, and thereafter, Taru sample displayed a lower loss due to higher A. All samples displayed a similar temperature profile and

agglomeration in FBC. Flue gas analysis showed better combustion behavior for Mui coal and higher oxygen requirement for Taru for a similar combustion. All the samples proved the potential for commercial exploitation; however, Mui coal was found to be better than Taru coal.

#### Data Availability

The data used to support the findings of this study are included within the article and are available from the corresponding author upon request.

#### Conflicts of Interest

The authors declare that they have no conflicts of interest.

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