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Lignite Coal Co-combustion Performance with Banana Tree Waste, Tree Leaves and Cow Dung Manure Blends for Emission Reduction During Power Generation

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Abstract

Biomass blended with lignite coal (LC) normally have better co-combustion property, which in turn improves electricity output and reduces emissions. Given that global warming caused by emissions of CO, NOx, SO_2, CO_2 and NO from manufacturing industries and power plants is growing, this study seeks to find environmentally friendly alternative fuel to be employed. Here, suitable particle size of LC was combined with tree leaves (TL), cow dung manure (CDM) and banana tree waste (BTW) in the ratio of 90:10, 80:20, 70:30 and 60:40 each to form 16 samples (4 single and 12 blends). Thermal and combustion characteristics studies conducted during their combustion in an electric muffle furnace at 700°C, helped declare all blends as favorable with higher heating values ranging from 521179-892952 Btu/lb to be used as fuel in coal-powered plants. For moderately low emissions of flue gases, better thermal combustion property, high heating value (i.e., 892952 Btu/lb) and the highest electricity output, LC90 + CDM10 is the best blend discovered by this study. However, LC *utilization still defeats the best performing blend in terms of lower emission with LC80 + TL20 having tolerably closer emission level compared to LC and a good substitute if emission must be kept as same level. Due to this shortcoming, further ratio adjustment or optimization and catalyst/additive addition is recommended to bring the emissions to environmentally friendly levels. It is also paramount to analyze the samples for chlorine concentrations to keep at desired composition in order not to risk a high temperature chlorine corrosion during co-combustion.*

Keywords: *Co-combustion, Co-firing, Heating values, Lignite coal, CHNS analysis*

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INTRODUCTION

Co-combustion of coal and biomass is nowadays getting the needed attention due its low emissions (NO, CO, NO_2, N_2O, CO_2 and SO_2) from chimney/stacks, simplicity and the ability to increase power generation [1]–[3], with the potential to take the place of the fast-depleting fossil fuel [4]. As an example, in order to overcome emission problems, combine combustion of biomass and coal is sometimes employed in the cement industry. Generic reasons for co-combustion are basically [5]: to get rid of waste/biofuel by co-firing them together with coal in a boiler or replace the later by utilizing the former, to attain a certain combustion temperature by burning coal having high heating value and a low heating value biowaste (e.g., sludge) and to augment short coal supply caused by price hikes with other biomass in any desired ratio, triggered by its availability. These biomasses are forestry and agricultural crops and residues (viz., tree leaves, wood pellets, wood chips, coffee husk, banana tree waste, rice husk, sawdust, straw etc.), sewage, industrial waste and animal residues (viz., cow, chicken litter) [6], usually combined with different types of coal, namely, pit, brown, lignite, anthracite, bituminous [7] and sub-bituminous coal. Among them and according to Sakthivel et al. (2018), lignite coal (LC) contains 52.13% total ash, 2.41% moisture, 24.96% volatile matter, 20.50% fixed carbon, 82.87% carbon, 0.0006% sulphur content, 23.11% lignite content and 4816.78 kCal/kg calorific value. It is largely studied with diverse blends with several biomass, as demonstrated in previous findings shown in Table 1.

Co-combustion and emission released therein have been heavily researched in the literature [9, 11, 20–22]. In this case, analysis often conducted are thermal and TGA [23]. It is realized in most cases that the resultant blend presents a different or unique characteristic due to change in composition of the original coal material which may possibly result in the establishment of an environmentally, economically and energetically friendly combustion process [24]. Normally, combustion properties [25] and reactivity of coal during co-utilization are affected mainly due to high volatile matter in the biomass, according to Aydemir et al. (2022). In a nutshell, biomass has higher oxygen content, low fixed carbon, higher moisture content, less sulfur content, low net calorific value and is more volatile than coal [27, 28]. This property led to numerous studies, including Soleh et al. (2023) who collectively examined the property (proximate and ultimate) of sawdust, rice husk, solid recovery fuel and coal as well as their blends in certain ratios to obtain the thermal characteristics and combustion performance applied to a steam power plant, using computational fluid dynamics. Hence, the goals set out to be achieved by this research includes, the study of the combustion behavior of LC and biomass blend through emission analysis, calculating the heat generation from the co-combustion and comparing the results with sole LC combustion. Overall, this study is aimed at establishing an environmentally acceptable combustion process by partially substituting fossil fuels, with specific target of decarbonizing the energy sector. It also adds the heating value and TGA outcome effects with regards to potential use of the blends for power generation, in contrast with Siddique et al. (2016). The selected biomass is banana tree waste (BTW), cow dung manure (CDM) and tree leaves (TL).

Table 1. Various Co-combustion Studies on Lignite Coal with Variety of Biomass Blends

Co-combustion	Burner	Study	Findings	Investigation
Woodchips + Lignite coal [10, 30 & 50 wt.% materials]	6m high and 108 mm internal diameter circulating fluidized bed combustor (CFBC) at 850°C	Effect of excess air ratio on flue gas emissions	CO, O_2, NO_2 & CO_2 emission amounts at optimum air ratio of 1.18, 1.32 & 1.41	[9]
Forest red pine chips + Lignite Coal [30% lignite + lignite with 2-2.9% sulfur]	750kW-thermal capacity CFBC system at 850±50°C	Sole lignite burning and effect upon co-firing with limestone to reduce SO_2 emission	CO emission is higher at low excess air ratio	[10]
High-sulfur lignite coal + Olive cake [50-50 wt.%]	CFBC	XRF, XRD & SEM/EDS of ash residue. Level of CaO, MgO & Al_2O_3 in ash	Muscovite was dominant phase in bottom ash	[11]
Rice husk & Olive milling residue + Low rank coal [blend have 5-20 wt.% biomass]	Thermal analyzer at 900°C	Differential thermal analysis (DTA) & Thermo gravimetric analysis (TGA) and effect of oxidizer type and blending ratio	Variations in combustion characteristic of the samples	[12]
Hydrochar + Lignite	Unspecified burner	Kinetic study	Hydrochar addition increases the burnout in line with 1st order reaction rate	[13]
Chicken litter + Coal	Laboratory-scale FBC	Temperature distribution along the combustor	Freeboard temperature rises with rise in litter fraction	[14]
Groundnut shell (GS) or Miscanthus	TGA analyzer at 900°C	Dried and grinded blend ignition and	Ignition and burnout temperature	[8]

(MC) + Lignite coal each at 10, 20 & 30 wt.% mixing ratio		burnout measurement	reduction at 80/20% & 70/30% coal/GS & coal/MC blend	
Biocoal (from red pine wood chips) + Lignite coal	30 kW-thermal capacity CFBC (6m high & 108 mm inside diameter)	Variation of oxygen concentration from 21-27 vol.%	Effective blend for flue gas emission reduction	[15]
Firewood + Lignite Coal	Locally made furnace	Influence of fuel feed rate, fuel mixture ratio and air staging	Acceptable temperature distribution, high combustion efficiency and low emissions	[16]
Corn stover + Lignite Coal	Lab-scale Fluidize Bed Reactor	Influence of input ratio (80:20 & 90:10), chlorine fraction in blend, air & calcium-sulfur mole ratio	Deposition rate are affected by the potassium chloride in the corn	[17]
Lignite Coal + Coal Gangue	SETARAM TGA analyzer at 1000°C	Thermal characteristics & kinetics of lignite coal, coal gangue & their blends	Best blend is 3:2 and blend had better combustion behavior	[18]
Biomass (Tree leaves, Cow dung manure & banana tree waste) + Lignite Coal	Electric muffle furnace at 1300°C	TGA, emission, proximate analysis and heating value determination for single sample and blends	LC90+CDM10 is the best for maximum electricity generation	This Study & [19]

METHODS AND ANALYSIS

Material Collection and Equipment

CDM, TL and BTW were the selected biomass materials for this study, as they are available in large amounts. They were collected from different locations in Sindh Province including Tandojam, Jamshoro and Kotri in Pakistan. For the blends LC obtained from Lakhra Coal Mine (Field) or Plant in Pakistan was used. Various equipment types like Stack gas analyzer for emissions analysis, electrical muffle furnace, grinder, crusher and laboratory sieving machine for different mesh sizes of materials were used at different stages of the research work summarized using Figure 1. Conditions at which various stages of the study were conducted were discussed accordingly.

Drying and Size Reduction

LC sample (500g) was put in vacuum oven and set to a temperature of 110^{o}C for 1 h in Chemistry Laboratory, Department of Chemical Engineering, Mehran University Jamshoro. After drying, the coal samples were removed from the oven, crushed and stored. Biomass samples selected for study were crushed using a Jaw Crusher to increase their surface area, as particle size play significant role during co-combustion, according to literature. Grinders were then used to reduce the particles into smaller size or powder form. Usually, sieving is carried out to obtain different sizes of materials after grinding. Sieving was done using sieve shaker machine having different sieves for measuring the particle size. This research work utilizes 100g of LC and biomasses during this stage. After that, the sieve shaker machine was started for 5 min to segregate the various particle sizes into different sieves. Weight of each sample in the sieves were lastly measured using an electronic balance.

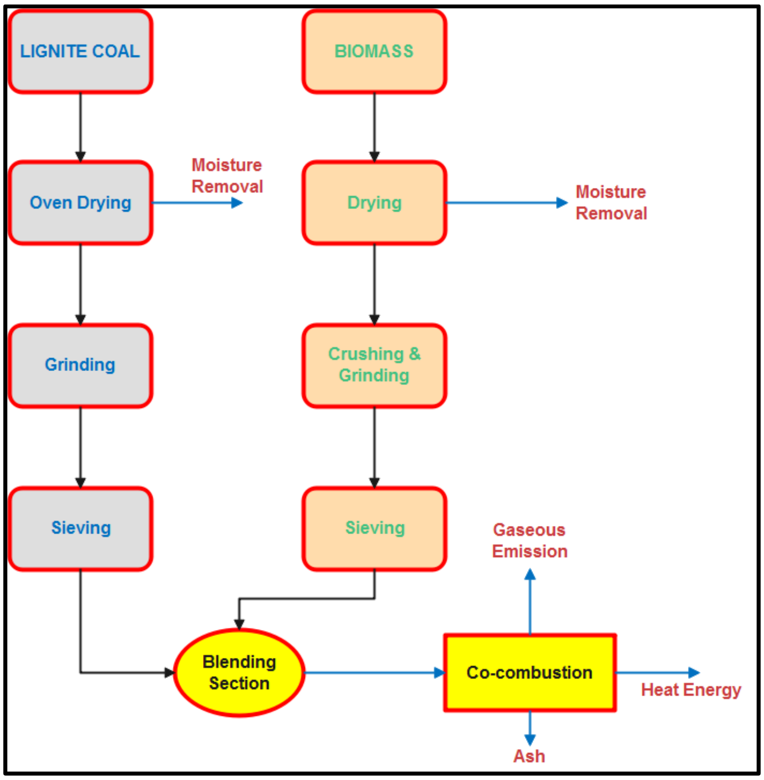

Figure 1. Research Methodology

Sample Blending

Different samples were blended using laboratory blender. Coal and biomass were blended in dissimilar ratios shown in Table 2-4. From the tables, the ratios are 9:1, 4:1, 7:3 and 3:2 of coal-biomass blend.

Table 2. Lignite Coal and Tree Leaves Blend

S/No.	Lignite Coal (%)	Tree Leaves (%)
1.	90	10
2.	80	20
3.	70	30
4.	60	40

Table 3. Lignite Coal and Banana Tree Waste Blend

S/No.	Lignite Coal (%)	Banana Tree Waste (%)
1.	90	10
2.	80	20
3.	70	30
4.	60	40

Table 4. Lignite Coal and Cow Dung Blend

S/No.	Lignite Coal (%)	Cow Dung (%)
1.	90	10
2.	80	20
3.	70	30
4.	60	40

Co-Combustion and Emission Analysis

Co-combustion is a process where two or more fuel source are combusted in the same plant for energy production. Co-combustion of LC as well as coal and biomass blends in Tables 2-4 were carried out in an electrical muffle furnace at 200-700°C. Stack gas analyzer was then employed to analyze the resulting emissions from the furnace. In the analyzer, different types of emissions of CO, CO_2, NO, NOx, SO_2, SOx, and H_2 were observed.

TGA and CHNS Analysis

TGA is a technique used to measure a sample weight as it is heated or cooled in a furnace as a function of time and temperature; because normally, upon heating a material, its weight decreases [29]. In TGA analyzer, the characteristics of the coal and biomass were studied as it measures the moisture content, volatile matter, fixed carbon and ash content present in the materials [30]. Essentially, TGA gives the dewatering temperature at which the sample starts to lose water, the ignition temperature at which the sample ignites, volatilization & burning temperature range for volatilization and burning of the sample, transition period temperature range for the transition period during the thermal degradation of the sample, char burning temperature range for the burning of the char residue after volatilization and burnout residue percentage showing percent residue remaining after complete combustion [31]. On the other hand, CHNS analyzer is an equipment used to detect the carbon (C), hydrogen (H), nitrogen (N) and sulphur (S) contents in the fuel, quantified usually by infrared spectroscopy. Altogether, both TGA and CHNS were carried out in this study.

Heating Value Determination

Two methods can be used to find the heating value (HV) of the samples. One is direct method (using bomb calorimeter) and the other is the use of an empirical Dulong formula (Equation 1) to compute the HV (in Btu/lb).

$$HV = 14600C + 62000\left(H - \frac{O}{8}\right) + 4050S \qquad (1)$$

In the current study, HV was calculated by applying Equation 1 [32], using the data from CHNS analyzer ultimate analysis.

RESULTS AND DISCUSSIONS

This research findings were as a result of studying coal and coal + biomass blends to observe their characteristics and emissions during co-combustion. In view of that, different types of tests performed comprised of particle size analysis, TGA, emissions analysis, CHNS analysis and calorific value determination.

Particle Size Analysis of Materials

Nine sieves of different mesh sizes (0.075-4.75 mm) contained in the sieve shaker gave 9 samples of LC, TL, BTW and CDM of various particle sizes. Mesh diameter of 0.075-0.6 mm contain 1.97441% LC, 39.986074% TL, 31.236982% BTW and 72.55225% CDM in cumulative amounts. There are 3.37096% lignite, 58.25558% TL, 61.64383% BTW and 26.351% CDM as summed weights in sieves of 1-2 mm diameter. Also, as shown in Table 5, sieves with diameters in the range of 2.8-4.75 mm collectively contain 94.07727% coal, 1.758354% TL, 7.191782% BTW and 1.09514% CDM.

In different types of boilers and fluidized bed combustor, it is necessary to analyze the particle sizes because in some type of boiler and fluidized bed combustor, particle size is an important parameter. Different types of material were analyzed to see which material is finer. At the lowest sieve size of 0.075mm, LC collected is lowest (0.657%) where the highest was 11.63587% CDM. Due to unforeseen errors, 9 sieves separately containing LC, TL, BTW and CDM contains 99.99888, 100, 100.0726 and 99.9984g of sample in total, indicating that there are minimal loses due to spillage or dust flaring during the analysis, compared to 100g originally taken. LC sieve with the highest sample collection is 4.75 mm sieve diameter, housing up to 85.20g of coal alone with the remaining distributed between sieve diameter 0.075-4 mm as shown in Figure 2. In this situation, more particles are retained in a sieve with a higher mesh diameter, indicating larger particle size. Fewer particles are retained in a sieve with a lower mesh diameter, suggesting smaller particle size. This scenario implied a distribution skewed towards larger particles.

Table 5. Sieve Analysis of Coal and Biomass

Sample No.	Diameter (mm)	Mass Fraction (%)			
		Lignite Coal	**Tree Leaves**	**Banana Tree Waste**	**Cow Dung Manure**
1.	4.75	85.19597	0.000345	0.342466	0
2.	4.00	3.9473	0.034471	0.684932	0.068446
3.	2.80	4.934	1.723538	6.164384	1.026694
4.	2.00	1.9736	11.72006	24.65753	4.4490
5.	1.00	1.9736	46.53552	36.9863	21.902
6.	0.60	0.98683	21.37187	12.32877	22.58727
7.	0.30	0.32894	10.68593	8.29178	25.32512
8.	0.15	0.00164	6.204736	5.479452	13.004
9.	0.075	0.657	1.723538	5.13698	11.63587

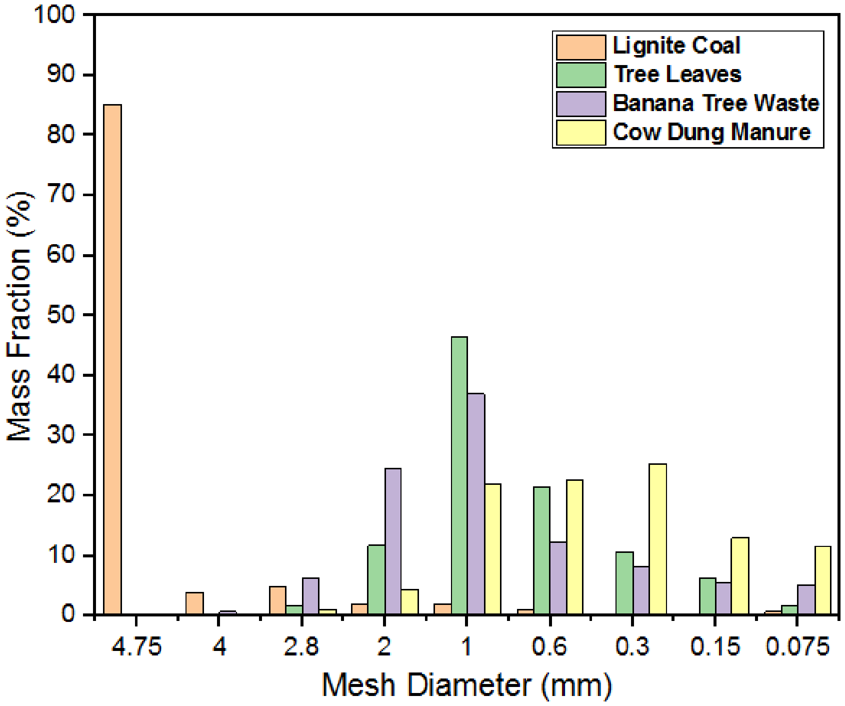

Figure 2. Weights of Each Category of Different Sizes of the Biomass and Lignite Coal

CDM particles was nearly collected equally in sieves with 0.3, 0.6 and 1mm diameter, equivalent to 69.82% of the total amount used. It appears that no CDM particle ≥ 4.75 in diameter was retained. In this case, fewer particles are retained in a higher mesh size sieve, and higher amounts are retained in the remaining sieves with lower mesh sizes, suggesting a particle size distribution that is skewed towards smaller particles. Diameter of 1mm retained 46.54g of grinded TL particle, being the maximum, as shown in Figure 2. Particles of this biomass are largely distributed across sieve mesh size of 0.15-2.00mm, unlike the LC particles. TL size distribution in Table 2 further describes a scenario where fewer particles are retained in a higher mesh size sieve, more are retained in a middle-size sieve, and even more in a small-size sieve. Implying a particle size distribution that peaks in the middle range. While, almost all sieves received considerable amount of BTW particles. It presents a distribution that generally shifts towards smaller particles but has a notable presence of moderate-sized particles in the smallest sieve.

CHNS Analysis

N is only present in CDM (0.364%) amongst sole biomass analyzed and totally absent in LC-TL blends. Where N is zero or very insignificant (e.g., LC70 + BTW30 & LC60 + BTW40), air quality is least impacted, as NH_3 and NOx pollutants are negligibly emitted. Excessive N can lead to incomplete combustion and reduced energy efficiency. As such, N amounts in the material can affect the combustion efficiency in addition to the composition of ash generated during combustion. It is uncommon for LC to have 0% N as obtained in Table 6, probably making it a specific LC deposit. Because N content in many biomasses ranged from 0.1-2 wt.% and its emissions, especially from LC ranges from 0.5-1.5 wt.%. The N composition observed in LC-CDM and LC-BTW are contributory of the CDM and BTW present in the respective blends.

As expected, an average of 50.12% C is contained in the 16 samples analyzed with the amount in LC sole sample the highest (58.66%), almost half the level (23.48%) obtained in Trif-Tordai & Ionel (2011). However, none of the blends' C content surpassed this percentage. Certainly, the overall C content in a blend is determined by the proportion of each component in the mixture. For instance, the blend containing significant amount of CDM (e.g., LC90 + CDM10) typically having lower C percent, is capable of bringing down the overall C content of the blend to 47.15%. And as the LC amount decreased and CDM increased from 90-60 and 10-40% respectively, the %C increased from 47.15-51.96%. Similar behaviors are showcased by LC-BTW and LC-TL biomass blend C contents. Hydrogen is an important element found in both LC and TL. Its absence in LC60 + TL40 blend after CHNS analysis can be attributed likely to: a) poor mixing leading to the use of non-representative sample for analysis, b) poor instrument sensitivity to detect negligible concentration of H, c) low threshold limit for element detection of the analyzer, and d) inaccurate calibration of instrument. LC typically contains 3-6% H while TL contains 5-7%. Sulphur is present in all 16 different samples reported in Table 6 at 2.8% mean amount compared to 4.14% mean amount of H and 0.08% average composition of N. This is a potential contributor to SO_2 emission. Though, SOx emission will not be significant in the blends, given that BTW, CDM and TL have low S contents [28]; and hence reduces the S in the blends to < 4.1 ppm. It is worthy of note that ultimate analysis of LC often reveals different compositions of C, H, N, O and S, based on findings of Schmidt (2001), Bahillo et al. (2003) and Kon & Caner (2021).

Table 6. Percent CHNS Compositions of LC, Biomass (TL, CDM, BTW) and Blends

S/No.	Sample Name	%C	%H	%N	%S
LC and Biomass					
1.	LC	58.662	4.640	0.000	5.369
2.	CDM	37.029	4.681	0.364	0.149
3.	BTW	35.953	4.726	0.000	0.309
4.	TL	52.210	5.266	0.000	0.071
CDM + LC Blend					
5.	LC90 + CDM10	47.148	4.527	0.226	2.380
6.	LC80 + CDM20	47.807	1.435	0.237	2.886
7.	LC70 + CDM30	53.825	4.709	0.191	4.103
8.	LC60 + CDM40	51.956	2.621	0.094	3.985
TL + LC Blend					
9.	LC90 + TL10	52.784	4.999	0.000	3.055
10.	LC80 + TL20	55.650	4.912	0.000	3.728
11.	LC70 + TL30	54.022	4.942	0.000	3.332
12.	LC60 + TL40	52.210	0.000	0.000	2.234
BTW + LC Blend					
13.	LC90 + BTW10	48.735	4.825	0.138	2.764
14.	LC80 + BTW20	52.938	4.710	0.046	3.44
15.	LC70 + BTW30	53.353	4.639	0.023	4.185
16.	LC60 + BTW40	47.602	4.572	0.000	2.850

Table 7. Emission Studies of LC, Biomass (TL, CDM, BTW) and Blends

S/No.	Material	O_2 (%)	CO (ppm)	CO_2 (%)	NO (ppm)	NOx (ppm)	SO_2 (ppm)
LC and Biomass							
1.	LC	16.89	901.83	2.19	30.66	30.63	325
2.	TL	15.33	925	3.03	40.66	40.66	269.33
3.	BTW	16.753	1510.5	1.633	68	64.66	66.667
4.	CDM	17.79	1322.16	1.798	32.166	30.83	68.4
TL + LC Blend							
5.	LC90 + TL10	13.2	1083.83	4.37	43.33	51.16	345.33
6.	LC80 + TL20	15.74	1103.66	2.878	45.33	45.5	138.16
7.	LC70 + TL30	15.74	1220	2.86	52.83	53.16	21.83
8.	LC60 + TL40	15.45	928.83	3.02	65.83	66.16	32.83
BTW + LC Blend							
9.	LC90 + BTW10	15.525	1136.16	3.105	45.66	45.83	9.83
10.	LC80 + BTW20	16.49	1247.5	2.505	45.83	42.66	40.1
11.	LC70 + BTW30	15.34	1449.16	3.205	54.5	44	35.2
12.	LC60 + BTW40	15.65	1644.16	2.97	55.33	55.5	44.3
CDM + LC Blend							
13.	LC90 + CDM10	16.31	1263.3	2.475	40.67	43.33	50.833
14.	LC80 + CDM20	16.553	839.5	2.49	48.16	48.33	1.1667
15.	LC70 + CDM30	14.045	684.67	3.921	38.5	39.33	36.31
16.	LC60 + CDM40	14.667	1073.3	3.501	40.17	41.333	35.32

Co-combustion of LC and Blends Emissions

Flue gas analyzer described earlier reveals the presence of O_2, CO, CO_2, NO, NOx and SO_2 in the emissions after LC, individual biomass combustion and co-combustion. Respectively, maximum amount of each of the flue gases are 17.79%, 1644.16 ppm, 4.37%, 68 ppm, 66.16 ppm and 345.33 ppm in CDM, LC60 + BTW40, LC90 + TL10, BTW, LC60 + TL40 and LC90 + TL10, as shown in Table 7. By implication: a 17.79% O_2 is indicative of a sufficient air supply enhancing the combustion process; CO concentration of 1644.16 ppm is relatively high and signals an incomplete combustion; CO_2 level of 4.37% is comparatively low for typical CO_2 emission, suggesting an incomplete burning; moderately low NO and NOx concentrations of 68 and 66.16 ppm, respectively, are irrelevant given their ability to cause air pollution and smog formation and; 345.33 ppm amount SO_2 release is significant and may cause environmental and health consequences.

It is now clear that 0% N reported earlier in this study in the LC analyzed is strange given that 30.66 and 30.63 ppm of NO and NOx nitrogen compounds were emitted during its combustion. A 0% report, might be influenced by sensitivity and detection limits of the analytical method used. Extremely low N concentrations might fall below the detection threshold of certain analytical techniques. It may further be blamed on impurities containing N compounds attached to the LC that contributed to the formation of N oxides during combustion or sample heterogeneity, in which a coal sample exhibit variations in composition across different portions of the sample and so, the portion analyzed had lower N content contributing to NO and NOx release. Same can be speculated on BTW, TL, LC-TL and LC60 + BTW40 samples combustions with zero N emission in Table 6.

Based on the data provided in Table 7, the blend that emits the lowest amount of pollutants is LC90 + CDM10. This blend emits the lowest amount of CO, NO, NOx, and SO_2 among all the blends listed in the table. Therefore, if the goal is to avoid air pollution, LC90

+ CDM10 would be the recommended blend, followed by LC80 + CDM20 and LC70 + CDM30 – despite the fact that LC90 + CDM10 blend has higher emissions of flue gases compared to LC. Among the BTW+LC and TL+LC blends, the blend with relatively lower emissions of pollutants is TL + LC blend with 90% LC and 10% TL (LC90 + TL10) and BTW + LC blend with 90% LC and 10% BTW (LC90 + BTW10). The blend that compares favorably with LC emissions is LC80 + TL20. This blend emits similar amounts of CO, NO, NOx, and SO_2 as LC, which is the base material. Therefore, LC80 + TL20 can be considered as a suitable alternative to LC if the goal is to reduce the use of LC while maintaining similar emission levels. It appears that none of the blends achieve the goal of reducing air pollution compared to LC combustion. All the blends show varying levels of emissions of flue gases, with some blends having even higher emissions than LC. In most co-firing tests, emissions of NOx, CO_2 and SO_2 were reduced [37], slightly deviating from this study findings. By adjusting the blend ratio or incorporating a combustion efficiency enhancement technique, such as a catalyst that facilitates the oxidation of CO and hydrocarbons, or promotes the reduction of NOx emissions, it may be possible to further lower the emissions of the LC90 + CDM10 blend below that of LC.

TGA of LC and Biomass Blends

TGA analyzer was used to see the thermal characteristics of material in which the different temperature at which the materials were dewatered, ignited, devitalized and burned was measured. From the result, it is observed that LC was dewatered at a temperature of 108.15°C and devolatilized within 200-520°C, leaving a burnout residue of about 15.21%. TL has a burnout residue of 11.49% with the leaves devolatilized at 200-510 °C at equal dewatering temperature with LC. Moisture is removed from BTW at 109.15°C and devolatilized at 200-500°C – and have a burnout residue 18.65%. For CDM, moisture removal occurs at 108.15 °C while devolatilization was within 200-490 °C, yielding a burnout residue of 16.67%, as shown in Table 8.

To determine which sample is suitable for co-combustion, there is need to consider the parameters related to thermal behavior and combustion characteristics of the samples. Based on the data provided in Table 8, the following observations can be made: all samples have similar dewatering temperatures, indicating that they have comparable moisture contents; all samples have ignition temperatures above 900°C, indicating that they are all suitable for combustion; all samples have similar temperature ranges for volatilization and burning, indicating that they have comparable thermal decomposition behavior; all samples have similar temperature ranges for the transition period, indicating that they have comparable thermal degradation behavior; all samples have similar temperature ranges for char burning, indicating that they have comparable char combustion behavior and; lastly, the burnout residue percentages for all samples are within a similar range, indicating that they have comparable ash content. The ash is the residue which is obtained by calculations involving volatile matter content. Kepys & Pomykala (2014) highlights the importance of this fly ash residue in suspension technologies commonly used in coal mines. Fly ashes are known to be rich in metallic mineral elements which are high after lignite combustion but low in concentration in coal/biomass blends, based on findings of Vamvuka et al. (2009). Based on these observations, it can be concluded that all samples are suitable for co-combustion, as they have similar thermal behavior and combustion characteristics. However, LC90 + TL10, LC80 + TL20, LC70 + TL30, LC60 + TL40 and LC80 + BTW20 can be considered as the best candidates for co-combustion. For power generation applications, the calorific value of the co-combustion blend is of utmost importance, as it directly impacts the energy output [1].

Table 8. TGA of LC, Biomass & Blends

Sample	**Dewa-tering (°C)**	**Ignition (°C)**	**Volatili-zation & Burning (°C)**	**Transition Period (ºC)**	**Char Burning (ºC)**	**Burnout Residue (%)**
LC	108.15	956	200-520	600-949.3	949.3-950	15.21
TL	108.15	955	200-510	590-949.3	949.3-950.3	11.49
BTW	108.15	954	200-500	580-949.3	949.3-951.3	18.65
CDM	108.15	953	200-490	570-949.3	949.3-951.6	16.67
LC90 + TL10	106.06	946	200-500	500-945.68	945.68-949.62	13.20
LC80 + TL20	108.38	947	220-510	510-948	948-948	15.67
LC70 + TL30	103.19	949	300-550	550-949.59	949.59-949.59	13.98
LC60 + TL40	104.78	948	250-750	700-948	948-949.59	15.90
LC90 + BTW10	109.57	950	200-550	550-949.59	949.59-951.19	17.84
LC80 + BTW20	107.98	949.6	190-500	500-949.59	949.59-949.49	18.42
LC70 + BTW30	106.38	949	210-550	550-949.59	949.59-949.50	17.47
LC60 + BTW40	106.38	948.5	200-500	500-948	948-949.59	19.19
LC90 + CDM10	104.78	949	200-550	550-949.59	949.59-949.59	13.58
LC80 + CDM20	106.38	948	300-550	550-948.04	948.00-949.59	14.9
LC70 + CDM30	106.38	947	300-570	570-948	948-948	14.79
LC60 + CDM40	107.98	948	250-500	500-948	948-949.59	14.10

Biomass, LC and Blends Heating Value

Sample "LC90 + CDM10" has a high HV of 892951.9 Btu/lb, indicating a significant energy content. This high HV value suggests that the "LC90 + CDM10" sample may be suitable for use in power generation applications where a high HV is desirable, followed by LC80 + BTW20 (HV = 844454.6 Btu/lb) and LC70 + TL30 (HV = 813468.4 Btu/lb). On the other hand, sample "LC80 + CDM20" with an HV of 537007.6 Btu/lb appears to have a lower HV compared to the other samples. This lower HV value suggests that "LC80 + CDM20" may not be as suitable for power generation compared to the other samples with higher HV values, as shown in Table 9. Reports of Belle-Oudry & Dayton (1996) has it that, co-firing of coal with biomass rapidly increases fuel sustainability without large capital investment in coal-fired power plants.

The HV range for power generation can vary widely depending on the type of fuel being used. For example, the HV of coal can range from around 5000-15000 Btu/lb, while the HV of natural gas can range from around 900-1100 Btu/scf. Hamdani & Haryanto (2022) had reported HV of LC in the range of 7277-7769 Btu/lb for various samples while Schmidt (2001) reports HV = 6700 Btu/lb, which are both < 730540 Btu/lb obtained here. Biomass fuels such as wood chips or pellets can have HV values ranging from around 6000-9000 Btu/lb. As such, all 16 sample variations can go into power generation, especially the biomass blends. Suitability of a sample for power generation also depends on other factors such as availability, cost, environmental impact, and compatibility with existing power generation technologies [37].

Table 9. HV of Samples Under Consideration

S/No.	Sample	HV (Btu/lb)
1.	LC	730539.9
2.	TL	794640.4
3.	BTW	809612
4.	CDM	712800
5.	LC90 + TL10	700743.3
6.	LC80 + TL20	703493.7
7.	LC70 + TL30	813468.4
8.	LC60 + TL40	771025.3
9.	LC90 + BTW10	797342.6
10.	LC80 + BTW20	844454.6
11.	LC70 + BTW30	817016.2
12.	LC60 + BTW40	632423.2
13.	LC90 + CDM10	892951.9
14.	LC80 + CDM20	537007.6
15.	LC70 + CDM30	521179.1
16.	LC60 + CDM40	783558.3

CONCLUSION

TL, CDM, BTW and LC together with 4 different ratios of LC-biomass blends (90:10, 80:20, 70:30 & 60:40) were subjected to emission, TGA, CHNS and energy content analysis to assess their combustion properties which will aid their selection for co-firing power plants. Initial proximate analysis reveals their potential for flue gas emissions and the findings tagged LC90 + CMD10, LC80 + CDM20 and LC70 + CDM30 as the best for minimal emission, still higher than LC level. There is no better choice of sample as TGA suggests suitability of all in co-combustion. LC90 + CDM10, LC80 + BTW20 and LC70 + TL30 have highest HV with strong potential to serve as fuel in coal power plants, even though all samples are favorable candidates. To improve the blends and reduce the emission of flue gases compared to LC, strategies including optimization of blend ratios, utilization of additives or catalysts, implementation of advanced combustion technologies and biomass pretreatment should be considered. Attention should be shifted towards co-firing of biomass with polymeric materials (e.g., tires and plastic) using fluidized bed technology as well as biomass & coal co-gasification, in addition to studying their kinetics. Also, the spontaneity of the LC combustion and blends can be determined based on functional group present during Fourier Transform Infrared Spectrophotometer (FTIR).

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