Journal of Basics and Applied Sciences Research (JOBASR)
ISSN (print): 3026-9091, ISSN (online): 1597-9962
Volume 2(3) September 2024
DOI: https://doi.org/10.33003/jobasr-2024-v2i3-58

# Development and Energy Potential of Co-firing Fuel from Blends of Several Biomasses and Low Rank Coal at Optimal Condition

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**ABSTRACT**
Briquette making business is not widely popular in Northern Nigeria, even though it plays a vital role in enhancing the efficient use of solid fuels in the region. The study aimed to produce bio-coal briquettes from low-rank coal and several biomasses under optimal conditions. Briquette produced using a manually operated briquetting machine was tested to evaluate the impact of the briquettes' combustion and physicochemical properties with respect to coal-biomass variation ratio, gasification temperature and compressive strength. Based on the experimental data, mathematical models were developed to predict the gross caloric value, ash content, moisture content, and relaxed density. To streamline repetitive tasks and lower experimental costs, Design Expert software was used to refine and optimize the briquetting process. Results of the study effectively revealed the impact of each dependent variable on achieving optimal bio-coal briquette production. The optimized results indicated that the calorific value increased from (27.10 to 27.74) MJ/kg, while the volatile matter content rose from (41.4 to 47.94) % by weight. Ash content and moisture content were reduced from (7.31 to 6.35) % and (11.9 to 9.8) % by weight respectively, while relaxed density and compressive strength were adjusted to meet target ranges of (0.8 to 1.09) KN/m$^2$ to (0.9 to 1.99) m$^3$/Kg respectively.The newly produced bio-coal briquette represents an improved, environmentally friendly solid fuel that can be effectively used in any type of charcoal stove.

**Keywords:**
Bio-coal briquettes,
Low-rank coal,
Waste biomass
Physiochemical,
Combustion.

## INTRODUCTION

Despite the increasing pressure on our forests for fuel-wood and charcoal production, which has led to severe environmental degradation and forest shrinkage, this situation has resulted in negative health and economic impacts for the region. The drive to harness this sustainable source stems from the need to diversify the world's energy mix, as it is readily available.

Similarly, in response to the recommendations of past similar research works for the need to expand research on bio-coal production based on available facts that slighted variation in raw materials would yield substantive change in bio-coal heating and combustion properties. This leads to the idea of developing another form of solid fuel source from what is considered as unwanted solid biomass waste available in our environs that can adequately be changed to a useful treasure for further utilization. The idea of mixing more than one fuel type in order to come up with new solid fuel source that can replace the function of coal, firewood, charcoal, biomass or any other type of single-solid-fuel source and performs better in terms of burning and combustion properties and characteristics.

Biomass is regardedas an alternative clean energy resource. The utilization of biomass to partially replace coal for power generation can not only reduce $CO_2$ emissions, but also even achieve negative $CO_2$ emissions by combining carbon capture technology (Liu et al., 2022; Spiegl et al., 2021). Many studies also found that co-firing of coal and biomass was conducive to reducing the emissions of other pollutants such as CO, NOx, $SO_2$ and $PM_{2.5}$ (Gungor, 2013; Jiang et al.,2022; Zhang et al., 2020). With continuous consumption of coal, the global coal reservoirs are declining. Biomass energy can lighten the energy crisis caused by the consumption of non-renewable energy (Saleem, 2022). Apart from a few countries with high levels of hydropower such as Norway, Canada, New Zealand and Switzerland, biomass power generation is the mainstream alternative in most countries (IEA Bioenergy, 2022). For example, China is also rich in biomass energy storage. From 2010 to 2019, the total biomass energy from terrestrial ecosystems was estimated to be $535.91 \times 10^{18}$J, equivalent to 18.29Gt standard coal. The total biomass from forest eco-systems was the most abundant, which has the greatest potential to partially replace coal (Yan et al., 2020).

Biomass co-firing with coal in the power production sector is an economically and environmentally appealing alternative. Co-firing is deemed cost effective because it does not necessitate major investments and uses of existing CFPP infrastructure (Roni et al, 2017). According to Life Cycle Assessment (LCA) modeling co-firing with a 10% combination of wood pellets and coal can result in a 9% reduction in GHG emissions (Morrison and Golden 2017). The technology and efficiency of co-firing are constantly being developed to reduce coal consumption. The type of biomass and the composition of the mixture utilized can impact on the boiler's efficiency. The pre-mixing conditions of biomass and coal are critical determinants in the performance of co-firing applications (Sidiq, 2022). Biomass with a high moisture content, a low calorific value and poor grind ability must be considered (Nudria, 2021). As a result, optimizing biomass quality is critical for achieving constant combustion performance.

Utilization of biomass, particularly from agricultural waste, is another option because it can be an environmental solution, especially given the abundance of materials. Sawdust, bark, wood chips, urban wood waste, rice straw, rice husks, and herbaceous plants are all examples of biomass that can be used in co-firing (Demirbas, 2003). Even co-firing with waste pellets at a 5% mixing ratio in a Circulating Fluidized Bed (CFB) CFPP is viable (Fadli et al. 2019).

The main focus of this work is making use of blends of solid waste in Sokoto city (such as wastepaper, rice husk, and groundnut shell) mixed with low-rank coal as a source of renewable energy for the development of co-firing biomass-coal fuel briquette for traditional cook-stove and non-ferrous melting crucible furnace, an effort towards augmenting energy crisis in Nigeria.

## MATERIALS AND METHODS

## MATERIALS

### Coal

Coal was a solid fuel source formed by the remains of animals' dead bodies and vegetable that was buried under ground millions of years ago under great pressure and temperature in the absence of air. Coal is a complex mixture of compounds composed mainly of carbon, hydrogen and oxygen with small amounts of Sulphur, nitrogen, and phosphorus as impurities. Nigeria has large coal deposit which has remained untapped since 1950's, following the discovery of petroleum in the country.

### Biomass Resources of Nigeria

Biomass is organic non-fossil material of biological origin. The biomass resources of Nigeria can be identified as wood, forage, grasses and shrubs, animal waste, and waste arising from forest, agricultural, municipal and industrial activities as well as aquatic biomass (Eapetu, O.P. 2000). Generally, biomass can be converted into energy either by thermal or biological process. Also, millions of tons of agricultural and residential wastes are generated in Nigeria annually. For the purpose of this work, groundnut shell, waste paper and rice husk are considered to be preferred biomass blended with coal for making the bio-coal briquette.

### Groundnut Shell

Groundnuts (Arachius hypogeal) are legumes whose fruits are formed underground; each fruit or nut usually contains two or three seeds, enclosed by the shell. It is one of most important annual cash crops grown in West Africa In Nigeria, the crop is grown mainly in Northern part of the country.

Groundnut shell which enclosed the seed is obtained by beating the pod with sticks or pounded using threshing machine which is known as shelling or decortications done by machine or manual to remove the shells. The seeds are separated from the shells by winnowing or using a shelling machine while the shells are dried and kept as a waste or an Agro residue.

### Rice Husk (Oryza Sativa)

This is outermost covering of the rice grain which is mostly abandon as an Agro residual waste after threshing rice pods. A link was created from Kalambaina area in Sokoto to obtain rice husk, where local rice is being processed by a mill factory after been purchased from Kebbi state.

### Waste Paper

Old and rejected news-prints from paper vendors and other types of waste paper from residential dump refuse sites in Sokoto were collected and used.

### Binder used in the production of this bio-coal briquettes

In this case cassava starch is the preferred option for this research work for its abundance availability and cheapness.

### Desulphurizing Agent

Calcium hydroxide is also known as slaked lime, hydrated lime, slake lime or picking lime. It is a chemical compound with the formula, $Ca(OH)_2$. It is a white powder or colorless crystal. Commercially, it is produced when calcium oxide $(CaO)$ (also known as quick lime or lime) is mixed with water. This process is known as slaking of lime.

$$CaO_{(s)} + H_2O \rightarrow Ca(OH)_{2(s)} \quad (1)$$

Naturally, calcium hydroxide occurs in mineral form called portlandite. Portlandite is a relatively raw mineral known from some volcanic, plutonic, and metamorphic rocks. It has also been known to arise in burning of coal dumps.

In Nigeria, calcium hydroxide is expected to be very cheap and available in abundance because there is large deposit of limestone in the country and besides, the production of calcium hydroxide is a simple process. Many investigations have shown that calcium hydroxide is an effective Sulphur fixation agent (Desulphurizing agent) for production of briquettes.

**Analysis Procedures**

The mode of implementing this research work entails; preliminary assessment of experimental material, developmental processes of the bio-coal product, followed by the laboratory experimentation sought to determine the physicochemical characterization of the briquetting materials and finally physicochemical assessment of the new developed briquette.

**Proximate Analysis of the Raw materials:**

The proximate analysis is widely the most preferred process used in determining physical composition of any non-chemically mixed substance and has been extensively treated in many studies before now (Mangalla et al, 2010).

This process has been standardized by the use of special codes, machines, procedures and processed formulae to aid investigations related to physical characterization of any non-chemically mixed substances requiring through investigation.

**Apparatus used for the experiment:**

Weighing machine, model MB-2610g; Manually operated briquette machine; Gas Stove; Oven furnace; Desiccator; Thermocouple Thermometer; Stop watch; Manual operated grinding machine; Petrol fueled grinding machine; Mortar and pestle; Basin; 1000ml plastic basin; Crucibles / aluminum pans; Analytical balance, sensitive to 0.1mg; Meter rule; and Sieves.

**METHODS**

For the execution of this study, three-tier approach has been employed in order to achieve desired result. Physicochemical characterization of constituents of briquetting material in the laboratory, direct experimental conduct and analysis of the co-firing product as well as design and numerical simulations analysis by the use of Design Expert Software (Design Expert 13) by the help of Response Surface Methodology of Box-Behnken Design (BBD) option were sequential arrangement for the execution of the research.

Briquetting technique is of threefold, briquetting of organic materials (agricultural wastes) requires significantly higher pressure as additional force is needed in order to break the natural cellular bond that exist within these materials. Essentially, this involves the destruction of the cell walls through some combination of pressure and heat. High pressure involved in this process suggests that organic briquetting is costlier than coal briquette.

**Procedure of Experiments for Material Characterization and Analysis**

The following tests were carried out in the laboratory:

**Proximate Analysis**

Proximate analysis provides percentage composition of biomass in terms of gross component such as Moisture content (MC), Volatile matter (VC), Ash content (ASH) and Fixed Carbon (FC). Table 1 and 2 depicted ASTM standard codes for determination of gross proximate and ultimate analyses of biomass components respectively.

**Table 1. Standard Codes for Proximate Analysis**

| Proximate Analysis parameter | Standard methods (ASTM) |
|---|---|
| Volatile Matter (VM) | E - 872 or E-871 - 88 (1998) |
| Ash (ASH) | E- 1755 (1998) or ASTM 1102-84 (2001) |
| Moisture Content (MC) | D 871 - 82 or ASTM E872 (1998) |
| Fixed Carbon (FC) | Using equation |

**Table 2. Standard codes for Ultimate analysis**

| Biomass constituent | Standard Method |
|---|---|
| Carbon | ASTME – 777 for RDF |
| Hydrogen | ASTM E - 777 for RDF |
| Nitrogen | ASTM E - 778 for RDF |
| Oxygen | By difference |
| Ash for biomass | ASTM E – 1755 |
| Moisture | ASTM E - 949 for RDF |

**Briquetting machines and Production**

Various briquetting machines have been designed, ranging from very simple types which are manually operated to more complex ones mechanically or electrically powered. Generally, briquetting operations have developed in two directions, mechanically compression (hydraulic or pistons) and worm screw pressing types.

**Plate 1: Locally constructed briquetting machine used by (Oladeji J. T. 2010)**

**Plate 2: Locally constructed Briquetting machine (for the present work)**

**Plate 3: Picture of pieces of produced Bio-coal briquette**

The production process of bio-coal briquette is very simple and cost effective. The raw materials; coal with mixed biomass are to be crushed and ground to fine powder using mortar-pestle, manually operated grinding machine and petrol fueled grinding machine. The coal powder obtained after grinding wassieved to obtain coal particle size of approximately 1mm, and then dried. The dried coal particles, a desulphurizing agent, binder and blends of biomass materials were mixed together in five different categories by ratio of the respective percentages, coal to biomass; 90:10, 80:20, 70:30, 60:40, and 50:50, as indicated in the table until a homogeneous paste is obtained. Then, the resultant mixture was compressed in a singled chamber briquetting machine of 100 mm external diameter (mold shape).

Selection of percentage ratio of the bio-mass used was based on the preliminary proximate analysis of the preferred biomass materials (i.e. groundnut shell, rice husk, and waste paper) and use of Design expert software in I-Optimal selection which shed light on prediction process has been indicated below.

Starch as a binder and desulphurizer in the ratio of 15% and 5% by mass respectively were added to the mixture. The stirred mixture was put into the mold and dressed todesired shape of the bio-coal briquette. For every ratio, 5±0.1 g of the mixture was compacted under constant pressure of about 8 MPa. The mass of mixture was determined using a manual weighing machine Camry Table Scale FAA-00335. A manually operated briquetting machine was used to compact the mixture in the mold using a hand crank. The pressing force was determined using the distance moved by teeth of a vertically travelled rack attached to the pressing plunger and the readings obtained was used to compute the result. The internal diameter and length of the mild steel mold were 80 mm and 100 mm, respectively. A 50 mm external diameter by 100 mm long hollow mild steel shaft having central hole of 30 mm diameter with a foot of dimension 80 x 30 mm external, and internal diameters respectively by 5 mm thickness attached to it, was used as a piston. During compression, the plunger compressed the briquette on a removable plate and the two pieces held together by a compression force applied by a crank handle as shown in Plate 2. The briquette having a central hole of 24 mm diameter removed when the plunger is retracted by reverse cranking with hand. Once the sample was compressed to the required force, the removable plate was removed and the briquette placed in the sun to dry.

The different ratios by weight of coal and mixed biomass were prepared according to experimental plans to ensure homogeneity in the properties of coal-biomass mixture. In every mixture, different sets of proportion were used based on proposed effective performance suggested by I-optimal model design of Expert Design 13 software. The established optimal predicted ratio endorsed for use is 70:15:9:6 ratios by weight of coal, groundnut shell, rice husk, and waste paper respectively as the best option to be maintained. For every ratio, 5±0.1 g of the mixture was compacted under constant pressure 8MPa. The mass of the mixture was determined using manual weighing scale (Camry table scale FAA-00335). A briquette of 80 mm diameter x 40 mm by size with a provision of 24 mm central hole to allow sufficient air for better combustion was produced each time.

**Thermal Characteristics of Bio-coal**

The study of the thermal behavior of briquette is of importance in understanding and improving the techniques of briquette gasification technology. Thermo-gravimetric itself is the technique of measurement of the weight of a sample with linear increasing of temperature.

The performance of the bio-coal was determined by the use of a selected stove of known performance status and the ultimate aim was water boiling and emission tests.

Combustion performance and emissions characteristics of each type of briquettes were investigated in a cylindrical combustion furnace equipped with measurement devices such as mass balance, thermocouple and exhaust analyzer. Combustion of fuel was supplied with air compressor at velocity of 0.5 m/sec and the LPG burner was used as a source of heat. In this experiment 5 pieces of each bio-coal briquette of different combination were selected and placed on the perforated plate. Burning rate of each experiment was recorded using digital mass balance at each 15 second. During combustion process, temperature of combustion chamber was carried out at around 2 cm behind the burning briquettes. Analysis was performed from the comparison of the data recorded in form of graphs and tables. Emissions of the bio-coal briquettes combustion were examined using digital smoke analyzer, MEXA Analyzer, during combustion process as shown in Figure 1.

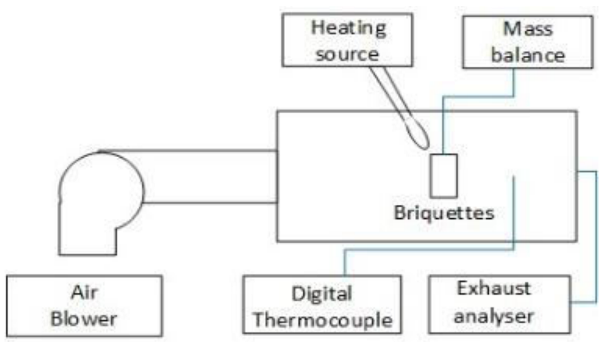


Figure 1: Schematic of experimental apparatus

Mathematical models to predict calorific value, volatile matter, ash content, moisture content, fixed carbon, and relaxed density as a function of input parameters were developed. The general mathematical model for each of these parameters was a second-order polynomial regression model (1), which was established by inputting the experimental data:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k} \beta_{ij} x_i x_j + \varepsilon, \qquad (2)$$

Where $k$ is the number of independent variables, where $x_i$ *and* $x_j$ are the independent input variables, $y$ is the responds variables, $\beta_0$ is the constant term, $\beta_i$ is the linear parameters coefficient, $\beta_{ii}$ is the quadratic parameter coefficient, $\beta_{ij}$ is the interaction parameter coefficient and $\varepsilon$ the experimental residuals.

Design-Expert 13 software package was used to generate the experimental points as per BBD methodology. The experimental points and data shown in Table 1 was used initially in the Design expert 13 software to establish model design that can provide design space used for analysis of ANOVA and statistical regression models. Furthermore, ANOVA was used to evaluate the statistical significance of the regression model. Factors investigated are shown in Table 1. The factors, coal-biomass composition, gasification temperature and compressive strength, are represented as A, B and C, respectively in the design expert software.

Appropriate selection of working factors can determine the success of the research work. As such, use of Design Expert software plays vital role in aiding this research taking. Preferential selection of factors reduces iterative experimental conduct, the extent of time, cost and possible errors to be encountered (Josephat K. T. (2016)).

In total, five sets of 17 samples (according to Box-Behnken Design methodology BBD as illustrated in (Plate1) are produced. Each set was tested for volatile matter, moisture content, ash content, gross calorific value, fixed carbon and compressive strength.Gasification temperature and relaxed density were conducted separately. Each sample was sun dried for seven days according to the experimental plan.

## RESULTS AND DISCUSSION

In this article, optimization was done to determine a combination of the three factors that produced briquette with the best properties. In that respect, gross calorific value was chosen as an optimization parameter to evaluate the thermal property of briquette, whereas compressive strength was left out because it had a small range. On the other hand, Ash content was used as optimization parameter to determine its effect on factors with respect to the briquette strength. By utilizing optimization code available in Design Expert software, it was established that optimized values of gross calorific value and volatile matter of bio-coal mixture stand at 27.97 MJ/kg and 75.36% by weight respectively, for 1.85kN/m$^2$ compressive strength at 500 °C gasification temperature and 79.8% coal/biomass composition ratio. At this point, ash content, moisture content, relaxed density and compressive strength of briquettes are 9.8%, 16.032%, 1.107 kg/m$^3$, and 1.87kN/m$^2$ respectively these results are in total agreement with that of (Josephat K. T., 2016) in which their findings wereGross calorific values for briquettes produced ranged between 27.15 and 30.67 MJ/kg, which compares well with the values obtained for wood char by other researchers.

**Table 3: RSM Experimental Run and Results of Bio-Coal Gasification as a function of input factors.**

| Sample | A:Coal-biomass composition (wt %) | B:Gasification temperature (°C) | C:Compressive strength (kN/m$^2$) | D:Calorific value MJ/kg | E:Volatile matter (wt %) | F:Ash content (wt %) | G:Moisture content (wt %) | H:Relaxed Density (kg/m$^3$) | I:Fixed carbon (wt %) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 60 | 500 | 1.8 | 27.56 | 52.6 | 8.2 | 8.6 | 0.96 | 25.8 |
| 2 | 60 | 500 | 1.8 | 27.56 | 52.6 | 8.2 | 8.6 | 0.96 | 25.8 |
| 3 | 60 | 800 | 2.2 | 27.43 | 48.1 | 7.8 | 10.2 | 1.08 | 33.4 |
| 4 | 60 | 500 | 1.8 | 27.56 | 52.6 | 8.2 | 8.6 | 0.96 | 25.8 |
| 5 | 30 | 800 | 1.5 | 25.72 | 53.0 | 9.3 | 12.8 | 0.91 | 13.28 |
| 6 | 30 | 500 | 1.3 | 25.89 | 53.5 | 9.5 | 13.2 | 0.88 | 11.2 |
| 7 | 60 | 200 | 1.6 | 27.38 | 51.4 | 8.4 | 8.9 | 0.98 | 21.6 |
| 8 | 30 | 500 | 1.2 | 25.88 | 53.6 | 9.8 | 14.2 | 0.885 | 10.41 |
| 9 | 30 | 500 | 1.2 | 25.88 | 53.6 | 9.8 | 14.2 | 0.885 | 10.41 |
| 10 | 30 | 200 | 1.1 | 25.67 | 51.85 | 10.0 | 14.5 | 0.84 | 10.1 |
| 11 | 60 | 200 | 1.4 | 27.32 | 51.70 | 8.8 | 11.2 | 0.94 | 18.3 |
| 12 | 60 | 800 | 2.2 | 27.43 | 48.10 | 7.8 | 10.2 | 1.08 | 33.4 |
| 13 | 90 | 500 | 3 | 27.30 | 39.80 | 6.4 | 8.9 | 1.14 | 44.4 |
| 14 | 30 | 500 | 1.3 | 25.89 | 53.50 | 9.5 | 13.2 | 0.88 | 11.2 |
| 15 | 60 | 500 | 1.8 | 27.56 | 52.60 | 8.2 | 8.6 | 0.96 | 25.8 |
| 16 | 60 | 800 | 2.1 | 27.40 | 48.70 | 8.0 | 10.4 | 1.05 | 30.4 |
| 17 | 90 | 800 | 2.6 | 27.18 | 38.60 | 6.0 | 8.82 | 1.17 | 45 |

**Overall effect of Coal-Biomass and processing conditions on briquettes properties.**

**Model Design for Calorific Value**

Multiple linear regression models were used to investigate the impact of compressive strength, raw material composition, and gasification temperature on each of the dependent variables. Gasification temperature never had significant interaction on compressive strength, ash content, and volatile matter content, while heating value increases with increase in coal ratio as coal has higher calorific value than biomass.

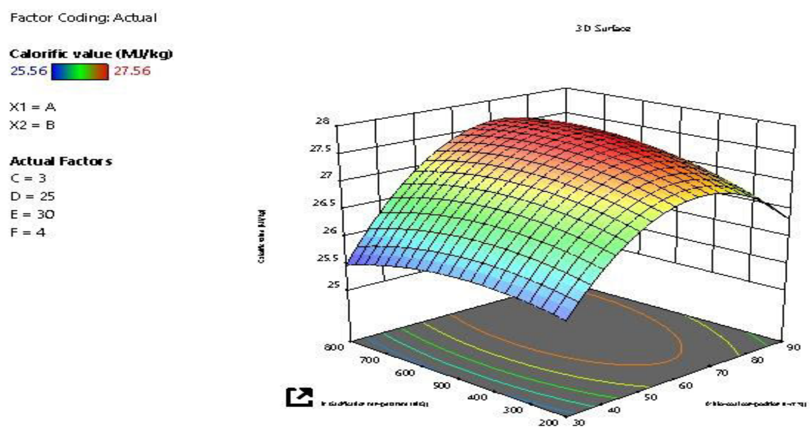


**Figure 2: Effect of coal-to-biomass ratio variation on Calorific value with respect to gasification temperature in 3D plot**

The concave shape depicted in 3D plot of Figure 2 signifies that the whole aim of the research work revolves round finding the best coal/biomass combination to produce briquette having the best combustion properties rather than the highest. The figure showed that the response of calorific value at low coal-ratio level was low also, but ascends to an appreciable height or level with the increase in coal ratio after which it started descending to lower level in aligned with change of gasification temperature. This means that the peak of the concave shape marks the area where the best character lies. This zone produces briquette that burn with smoke-free flame and maintain best burning properties the calorific value 27.70 MJ/kg was noticed.

**Analysis for the Effect of Volatile Matter**

Volatile matter plays double role in bio-coal briquette making. It is needed for it reduces the ignition time and at the same time, corresponds to the smoke level of the briquettes which therefore makes preference of low to high volatile matter content. The volatile matter content increases with increase in biomass which implies that the low biomass ratio is sufficient for quick ignition and sustenance of constant burning. This is the most preferred condition for keeping it moderate will favor better combustion properties of briquette.

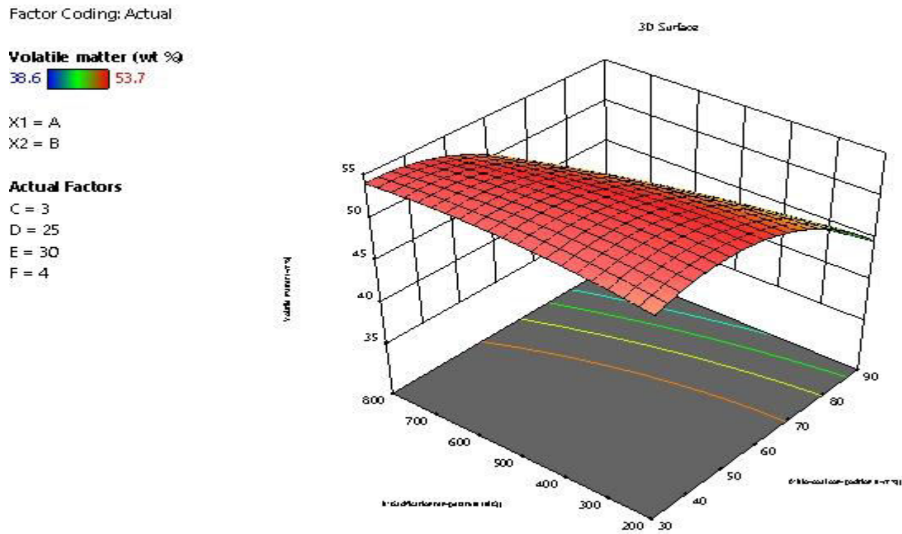


**Figure 3. The effect of coal-to-biomass ratio variation on volatile matter with respect to gasification temperature in 3D plot**

### Analysis for the Effect of Ash Content

The ash content of briquettes was observed to increase with proportional increment in biomass ratio. This condition is not desirable in optimal bio-coal production, therefore requires measures to minimize ash content production.

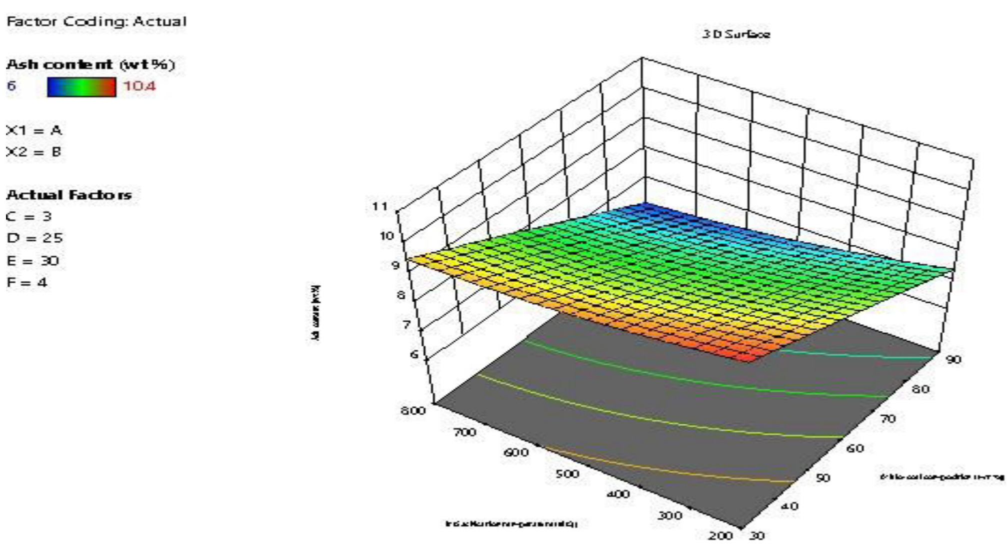


**Figure 4. The effect of coal-to-biomass ratio variation on ash content with respect to gasification temperature in 3D plot**

Figure4 shows that ash content has linear effect with coal-biomass composition, ash content decreases inversely with the increase in coal ratio. This is attributed to the fact that coal contain less ash than biomass. It was indicated that gasification temperature has no influence on ash content of briquette. The yellowish color coding of the software in ash content 3D plot reflected that the best ratios of bio-coal production occurs around the range of 60% to 40% coal-biomass ratio. The highest ash content region was found around 30/70% biomass-coal ratio.

### Analysis for the Effect of Relaxed Density

Moderate Relaxed density is preferred in production of best bio-coal briquette as porosity plays important role in maintaining sustainable burning culture of the briquette.

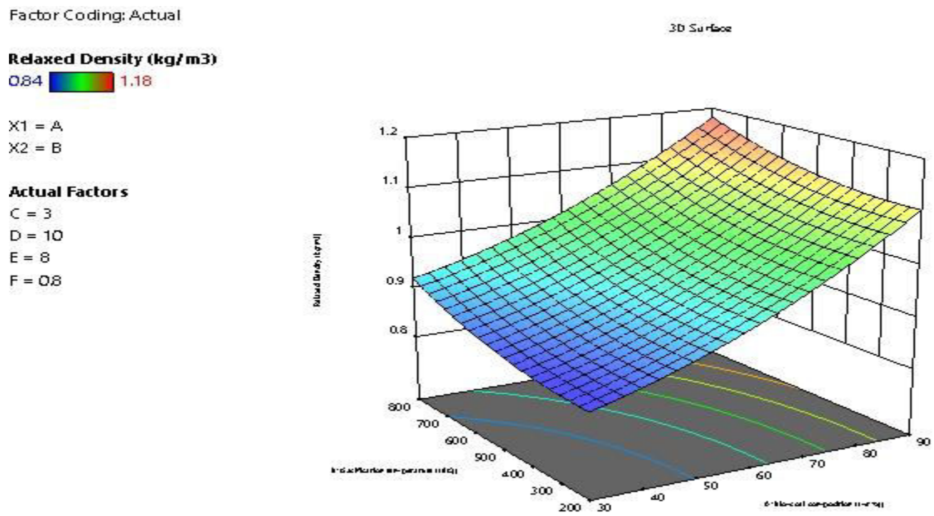


**Figure 5. The effect of coal-to-biomass ratio variation on relaxed density with respect togasification temperature in 3D plot**

This stance is achieved considering the response depicted in Figure5 where value of relaxed density ranged between 0.9 to 1.9 KN/kg. Relaxed density increases with the increase in bio-coal ratio maintaining linear behavior but gasification temperature had less influence on relaxed density in bio-coal combustion as indicated by the Figure5

**Analysis for the Effect of Moisture Content**

Moisture content is the amount of water remains in the briquette after drying process. It greatly contributes to reduction of briquette heating value; therefore, its presence deters the performance of the bio-coal.

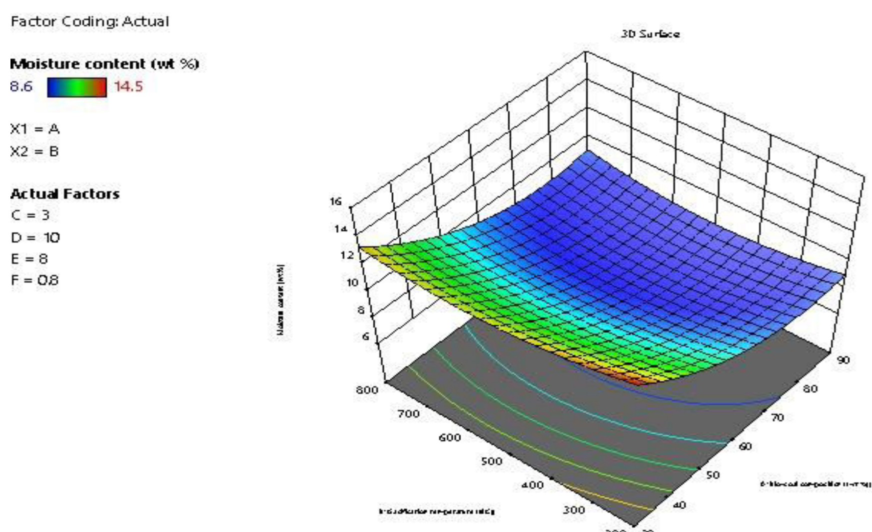


**Figure 6. The effect of coal-to-biomass ratio variation on moisture content with respect to gasification temperature in 3D plot**

Figure6 portraits convex shape of effect of moisture content in 3D plot whereby it is clearly indicated that the lowest part is the region where best bio-coal production feature lies. Moisture content value ranges from 9.8% to 11.9% by weight, whereby 9.8% weight is least amount in the briquette.

**Analysis for the Effect of Compressive Strength**

Compressive strength is the measure of physical ability of a material to withstand shock impact. It is highly needed to aid safe storage and transportation of bio-coal end use. This also needs to be at moderate value due to the fact that excessive amount will affect the performance of the bio-coal that requires sufficient air to sustain efficient combustion.

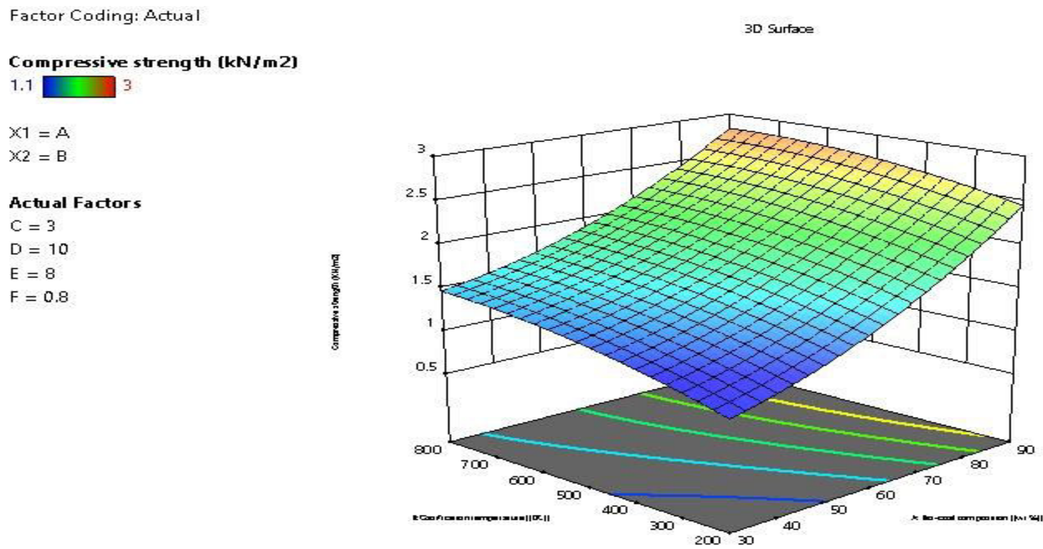


**Figure 7. The effect of coal-to-biomass ratio variation on compressive strength with respect to gasification temperature in 3D plot**

According to Figure7 the best production point was indicated around 60% to 80% coal-biomass ratio. The 3D plot also supported past research(Josephat K. T. 2016) that compressive strength has linear effect on coal-biomass composition ratio, it increases with increase in coal ratio but has little or no effect on gasification temperature. According to the plot it ranges between 1.46 to 2.85 kN/m$^3$.

**Table 4: Complete Final Equations of all Dependent Parameters in terms of Coded factors**

| | Intercept | A | B | C | AB | AC | BC | $A^2$ | $B^2$ | $C^2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Compressive strength | 1.8 | 0.725 | 0.225 | 0.075 | -0.05 | - | - | 0.2 | -0.1 | 0.1 |
| Fixed carbon | 25.8 | 16.2044 | 3.5631 | 0.9112 | - | - | - | 1.9206 | - | - |
| Moisture content | 8.6 | -2.2315 | -0.2218 | -0.4815 | 0.2812 | 0.3056 | 0.525 | 1.8590 | 0.9221 | 0.6528 |
| Relaxed Density | 0.96 | 0.1342 | 0.0420 | 0.0078 | - | -0.0062 | - | 0.0295 | 0.0220 | 0.0304 |
| Calorific value | 27.56 | 0.60546 | 0.1660 | 0.0437 | 0.26 | - | - | -1.1353 | -0.2746 | 0.0968 |
| Volatile matter | 52.59 | -6.0193 | -1.4912 | - | 2.11437 | - | - | -4.3566 | -0.9066 | 1.58919 |
| Ash content | 8.15 | -1.5734 | -0.5156 | -0.1171 | -0.125 | - | - | - | 0.1985 | -0.1047 |

## CONCLUSION

This thesis focused on finding the best coal-biomasses combination that can produce bio-coal briquette with better and enhanced quality. Quality heating and combustion characteristics of a briquette include producing smokeless flame with high heating value. The briquette is also required to ignite in lesser time and sustain burning with resultant reduced ash and carbon deposit.

Appropriate selection of working factors can determine the success of the research work. As such, use of Design Expert software plays vital role in aiding this research taking. Preferential selection of factors reduces iterative experimental conduct, the extent of time, cost and possible errors to be encountered.

Investigation revealed that varying the material composition had great influence in most of the dependent parameters and affect the physicochemical and combustion properties of the briquette. Results of the study effectively revealed the impact of each dependent variable on achieving optimal bio-coal briquette production. The optimized results indicated that the calorific value increased from (27.10 to 27.74) MJ/kg, while the volatile matter content rose from (41.4 to 47.94) % by weight. Ash content and moisture content were reduced from (7.31 to 6.35) % and (11.9 to 9.8) % by weight respectively, while relaxed density and compressive strength were adjusted to meet target ranges of (0.8 to 1.09) $KN/m^2$ to (0.9 to 1.99) $m^3/Kg$ respectively. The newly produced bio-coal briquette represents an improved, environmentally friendly solid fuel that can be effectively used in any type of charcoal stove.

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