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Production and Optimisation of Parameters for Density and Ash Content of Briquettes Produced from Sorghum Stalks and Groundnut Shells Using African Locust Bean (*Parkia biglobosa*) Pulp as a Binding Agent

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Abstract

To address the climatic challenges posed by conventional fossil fuels, prioritizing research on renewable energy sources is essential. This study aims to develop briquettes from a blend of carbonized sorghum stalks and groundnut shells to mitigate environmental issues associated with the use of fossil fuels. The biomass materials were subjected to carbonization at 400°C for 1 hour within a muffle furnace. The production process utilized a D-Optimal Design of Experiment to optimise independent variables, including the ratios of sorghum stalks and groundnut shells, compaction pressure, and particle size, with briquette density and ash content as response parameters. The results revealed a biochar yield of 37.25% for sorghum stalks and 57.50% for groundnut shells. Briquette densities ranged from 0.64 to 1.36 g/cm³, and ash content varied from 7.55% to 18.55%. Statistical analysis revealed that increased compaction pressure and reduced particle size resulted in higher briquette density, whereas the ratios of biomass materials had a minimal effect on this outcome. The optimal briquette formulation was determined to be 30 wt.% sorghum stalks and 30 wt.% groundnut shells, with a compaction pressure of 12 MPa and a particle size of 0.78 mm. This formulation yielded a density of 1.2 g/cm³ and an ash content of 8.710%, resulting in a maximum desirability index of 0.944. The successful creation of these briquettes suggests a viable renewable energy source that could help reduce reliance on conventional fossil fuels and address climate change. This development supports renewable energy production and sets the stage for further research and policy efforts in biomass energy technology.

Keywords: *Biomass, briquettes, locust bean, groundnut shells, sorghum stalks, compaction pressure, optimization.*

1.0 Introduction

The rapid growth of traditional fossil fuel consumption has led to two major concerns: the dwindling supply of these limited resources and increasing environmental pollution, both of which have severe consequences [1]. Given the pressing need for cleaner and sustainable energy solutions, biomass becomes imperative. Biomass stands out as a highly promising alternative energy source due to its carbon-neutral profile and diverse supply options [2]. Its renewable nature ensures a virtually limitless supply, making biomass a reliable and sustainable energy option that is far less detrimental to the environment than the traditional sources, such as coal and crude oil [3]. With an impressive biomass potential of approximately 144 million tons annually, countries like Nigeria demonstrate the vast opportunities for harnessing this resource [4]. Agricultural residues, one of the promising sources of biomass, depending on the mode of handling, both field-based and process-based residues have high potential for energy production [4].

The direct burning of agricultural residues for energy in homes and industries is a notably inefficient practice. Moreover, problems associated with handling, storage, and transportation were inherent in its use. However, effective biomass technologies that convert the chemical energy of biomass to a more useful form will be needed [5]. One of the approaches consistently practiced globally to improve and enhance the efficient utilization of agricultural and other biomass residues is their densification to produce pellets or briquettes [5]. The process of compacting biomass materials to form solid pieces of uniform and homogeneous sizes with high bulk density, which is conveniently used as a fuel, is referred to as briquetting [6].

One of the advantages of biofuel briquettes is their ability to offer several benefits, including local production, reduced reliance on oil and gas, rural job creation, and waste-to-wealth opportunities through effective waste management [7]. Another advantage of biofuel briquettes, especially those made from carbonized materials, is their clean-burning nature. They can be preserved over long periods without degradation and deterioration [8]. The carbonization process is necessary for briquette production to decompose organic compounds into activated carbon. As a result of carbonizing lignin and cellulose content, a black solid byproduct (charcoal) and volatile gases are produced [9].

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Thus, several studies have shown that cassava starch was the most commonly used binding agent for briquette production [10]. For instance, [11] produced briquettes from peanut shells using cassava starch as a binder to evaluate the carbonization process and the physicochemical characteristics of the produced briquettes. Additionally, [12] examines the physicochemical and combustion properties of briquettes produced from a mixture of rice husk and corncob, utilizing cassava starch as a binding agent. At the same time, [13] characterize charcoal briquettes produced from rice husk using cassava starch as a binder.

Nevertheless, numerous researchers illustrate the value of cassava starch when utilized in other research sectors. For instance, [14] reported that in some West African countries, cassava starch is traditionally consumed as tapioca in its raw form at the household level, [15] opined that blending cassava flour and starch with other starches in food formulations can impart a variety of desirable properties to finished products, such as bread. In the same vein, [16] reported that cassava starch can be used as a thickening agent, gelling agent, binder, texture enhancer, and coating in many edible products. It was also found that cassava starch and flour can be used to eliminate disease-causing properties from gluten products. Despite extensive research on briquette production with various binding agents (e.g., [18], [19]), a notable gap exists in studies focused on optimising process parameters—specifically, biomass mixing ratios, compaction pressures, and particle sizes—when using alternative binders such as African locust bean pulp. These parameters critically influence the physical and combustion properties of briquettes, impacting energy density, efficiency, and emissions. Optimising these parameters helps to produce durable, high-quality briquettes that serve effectively as renewable energy sources. Although cassava starch has been thoroughly studied, the potential of African locust bean pulp as a binding agent remains largely underexplored. This creates an opportunity to investigate its efficacy further and refine briquette production parameters to improve both the density and ash content of the final product, advancing sustainable biomass energy solutions.

Moreover, African locust bean (*Parkia biglobosa*) pulp, an organic material collected in appreciable quantities from the African locust bean seed, which is usually discarded as a by-product, appears promising as a binder. The sweetness of ripe fruit pulp indicates its natural sugar content, making it a possible source of energy [20]. Analysis of the yellow pulp obtained from the African locust bean reveals a composition of 2.69% ash, 7.14% moisture, 72.68% carbohydrates, and 32.14% starch [21]. Hence, the features of the organic binder for briquette production have been displayed by the pulp. Therefore, this study aims to optimise the mix ratios and process parameters for the density and ash content of briquettes produced from sorghum stalks and groundnut shells using African locust bean pulp as a binding agent.

2.0 Materials and Methods

2.1 Materials

Materials used for this research work include; sorghum stalk, groundnut shell, African locust bean pulp (binder), digital weighing balance (Model: AR3130 OHAUS CORP China), briquetting machine stop watch, oven dryer (Model: PBS118SF GENLAB WIDNES ENGLAND), muffle furnace (Model: HSX-2-6-13), water bucket, bowl, briquette stove, Bunsen burner, and cooking pot. Sorghum stalks and groundnut shells (Figure 1) were used for briquette production. The selected crop residues were obtained from Gidan Kwano Village, located near the Federal University of Technology, Minna main campus, Niger State, Nigeria. Choosing materials for briquette production, such as sorghum stalk, groundnut shell, and African locust bean pulp as a binder, is vital for achieving maximum energy output and efficiency. Sorghum stalks are abundant and provide a fibrous structure, while groundnut shells, as a by-product, enhance combustion properties when combined with other materials. The methodology utilizes precise equipment, including a digital weighing balance for accurate measurement, a briquetting machine to compress biomass, and an oven dryer to control moisture content, all of which are essential for producing high-quality briquettes. By sourcing materials locally from Gidan Kwano Village, the research not only reduces transportation costs but also promotes environmental sustainability and supports local farmers, effectively addressing regional energy needs.

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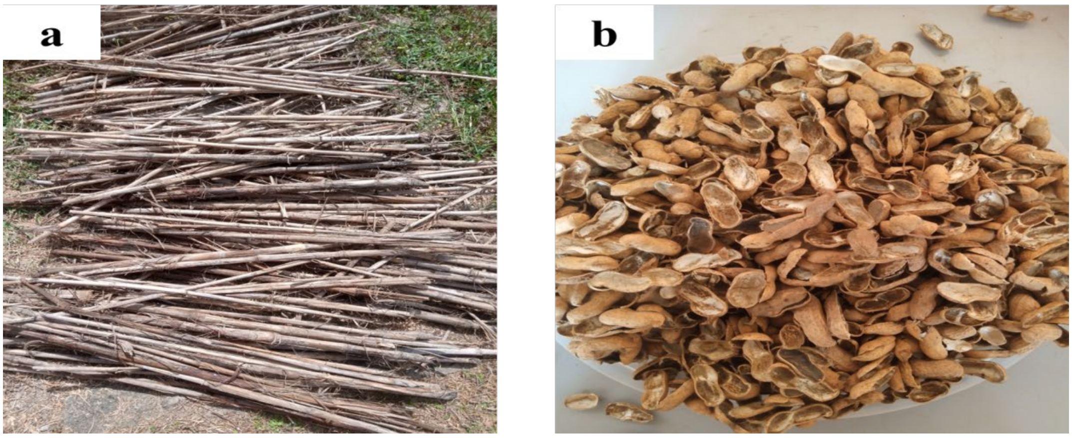

Figure 1: (a) Sorghum stalks, (b) Groundnut shells

2.2 Materials Pre-treatment

Sorghum stalks were sorted to remove impurities (such as pieces of bone and metal) and then chopped to approximately 400 mm in size. Groundnut shells were also subjected to sorting operation. The sorghum stalks were subjected to sun drying (28 to 32°C) for 24 hours to remove excess moisture content in the material. The groundnut shell feedstock was not subjected to sun drying because of their low moisture content. The materials were milled to reduce their size to approximately 12mm using an agricultural material milling machine obtained from the Department of Agricultural and Bioresources Engineering at the Federal University of Technology, Minna. Flow diagram of materials preparation is shown in Figure 2. The materials were then carbonized in a limited air environment using a muffle furnace (Model: HSX-2-6-13) at 400°C for 1 hour to form biochar, which was used for briquette production. The biochar yield was determined using Equation (1).

$$Biochar\ yield\ (\%) = \frac{weight\ of\ carbonized\ biomass\ materials (kg)}{Initiial\ weight\ of\ biomass\ materials\ (kg)} \times 100 \qquad (1)$$

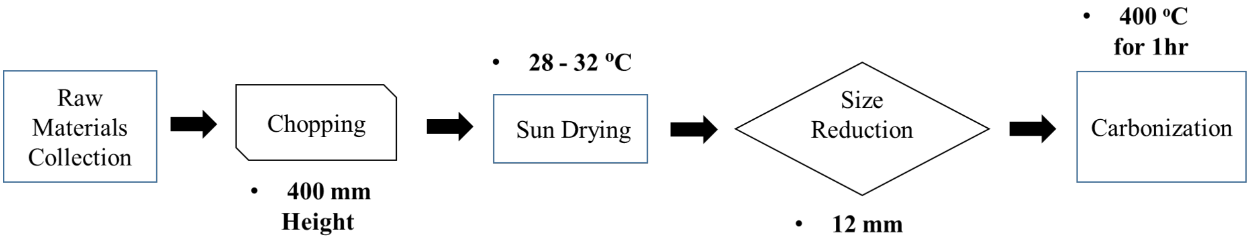

Figure 2: Flow diagram of materials preparation

2.3 Binder Preparation

The binder was prepared by sieving the African locust bean pulp to remove stones and other impurities that could hinder the proper mixture of the binder. 400 ml of water was poured gently into the bowl containing 500 g of African locust bean pulp, and the mixture was stirred until a smooth, homogeneous starch solution was observed, as shown in Figure 3.

Figure 3: Binder preparation

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2.4 Briquette Production Formulation

D-Optimal design of experiment (DOE), a feature of Design Expert, was employed for this purpose; two mixture variables or factors (sorghum stalk and groundnut shell) at high and low levels, and two process variables (compaction pressure and particle size) were considered. The D-Optimal design in experimental design (DOE) offers significant benefits, especially in making efficient use of resources by choosing a specific set of experimental runs that provide the most information about the processes being studied. This approach effectively handles the complexities related to mixture variables, such as sorghum stalk and groundnut shell, as well as process variables like compaction pressure and particle size. It improves predictive accuracy and ensures that the experimental results are both relevant and practical. The low and high levels of the mixture and process variables are shown in Tables 1 and 2.

Table 1: Mixture variables used for design of experiment

Factors	(-) Low level	(+) High level
Sorghum stalk (%)	20	40
Groundnut shell (%)	20	40

Table 2: Process variables used for design of experiment

Factors	(-) Low level	(+) High level
Compaction Pressure (MPa)	10	15
Particle Size (mm)	0.3	0.8

2.5 Mixing Process

The binder and carbonized materials were mixed according to the mixing ratios generated by the D-optimal design. A sample has a total weight of 70 g, consisting of 60% carbonized materials (sorghum stalk and groundnut shell) and 40% binding material.

2.6 Determination of Density and Ash Content of Briquettes

2.6.1 Density

Density is an essential property of briquettes because of its ability to determine how long the briquette will burn and its links to the briquette's durability. A longer burning process is expected from a high-quality fuel source of higher density. Also, the separation of combined materials that form a briquette into separate parts during transportation, storage, and even combustion is prevented by the briquette's higher density [22].

The density of the briquette was determined using the procedure described in [23], where the weight of the briquette was measured with a digital balance. The volume of the briquette was determined through a simple calculation that relies on the direct measurement of its diameter and height, as briquettes are cylindrical. The density was then calculated using Equation (2),

$$P_{br} = \frac{M_{br}}{V_{br}} \quad (2)$$

where P_{br} = density of briquette
M_{br} = weight of briquette (g)
V_{br} = volume of briquette (cm^3)

2.6.2 Ash content

Briquette's ash content is linked to its heat value, as the higher the ash content, the lower the calorific value. Ash content was determined by heating 2 g samples in a furnace at 555 °C for 4 hours, following ASTM E-1755-01 standards [24]. And calculating the percentage mass loss using Equation (3),

$$W_A\ (\%) = \frac{W_b}{W_i} \times 100 \quad (3)$$

where W_A = percentage weight of ash in the sample (%)
W_b = weight of sample after burning (g)
W_i = weight of sample before burning (g)

2.7 Moulding and compaction of briquettes

The properly mixed 70 g of materials was fed into the hydraulic press briquettes mould, which had dimensions of 40 mm by 120 mm. The lid of the mould was closed, and pressure was exerted using a hydraulic jack. The

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materials were compacted at a range of compaction pressures (10 to 15 MPa) and allowed to settle for a dwelling time of 1 minute. Then the briquettes were subjected to oven drying at 105°C for twenty-four (24) hours.

Figure 4: Briquette production

3.0 Results and Discussion

3.1 Yield of Biochar

The yield of biochar after carbonization is shown in Table 3. The yield of a thermochemical process is a function of the severity of the temperature used. Sorghum stalks yielded 37.25% of biochar which showed that more than 60% of the Sorghum stalks were lost as volatiles. As for the Groundnut shells, 57.50% of biochar was recorded which showed that, it has less of volatiles compared to the Sorghum stalks. The differences in the biomass compositions could be the reason for the differences in the obtained yields.

Table 3: Yield of the produced biochar

Biomass type	**Initial weight (kg)**	**Final weight (kg)**	**Biochar yield (%)**
Sorghum stalk	4	1.49	37.25
Groundnut shell	4	2.30	57.50

3.2 Briquettes Production Formulation

Following the D-Optimal design, briquettes were manufactured, and their responses were measured, with the results shown in Table 4. The density results obtained for the briquettes ranged from 0.64 to 1.36 g/cm³, while the ash content results ranged from 7.55% to 18.55%, respectively. ANOVA results (Tables 5 and 6) indicated that compaction pressure is the most significant factor influencing briquette density (P-value < 0.0001). At the same time, particle size was found to be the factor with the most impact on ash content of the briquette (P-value <0.0001).

Model equations were transformed into inverse form, from which they were generated purposely to represent the response density and ash content as functions of Compaction pressure (C) and Particle size (D). The developed equations are presented in Equations 4 and 5.

Table 4: Variables used and results obtained

Run	**Sorghum stalks (%)**	**Groundnut shells (%)**	**Compaction pressure (MPa)**	**Particle size (mm)**	**Density (g/cm³)**	**Ash content (%)**
1	30	30	10	0.3	0.91	12.25
2	40	20	10	0.3	0.94	15.9
3	30	30	10	0.8	0.73	9.7
4	30	30	10	0.3	0.93	12
5	20	40	15	0.8	1.32	8.45
6	20	40	15	0.8	1.29	11.5
7	30	30	10	0.8	0.77	7.55
8	40	20	13.75	0.68	1.12	11.55
9	40	20	10	0.3	0.87	17.8
10	20	40	10	0.8	0.72	8.25
11	25	35	13.75	0.68	1.02	11.6

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Run	Sorghum stalks (%)	Groundnut shells (%)	Compaction pressure (MPa)	Particle size (mm)	Density (g/cm³)	Ash content (%)
12	20	40	10	0.3	0.81	16.05
13	20	40	10	0.8	0.77	8.35
14	30	30	15	0.3	1.36	14.3
15	25	35	11.25	0.43	1.23	16.5
16	40	20	10	0.8	0.64	8.45
17	25	35	13.75	0.43	1.2	14.85
18	20	40	12.5	0.5	0.93	11.35
19	40	20	15	0.3	1.28	18.55

$$1.0/(\text{Density}) = 0.92 - 0.24\,C + 0.064D - 0.069CD - 4.35C^2 + 4.44D^2 \quad (4)$$

$$1.0/(\text{Ash Content}) = 0.086 - 7.103E\text{-}003C + 0.024D \quad (5)$$

In the polynomial models (Equations 4 and 5), positive coefficients signify synergistic effects. In contrast, negative coefficients signify antagonistic effects of factors C and D. The models' adequacy is supported by statistically significant F-values of 27.24 and 31.03 for density and ash content, respectively.
Table 5 shows the analysis of variance of the developed quadratic model for density.

Table 5: Analysis of variance of the developed quadratic model for density

Source	Sum of squares	Df	Mean square	F Value	P-value Prob>F	
Model	1.03	5	0.21	27.24	<0.0001	Significant
C	0.69	1	0.69	92.08	<0.0001	
D	0.050	1	0.050	6.59	0.0234	
CD	0.057	1	0.057	7.52	0.0168	
C^2	0.050	1	0.050	6.60	0.0233	
D^2	0.051	1	0.051	6.71	0.0224	
Residual	0.098	13	7.33E-003			
Lack of fit	0.087	8	0.011	5.18	0.0633	
Pure Error	0.011	5	2.108E-003	27.24	<0.0001	
Cor Total	1.12	18	0.21	92.08	<0.0001	

P-values of less than 0.05 indicated the significance of the model terms. From Table 5, it was observed that significant linear, interactive, and quadratic terms were identified as (C, D), (CD), and (C^2, D^2), respectively.
Table 6 shows the analysis of variance for the generated quadratic model for ash content

Table 6: Analysis of variance of the generated quadratic model for ash content

Source	Sum of squares	Df	Mean square	F Value	P-value Prob>F	
Model	8.893E-3	2	4.447E-3	31.03	<0.0001	Significant
C	6.896E-4	1	6.896E-4	4.81	0.0434	
D	8.357E-3	1	8.357E-3	58.32	<0.0001	
Residual	2.293E-3	16	1.433E-4			
Lack of fit	1.344E-3	11	1.222E-4	0.64	0.7480	
Pure Error	9.485E-4	5	1.897E-4			
Cor Total	0.011	18				

In Tale 6, the linear terms (C and D) were significant (P-values < 0.05). The regression coefficients R^2 and Adj R^2 in Table 7 supported the model's adequacy.

Table 7: Statistics of R^2 for the regression models

Response	R^2	Adj R^2	Pred R^2	Adq Pre	Std Dev	Mean	C.V %	PRESS
Density	0.9129	0.8793	0.7983	13.502	0.087	1.01	8.18	0.23

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Ash content	0.7950	0.7694	0.7016	12.903	0.012	0.087	13.71	3.338E-3

The values (0.9129 for density and 0.795 for ash content) indicate a good fit for the regression models. Specifically, the models explain 91.29% and 79.5% of the data variation for density and ash content, respectively. According to [25], an R^2 value of at least 0.75 suggests model accuracy.

The adjusted R-squared values for density (0.8793) and ash content (0.7694) confirmed the models' significance and suggest good agreement between the predicted and experimental data. As it was obtained from [25], the Adj R^2 (that measures the extent of mean variation explained by the model) and the Pred R^2 (that measures the model ability to predicts the response value) is expected to be within 20% i.e it shouldn't be less than 0.2 for better agreement between actual and predicted values of model response. This study met the requirements, with predicted R^2 values of 0.7983 for density and 0.7016 for ash content. The low standard deviations (0.087 for density and 0.012 for ash content) indicated that the responses are close to the mean, further validating the model. The C.V values (8.18 for density and 13.71 for ash content) reflect good experimental precision. The low PRESS values (0.3 for density and 3.338 × 10^ (-3) for ash content) suggest that the model effectively predicts future responses, with minimal unexplained variation.

Figures 5, 6, 7, 8, and 9 indicate the 3D surface plots. These figures illustrate how the independent variables combined to influence the responses.

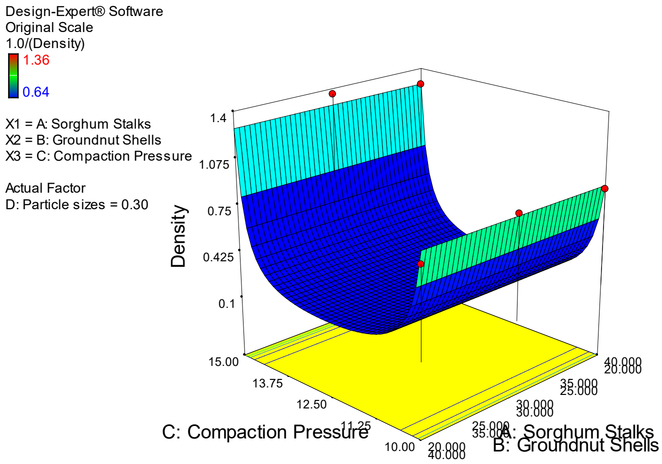

Figure 5: Effects of sorghum stalk and groundnut shell mixing ratios, compaction pressure, and particle size on density

The effects of interaction between the compaction pressure and sorghum stalks/groundnut shells mixing ratios (at a constant particle size of 0.3 mm) on the density of the briquette are illustrated in Figure 5. The response surface plot shows that as the compaction pressure increases from 10 to 15 MPa, the density increases from 0.81 to 1.36 g/cm³. At the same time, the mixing ratios of sorghum stalks and groundnut shells demonstrate a negligible effect on the briquette density. A positive association was found to exist between compaction pressure and briquette density [26].

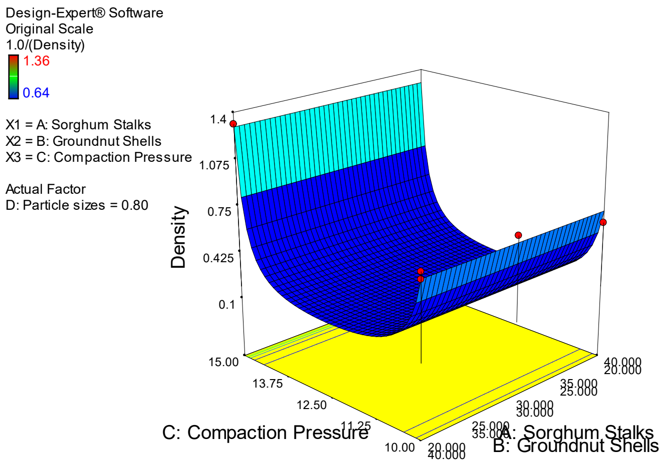

Figure 6: Effects of sorghum stalk and groundnut shell mixing ratios, compaction pressure, and particle size on density

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The effects of interaction between the compaction pressure and sorghum stalks/groundnut shells mixing ratios (at a constant particle size of 0.8 mm) on the density of the briquette are illustrated in Figure 6. The response surface plot shows that as the compaction pressure increases from 10 to 15 MPa, the density increases from 0.64 to 1.32 g/cm³. At the same time, the mixing ratios of sorghum stalks and groundnut shells demonstrate a negligible effect on the briquette density. Varying the compaction pressure affects the density of the briquette. As the compaction pressure increases, the briquette's density rises [27]. This is because the decrease in inter-partle spacing was experienced at high compaction pressure, which leads to the reduction in volume and an increase in density. High compaction pressure in briquette production influences the mechanical interlocking and increases the bonding ability among the particles, forming intermolecular bonds in the contact area [27].

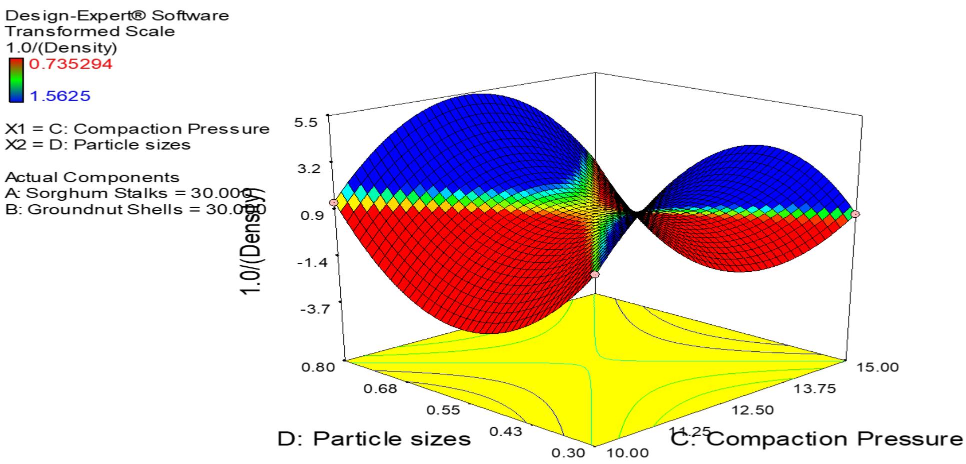

Figure 7: Effects of particle size and compaction pressure on briquette's density

The interaction effects between the particle size and compaction pressure (at a constant sorghum stalks/groundnut shells mixing ratio of 30 %) on the density of the briquette are expressed in Figure 7. The 3D surface plot indicates that as the particle size increases from 0.3 to 0.8 mm, the density of the briquette decreases from 1.36 to 0.73 g/cm³. As the compaction pressure rises from 10 to 15 MPa, the density of the briquette increases from 0.73 to 1.36 g/cm³. Varying the particle size in briquette production affects the briquette density in the sense that as the particle size increases, the density of the briquette decreases [27].

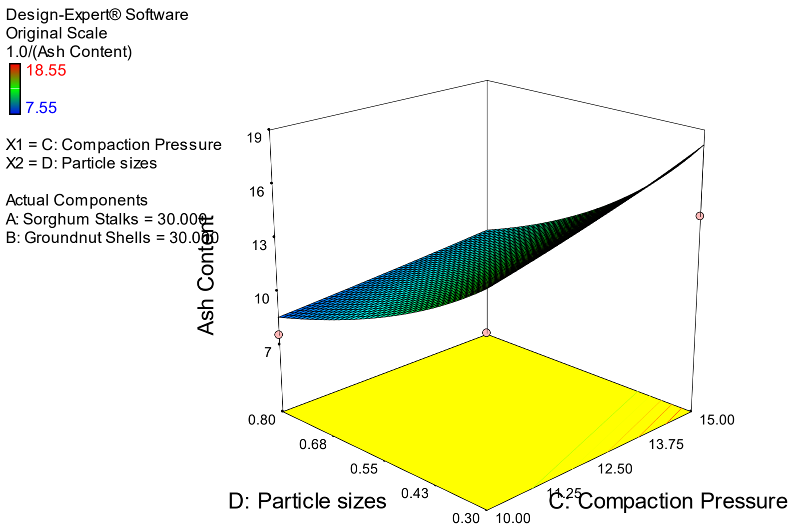

Figure 8: Effects of compaction pressure and particle size on ash content

Figure 8 illustrates the effects of the interaction between compaction pressure and the ratio of sorghum stalks to groundnut shells (at a constant particle size of 0.3 mm) on the ash content of the briquette. The response surface plot indicates that as the compaction pressure increases from 10 to 15 MPa, the ash content increases from 12 to 18.55%. At the same time, the mixing ratios of sorghum stalks and groundnut shells express a negligible effect. This demonstrates a positive association between compaction pressure and briquette ash content. The

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variation in briquette ash content could be attributed to non-combustible elements found in smaller particles of briquette materials when densified at different compaction pressures [28].

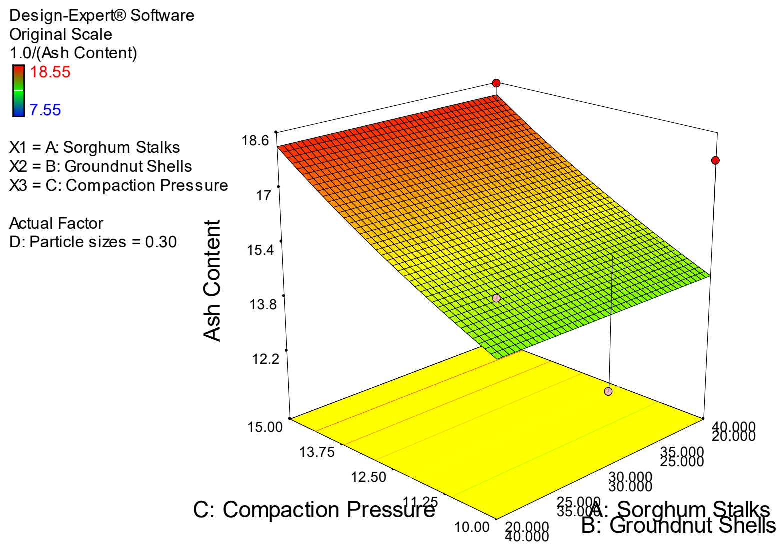

Figure 9: Effects of sorghum stalk and groundnut shell mixing ratios and compaction pressure on ash content

Figure 9 illustrates the interaction effects of particle size and compaction pressure (at a constant mixing ratio of 30% sorghum stalks to groundnut shells) on briquette ash content. The response surface plot indicates that as the particle size increases from 0.3 to 0.8 mm, the ash content of the briquette decreases from 14.3% to 7.55%. As the compaction pressure rises from 10 to 15 MPa, the briquette ash content increases from 7.55% to 14.3%. The particle size of the biomass materials has a significant effect on the ash content of the briquette, in that smaller particles have a higher ash content than larger particles [29].

3.3 Numerical Optimisation

Due to the difference in optimal conditions for response to the other, optimising the suitable procedure for the responses becomes paramount. Table 8 presents the constraints for optimising the briquette to achieve a minimum ash content and a target density value. Table 9 presents the numerical optimisation for the independent variables and response parameters. The sorghum stalk (30 wt.%), groundnut shell (30 wt.%), compaction pressure (12 MPa) and particle size of (0.78 mm) with density and ash content as the responses with optimum values of 1.2 g/cm^3 and 8.710% respectively, are considered for optimum quality of the briquettes having the maximum desirability of 0.944.

Table 8: Constraints for numerical optimisation for briquette production

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: Sorghum stalk	Target	20	40	1	1	3
B: Groundnut Shell	Target	20	40	1	1	3
C: Compaction pressure	Range	10	15	1	1	3
D: Particle size	Maximize	0.3	0.8	1	1	3
Density	Target	0.64	1.36	1	1	3
Ash content	Minimize	7.55	18.55	1	1	3

Table 9: Numerical optimisation parameters

No.	SS (%)	GS (%)	CP (MPa)	PS (mm)	Density (g/cm^3)	AC (%)	Desirability
A: Sorghum stalk	30	30	12	0.78	1.2	8.710	0.944

Note: SS = Sorghum stalks, GS = Groundnut shells, CP = Compaction pressure, PS = Particle size, and AC = Ash content

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Conclusion

The study investigated the effect of mix ratios and process variables (compaction pressure and particle size) on the quality of carbonized briquettes produced from sorghum stalks and groundnut shells. The compaction pressure and particle size were found to have a significant effect (P <0.05) on the density and ash content of the briquettes produced from the blend of carbonized sorghum stalks and groundnut shells. Optimum conditions for the production of the best briquettes from the different combination of the variables were established. The established optimum conditions were 30 % of sorghum stalks, 30% of groundnut shells, 12 MPa of compaction pressure and 0.78 mm of particle size with the highest desirability index of 0.944. The produced briquettes are thereby recommended for domestic and industrial applications.

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