Evaluation of the Fuel Properties and Pollution Potentials of Lignite Coal and Pellets of its Blends with Different Biowastes

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Authors' contributions

This work was carried out in collaboration between all authors. Author CNI designed the study. Authors MCA and CNI performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author MCA managed the analyses of the study. Authors MCA, CNI and CNA managed the literature searches. All authors read and approved the final manuscript.

Original Research Article

ABSTRACT

The fuel properties and pollution potentials of lignite coal, wood chippings, cashew leaf litter, yam peels and rice husks were improved by blending, carbonisation and pelletization. Four blends of lignite coal with the biomass samples were prepared in 20:80 ratio and made into pellets using vegetable oil as binder. The lignite coal, biomass and their blends were carbonised at 623 K. Proximate and ultimate analyses were carried out while the calorific values, lignocellulosic content of each biomass and their blends were determined. Also the pollution potentials of each fuel in a hypothetical pulverised fuel combustion plant were derived using a metallurgical and thermochemical data base (MTDATA). The quantities of CO_2, NO_2 and SO_2 that would be emitted per hour from the plant were calculated. The results of the proximate analysis for the raw samples showed that lignite coal had the highest fixed carbon (26.10%) and moisture content (31.50%). Except for lignite, the carbonised samples had an improved fixed carbon and volatile matter contents, relative to the uncarbonised blends. The ultimate analysis of carbonised blends showed an increase in hydrogen and oxygen content with a decrease in sulphur and nitrogen contents.

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However, the calorific values of the pelletised blends almost doubled, showing clearly the improvement in energy content of the blends. For the simulated pulverised fuel combustion power plant analysis using MTDATA, each fuel showed that blending and carbonisation can improve lignite coal, thereby reducing the high moisture content, high ash and also the SO_2, CO_2 and NO_2 emissions to an extent. It also proves that most of the NO_X gases are generally thermal in nature. Therefore, blending of lignite coal with different biomass and waste materials should be encouraged in coal fired power plants to reduce environmental pollution, increase energy and power output.

Keywords: Lignite; biomass; pelletization; pollution; fuel.

1. INTRODUCTION

Environmental pollution due to combustion of fossil fuels is a global problem which has gained a lot of attention. The fossil fuels include coal, peat, petrol, diesel, natural gas and fuel oil. Coal is a solid fuel that has diverse domestic and industrial applications such as electricity generation, cooking e.t.c. The different ranks of coal in order of decreasing energy content and increasing air pollution potential are as follows: Anthracite, bituminous, sub-bituminous and lignite. Lignite, which is a low rank coal accounts for more than 50% of the world coal reserves but their applications are limited due to their low heating value, spontaneous combustion property and pollution potential. The green house gas emissions of primary concern from the combustion of coal in power plant systems are CO_2, SOx, NOx, N_2O, CO e.t.c.

A biomass fuel fired in a combustion boiler behaves differently from coal. This is due to the fact that biomass in general is characterised as having a higher volatile matter and alkali content, lower heating values, less carbon, more oxygen, higher moisture content, usually lower density and wider size distribution when compared with coal compositions [1]. Carbon dioxide is a major product from all biomass combustion, originating from the carbon content in the fuel. However, carbon dioxide emissions from biomass combustion are regarded as being carbon dioxide - neutral with respect to the greenhouse gas effect and this is considered to be the main environmental benefit of biomass combustion [2]. The utilisation of different forms of biomass as fuel seems to be an effective means of reducing carbon dioxide emissions and invariably global warming. Additional benefits, such as increasing the use of waste materials and decreasing the demand for their disposal, are equally achieved. Also co-firing of biomass with coal is among the less expensive alternatives for environmental benefits and power utilities. It is imperative that several studies are carried out on coal and biomass blends in order to determine their fuel properties and pollution potentials.

Biomass and waste materials are also relatively free from wide price fluctuations, and this is another major advantage of using these feedstocks for value-added products, and justifies research and development efforts in co firing of coal with biomass for better electricity and energy generation. When co-firing biomass with coal in a power plant, a continuous supply of biomass would not be an issue, because the boiler plant would always have the primary coal fuel for 100% combustion. Co-firing, apart from solving pollution problems, such as release of harmful gases into the atmosphere due to burning lignite alone also solves the problem of moisture control from burning biomass or lignite alone. Some typical biomass fuels found in coal co-firing studies are: cattle manure, switchgrass, sawdust and sewage sludge [3]. These studies highlighted a reduction of gaseous emissions but difficulty in crushing the biomass e.g cattle manure to the same particle size as coal.

Further processing of coal or biomass in terms of compacting has the advantage over unprocessed biomass of being stored for a longer time and easily transported [4]. There are different ways of compacting fuels e.g. briquetting and pelletization. A lot of studies have been carried out on briquetting of coal, biomass and coal/biomass blends [5,6]. However there are very few studies on pelletization of coal and biomass, which is a compressing technique that reduces the volume of the biomass/coal drastically, thus improving the energy density while reducing transportation cost of biomass pellets. Also, biowastes such as cashew leaf litter, wood chippings, yam peels and rice husks are readily available in large quantities in several countries and should be exploited.

Therefore, this study is aimed at evaluating the fuel properties and pollution potentials of lignite and its blends with biowastes (wood chippings, cashew leaf litter, yam peels and rice husks). In addition, is the determination of the effect of blending and pelletization on the energy content of Lignite and its blends with the biowastes.

2. METHODOLOGY

2.1 Sampling

The cashew leaf litters and rice husks were obtained from farms. The wood chippings were collected from a timber shade, while yam peels were obtained from domestic wastes. All the biowastes were obtained from Kogi state, Nigeria. However, the lignite coal used was gotten from Adamawa coal mine in Yola, Adamawa state, Nigeria.

2.2 Sample Preparation

The cashew leaf litter, yam peels, rice husks and wood chippings were properly dried under the sun to reduce moisture and milled. They were milled in a Kenwood blending machine to particle sizes of about 0.01-0.5 mm, while the lignite coal was milled in a commercial grinding engine to a particle size of 0.01-0.05 mm. Each grinded biomass material (cashew leaf litter, rice husk, wood chippings, yam peels), and lignite coal were all stored separately in clean and dry transparent containers with tight lid. Blends of the biomass and lignite were prepared in the ratio 20:80 respectively which is typical of co-firing applications in European industry [7].

2.3 Pelletization of Blends

The pellets were formed using the blends of lignite and the biowastes with waste vegetable oil as binder. The blended samples; lignite-rice husk, lignite-yam peels, lignite-wood chippings and lignite-cashew leaf litters, were further subjected to more milling conditions to further reduce the particle size of the blends to about 0.05-0.1 mm. The waste vegetable oil (0.5%) was sprayed into the lignite-biomass mixtures for even distribution before Pelletization using a Pelletizing machine. This was carried out at 120°C under 150 MPa compacting pressure. The resulting material was then extruded through a die of 10 mm, the product obtained were pellets of 10 mm which after extrusion were very hot. They were then allowed to cool before drying

with moderate heat from the LAC muffle furnace at a temperature of 60°C.

2.4 Carbonisation of Blends

The samples were carbonised at a temperature of 350°C for thirty minutes each, in a LAC muffle furnace L15S. 50 g of each sample (wood chippings, cashew leaf litter, yam peels, rice husks and lignite coal) were carbonized. Carbonization process was performed both on fresh samples and their various blends of the biomass with lignite coal.

2.5 Analysis

The proximate analysis and ultimate analysis of the carbonised and uncarbonised samples and their blends were carried out using ASTM D-3172-89 and ASTM D-3176-3179 methods respectively. The cellulose and hemicellulose contents for each sample material were determined spectrophotometrically by the anthrone reagent method using a UV-Visible spectrophotometer S23A [8] while the lignin content for each sample was calculated using Equ 1 below [9].

$$HHV = 0.0889(LC) + 16.8218 \qquad (1)$$

Where,

HHV = high heating value and
LC = lignin content.

The calorific value of the single samples, blends and pellets was determined using a LECO AC 350 bomb calorimeter.

2.6 MTDATA Analysis

Thermodynamic equilibrium modelling of major elements (C, H, N, O, S) to indicate their partitioning behaviour on a chemical equilibrium basis for the combustion of carbonised blends of the biomass with lignite coal (at the conditions of a pilot-scale experiment) was carried out using MTDATA software package (National Physical Laboratory, Teddington, London, UK) case of the major elements (C, H, N, O, S). The species included were known from prior knowledge to be present in the fuel gas of the combustion system. The protocol adopted was therefore to assume a notional composition (for all the elements with the conditions of the experimental combustor used) and to perform a sensitivity analysis of the

equilibrium composition. Element species found to be formed at all concentrations were included in a simplified database. The relevant simplified database was then used to calculate the equilibrium composition for specific element in each test. This test was performed for Lignite and its blends with carbonised biomass using the values of their elemental analysis.

3. RESULTS AND DISCUSSION

The results of the proximate and ultimate analysis for the singles wastes are shown in Table 1.

Uncarbonised lignite coal gave the highest moisture content (31.50%) compared to the other biomass materials used in this study. After carbonisation at 623K the fixed carbon content of each of the biomass materials increased considerably, with a decrease in their moisture content. The low moisture content of each biomass material after carbonisation is an indication that the thermal conversion of the fuel would be considerably high. These results are in agreement with the study of Basu [10], which shows a direct relationship between moisture content and the heating value of biomass. Furthermore, the low ash content of the carbonised biomass materials indicates a low risk of fouling and slagging of the thermal conversion equipment during combustion. For the ultimate analysis, the carbon and hydrogen content of the carbonized biomass fuels increased considerably when compared with the uncarbonised samples. The improvement of the carbon content of each biomass fuel is attributed to the increase in lignin content during carbonisation as shown in Table 3.

The data of proximate and ultimate analysis of the uncarbonised and carbonised blends are presented in Table 2. The results shows a favourable impact of the blending of the biomass with Lignite since the moisture content of the blends were lower than that of lignite alone except for the carbonized cashew leaves and rice husks with initially high moisture contents. Also the ash content of lignite was reduced after blending with all the biowastes. Therefore, without the removal of particularly the moisture content from lignite by carbonisation the fuel blends generated are likely to have low calorific value due to high moisture content, thereby reducing the efficiency of most power plants [11].

The results of the ultimate analysis presented shows considerable differences between uncarbonised and carbonised blends. The carbon and oxygen contents of each blend increased slightly after carbonisation. However, the sulphur contents reduced slight increase in the nitrogen contents. The elemental composition of the blends after carbonisation shows that there will be less pollution during combustion of the fuels.

Cellulose, hemicelluloses, lignin, lipids, organic acids and minerals comprises over 90-95% of biomass in plant [12]. Lignin was very low in fresh samples of biomass while cellulose and hemicelluloses contents were high. After carbonisation at 623 K the lignin content of the biomass increased considerably. Lignin forms mainly chars since it is not readily cleaved to lower molecular weight fragments. The lignin content of each biomass sample after carbonisation in this study were as follows; wood chippings (25.16%), rice husk (22.16%), cashew leave litter (21.87%), and yam peels (20.02%). This result is in correlation with the considerable increase in fixed carbon content of each biomass as shown on Table 1. Lignin content varies in different biomass. For instance, Lignin content is increased or decreased in wood formed under gravitropic stimulation or mechanical stress (known as reaction wood. In softwoods (gymnosperms), compression wood may be up to 40% lignin, and in hardwoods (angiosperms), tension wood fibers have a specialized gelatinous cell layer that is almost devoid of lignin [13]. Also, It is important to note that the initial degradation of cellulose includes the following; depolymerisation, hydrolysis, oxidation, dehydration and decarboxilation, under high temperatures (623 K) such as was adopted in this research for the carbonisation of each sample, the resultant effect is the residue left behind which comprises of some water soluble materials, in addition to char and undecomposed cellulose [9]. The results of un-decomposed cellulose are seen in the blends (LiWc, LiYp, LiRh except for LiCl). After carbonisation the presence of hemicellulose was not detectable. This behaviour can be attributed to the increase in the volatile matter of the blends, since hemicelluloses have weaker bonds compared to cellulose.

Results of the Calorific value (KJ/Kg) determination were 17000.02, 16000.93, 16000.11, 13000.97, 13000.76 for wood chippings, cashew leaf litter, yam peels, rice husks and lignite coal, respectively; while the carbonized forms gave 18000.47, 17000.06,

16000.61, 17000.19, 10000.17 KJ/Kg, respectively. This clearly shows that carbonization increased the calorific values of the biomass but slightly reduced that of the lignite. The drop in calorific value observed in lignite coal is possibly due to the use of the heat energy to remove most of the inherent moisture [14], as it is known that lignite coal has a high moisture content when compared to other coal ranks such as sub-bituminous, bituminous and anthracite. Each of the biowastes (biomass materials) recorded relatively high calorific value both as carbonised and un-carbonised. This can be attributed to their low moisture content and high volatile matter content [15].

As shown in Table 4, the calorific values of carbonised blends increased although they were proportionate to those of carbonised pure biomass samples. This is due to the high moisture content of lignite coal and as such in the course of blending and carbonisation; the inherent moisture is removed by the heat generated and invariably leads to a decrease in the calorific value of the carbonised blends [14]. The calorific value of pelletized uncarbonised blends is about twice the calorific value of both carbonised and uncarbonised biomass-lignite blends. This shows the positive effect of Pelletization on the calorific values of fuels. Pellets have more heat energy per kilogramme.

Table 1. Results of proximate and ultimate analysis of uncarbonised and carbonised biomass materials and lignite coal

Parameters samples	Moisture content (%)	Volatile matter (%)	Fixed carbon (%)	Ash (%)	%C	%H	%O	%S	%N
UWc	3.97	69.94	19.26	6.75	47.35	5.60	43.88	0.02	0.34
UCl	9.90	62.63	18.72	8.60	46.18	5.33	38.69	0.13	1.12
UYp	12.01	58.20	18.65	11.04	41.40	4.18	30.26	0.17	0.87
URh	20.23	41.99	19.24	18.70	30.47	3.56	33.57	0.07	1.63
ULi	31.50	30.60	26.10	11.80	41.40	5.60	26.05	1.50	0.80
CWc	2.50	71.03	24.16	2.31	48.41	5.91	46.60	0.01	0.39
CCl	6.10	64.31	23.71	3.37	47.12	5.41	40.78	0.11	0.01
CYp	3.76	69.85	22.87	6.14	47.54	4.89	42.92	0.07	1.13
CRh	7.10	64.14	20.45	6.55	47.80	5.11	38.92	0.04	0.71
CLi	3.87	27.88	14.81	27.28	31.62	3.69	35.15	0.16	1.76

UWc (uncarbonised wood chippings), UCl (uncarbonised cashew leaf litter), UYp (uncarbonised yam peels), URh (uncarbonised rice husk), ULi (uncarbonised lignite coal), CWc (carbonised wood chippings), CCl (carbonised cashew leaf litter), CYp (carbonised yam peels), CRh (carbonised rice husk), CLi (carbonised lignite coal)

Table 2. Results of Proximate and ultimate analysis of uncarbonised and carbonised biomass-lignite blends

Parameters samples	Moisture content (%)	Volatile matter (%)	Fixed carbon (%)	Ash (%)	%C	%H	%O	%S	%N
ULiWc	25.99	38.47	24.75	10.79	50.77	5.60	33.62	0.22	0.71
ULiCl	27.18	37.01	24.65	11.16	50.53	5.55	32.58	0.24	0.86
ULiYp	27.06	36.12	25.45	11.65	49.58	5.32	30.89	0.25	0.81
ULiRh	29.25	32.88	25.17	13.18	47.39	5.19	31.54	0.23	0.96
CLiWc	3.59	36.51	37.61	22.29	57.20	5.63	37.44	0.13	1.16
CLiCl	4.32	35.17	38.02	22.49	56.94	4.13	36.28	0.15	1.08
CLiYp	3.85	36.27	36.83	23.05	57.08	3.93	36.70	0.14	1.31
CLiRh	4.52	35.13	37.22	23.13	59.33	3.97	35.90	0.14	1.22

ULiWc (uncarbonised lignite-wood chippings), ULiCl (uncarbonised lignite-cashew leaf litter), ULiYp (uncarbonised lignite-yam peels), ULiRh (uncarbonised lignite rice husk), CLiWc (carbonised lignite-wood chippings), CLiCl (carbonised lignite-cashew leaf litter), CLiYp (carbonised lignite-yam peels), CLiRh (carbonised lignite-rice husk)

Table 3. Results of the lignocellulosic content of the uncarbonised and carbonized biomass samples and blends of lignite and biomass

Parameters samples	% cellulose	% hemicellulose	% lignin
Wood chippings	37.26	29.14	12.02
Cashew leaf litter	31.45	23.24	10.87
Yam peels	39.90	29.76	6.70
Rice husk	35.30	25.22	9.26
Carbonized wood chippings	11.18	None	25.16
Carbonized cashew leaf litter	9.45	None	21.87
Carbonized yam peels	11.97	None	20.02
Carbonized rice husk	10.59	None	22.31
Carbonized lignite-Wood chippings	6.50	None	12.92
Carbonized lignite-Cashew leaf litter	3.50	None	16.29
Carbonized lignite-Yam peels	10.16	None	16.60
Carbonized lignite-Rice husk	17.90	None	14.66

Table 4. Calorific value for blends of biomass-lignite coal and pellets

Parameters blended samples (20-80)%	Calorific value of uncarbonised blends (KJ/Kg)	Calorific value of carbonised blends (KJ/Kg)	Calorific value of the pellets (KJ/Kg)
LiWc	16000.00	17000.97	28000.38
LiCl	15000.94	16000.17	30000.46
LiYp	15000.45	16000.47	26000.42
LiRh	14000.86	15000.53	24000.48

This is because loose materials are compressed under pressure into a smaller volume. Hence, Pelletization does not necessarily increase the calorific value of the fuel, it increases its energy per unit mass. In addition, the Vegetable oil added as binder can actually lead to an increase of the calorific value. 0.5% dosage of motor oil and vegetable oil increases calorific values, and 0.5% corn starch additive decreases calorific values by about 0.5 MJ/kg [16].

For the MTdata analysis on the pollution potential of the fuels, Fig. 1 shows that at about 1000 K the carbon content of the coal was used up which invariably lead to the stable emission of CO_2. This occurance proceeded throughout the course of the reaction giving a total CO_2 emission of minus 0.05 g/Kg. There was no emission of NO_2 observed throughout the progress of the reaction.

Fig. 2, shows that the emission of CO_2 from the graph is in correlation with that of Fig. 1. The SO_2 emissions observed at 700 K reveals the inherent ability of sulphur to be in cooperated in coal fixtures during coalification. The SO_2 emission pseudo-steadily increased throughout the course of the reaction with a total SO_2 emission of 0.6 g/Kg. This behaviour is one of the reasons for blending lignite coal with different biomass materials to help reduce its pollution level and increase its usage for power generation in industries.

However from Fig. 3, NO_2 was not formed in the course of the combustion process. Although the presence of NO and N_2O was observed, the N_2O emission remained constant without any appreciable increase throughout the course of the combustion process, but the presence of NO was actually observed at 570°C with a gradual increase to minus Log_{10} 3.9/Kg (0.6 g), which is very minimal. The CO_2 emissions noticed at about minus Log_{10} 0.2/Kg (-0.7 g) began to increase to 0.6 g at 570°C, which was still minimal at the end of the combustion process. This implies that the blend of fuel used in this case will cause no pollution problems. In Fig. 4, the behaviour of CO_2 remained the same and there was no SO_2 emissions observed. Hence the use of blends of carbonised wood chippings with lignite coal in a pilot plant will cause less pollution problems. But the presence of CO_2 emission was observed from the start of the combustion process and gradually increased to a highest peak at 800°C which is a typical product

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found in flue gas emission, although its amount in this case remained constant throughout the course of the reaction in very small fractions. As pointed out by Artos et al. [17] the carbon loss associated with elutriation rate is proportional to the carbon load. Increase of carbon loading (i.e. fuel feed rate) enhances the rate of particle attrition resulting in greater elutriation loss, which causes the carbon utilisation efficiency to decrease.

Fig. 5, shows that the presence of NO_2 emission was not observed as was the case with wood chipping blends with lignite coal, although N_2O

and NO emissions were observed. The presence of N_2O began from the start of the reaction and remained constant throughout the combustion process. NO gas did not appear until at 570°C and continued to increase with increasing temperature and this can be attributed to the fuel rich regions formed on the burners due to the high volatile matter of the biomass content. The hypothetical graphs of Fig. 5 and Fig. 6 revealed similar pattern of gaseous emission. However for Fig. 7, the presence of CO_2 in the blended fuel was observed from the beginning of the combustion process and started to decrease with increase in temperature throughout the course of
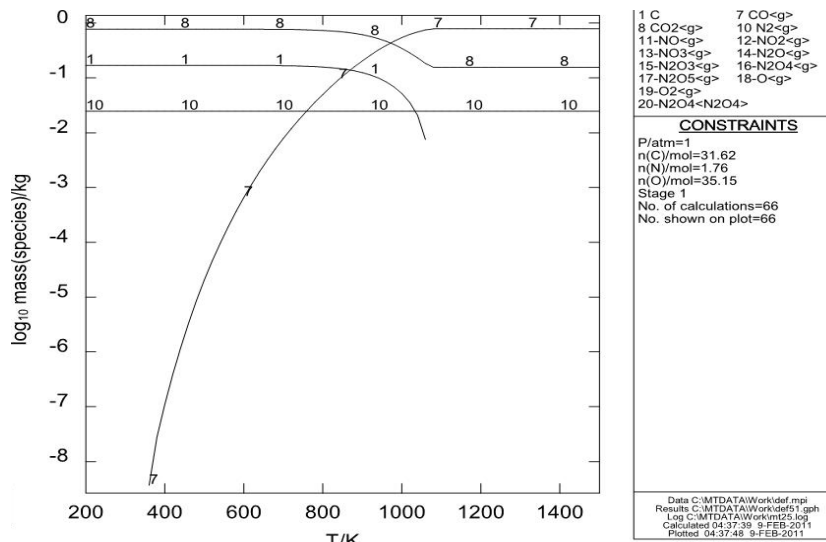
Fig. 1. NO_2 and CO_2 gaseous emissions from carbonised lignite coal
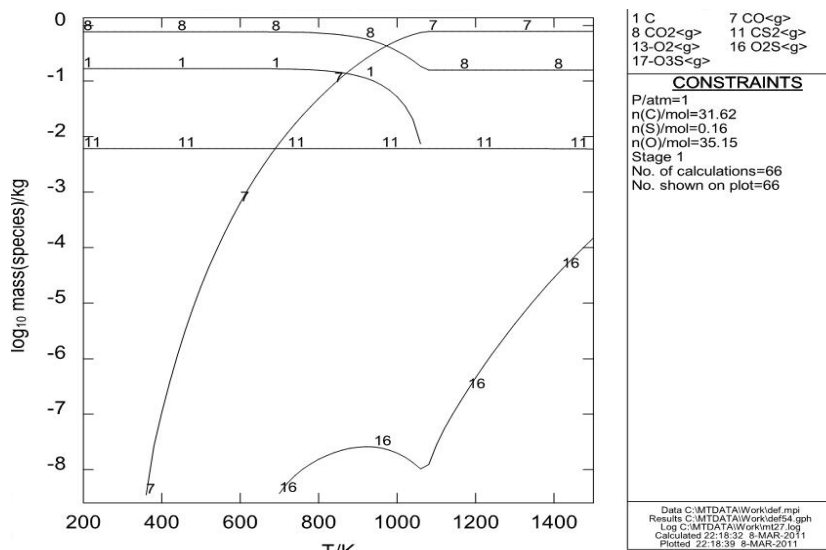
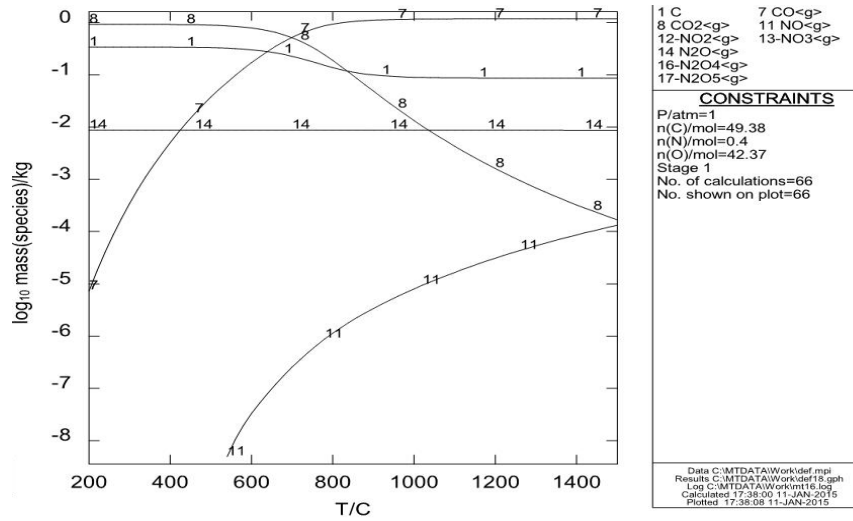**Fig. 2. SO_2 and CO_2 gaseous emissions from carbonised lignite coal**

Fig. 3. NO_2 and CO_2 gaseous emissions from carbonised wood chippings/ lignite coal
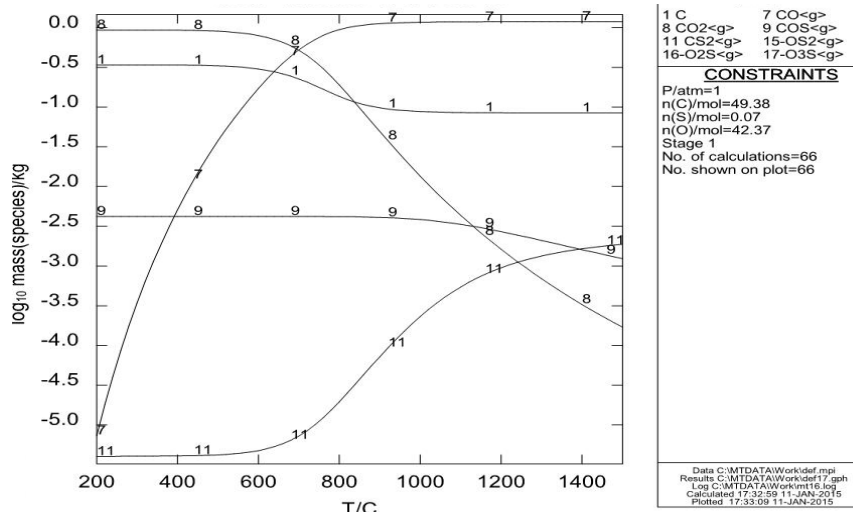

Fig. 4. SO_2 and CO_2 gaseous emissions from carbonised wood chippings/ lignite coal

the reaction, the value obtained for CO_2 emission was 0.6 g which is very minimal. The presence of SO_2 was not noticed.

From Fig. 8, the analysis reveals that the gaseous emission behaviour of carbonised yam peels with lignite coal was similar to those of carbonised wood chippings-lignite and cashew leaf litter-lignite coal in Figs. 2, 3, 4 and 5 respectively. The behaviour of SO_2 gas emission in rice husks shown in Fig. 9, reveals a total variation from the behaviour of SO_2 emissions in the other fuels. The presence of SO_2 emission in carbonised blends of rice husk/lignite was at 570°C (0.9 g) and dropped abruptly at 770°C,

this shows that the SO_2 released would cause no problems if process operation is properly handled. The CO_2 emission observed from the start began to drop from about 570°C to a minimal level of minus Log 3.9/Kg (0.6 g).

As shown in Fig. 10, NO_2 was not observed in all the fuel blends which is in correlation with literature that thermal NOx are the major NOx pollutants and not fuel NOx due to the external air needed for complete combustion, as such, if the residence time of the flue gas in the combustion chamber is increased, the NOx gases will decompose back into N_2 and O_2 [18].
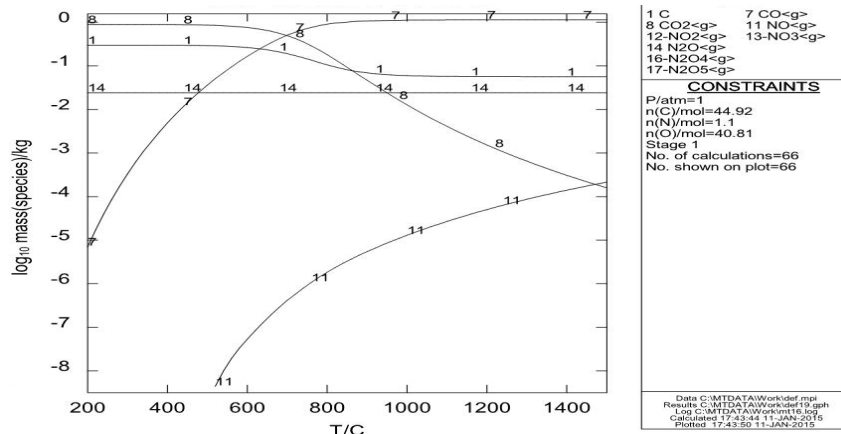
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Fig. 5. NO_2 and CO_2 gaseous emissions from carbonised cashew leaf litter/lignite coal
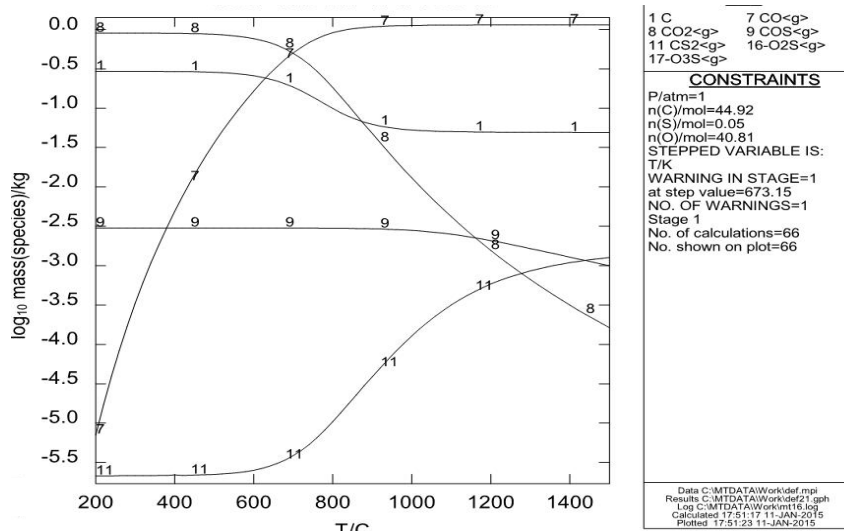

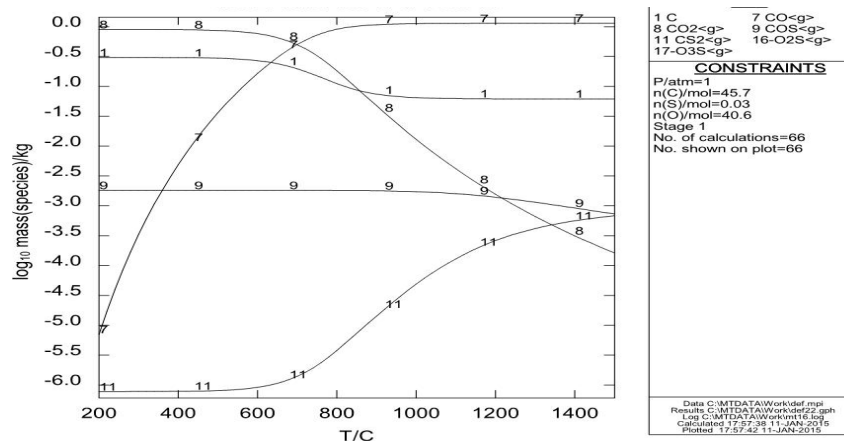**Fig. 6. SO_2 and CO_2 gaseous emissions from carbonised cashew leaf litter/lignite coal**

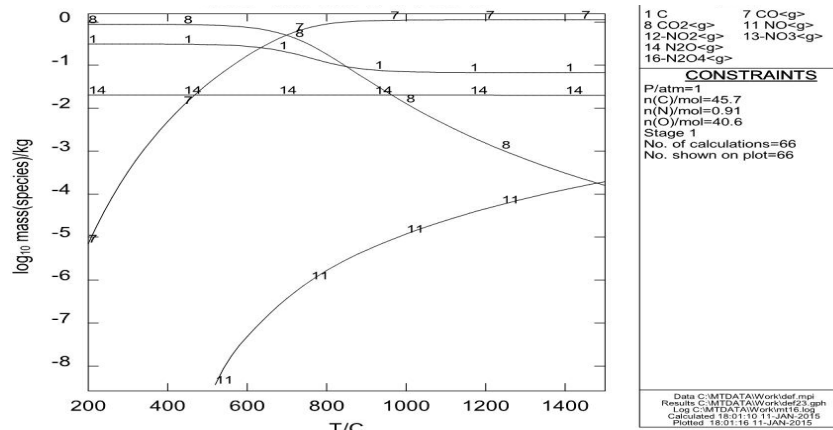**Fig. 7. SO_2 and CO_2 gaseous emissions from carbonised yam peels/lignite coal**

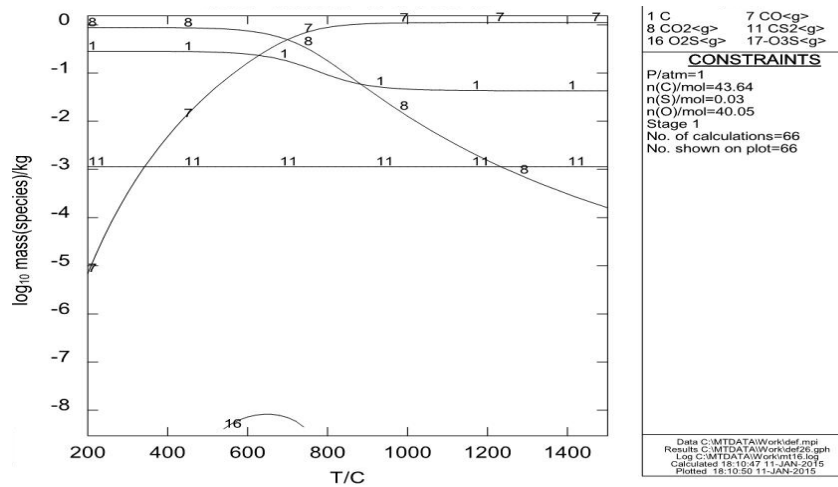**Fig. 8. NO_2 and CO_2 gaseous emissions from carbonised yam peels/lignite coal**

Fig. 9. SO_2 and CO_2 gaseous emissions from carbonised rice husk/lignite coal
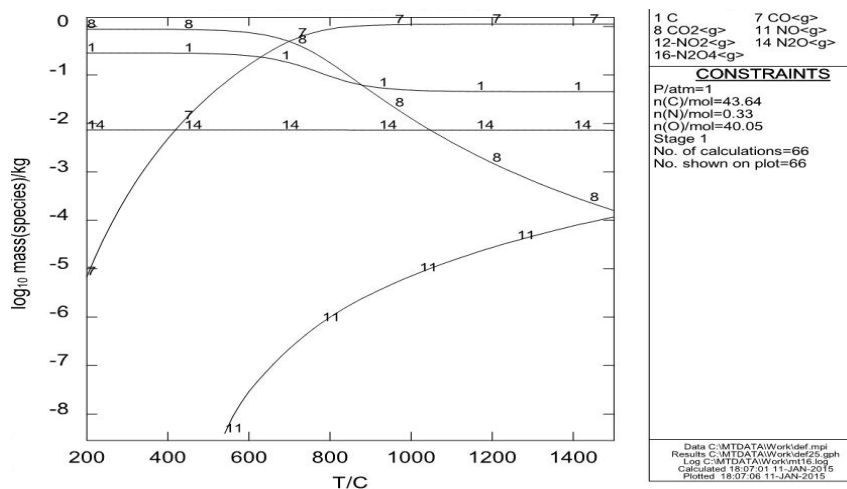

Fig. 10. NO_2 and CO_2 gaseous emissions from carbonised blends of rice husk/lignite coal

4. CONCLUSION

The carbonised blends and pellets of lignite coal with the biowastes have lower moisture and sulphur contents, high calorific value, storage capacity and surface area for heat transfer. This study reiterates the advantages of carbonisation on pure biomass fuels and blends. Using the fuel blends from this study will improve the efficiency of most domestic stoves, because they have less pollution problems to handle, as well as good thermal efficiencies. In addition, the MTDATA results of a hypothetical power plant reveals that there were no NO_2 and SO_2 emissions when using the carbonised fuel blends except for carbonised blend of rice husks with lignite coal which showed slight presence of SO_2 but dropped drastically without any appreciable increase. The entire study stands to be of utmost benefit to electric power stations and various industries such as the textiles and confectionary industries, for production of needed heat and power with little or no pollution problem. Therefore, the vast deposits of lignite coal should be blended with various waste biomass and this should be further exploited in order to effectively utilize lignite as source of fuel as well as reducing pollution problems or cost of desulphurisation to generate the needed fuel and electricity.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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