

Characterization and Optimization of Fuel Nugget from Waste Materials

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Abstract: The increasing global demand for energy, coupled with inefficient waste management practices, presents significant environmental and sustainability challenges, particularly in developing countries. This study addresses these issues by investigating the production, characterization, and optimization of fuel nuggets derived from agricultural waste materials specifically, palm kernel shells (PKS), corn cobs (CC), and plastic straws (PS)

The methodology involved using a face-centered central composite design (FCCCD) to optimize the blending ratios of PKS, CC, and PS. Fuel nuggets were fabricated through a process of grinding, mixing, and compressing the biomass materials at high pressure and temperature. The experimental data were analyzed using Design-Expert software to develop quadratic models, with statistical validation performed through Analysis of Variance (ANOVA).

The results demonstrated that higher proportions of PKS significantly enhanced the calorific value (up to 24.12 MJ/kg), reduced ash content (as low as 0.90%), and increased bulk density (1.63 g/cm³). CC contributed to lowering moisture content (as low as 2.87%) and increasing volatile matter, which improved ignition properties. The optimal blend achieved a combustion efficiency of up to 93.88%. The models showed high reliability, with adjusted R² values above 0.98 across all response variables.

In conclusion, the study confirms that fuel nuggets produced from agricultural waste are a viable, sustainable alternative to traditional fossil fuels. These nuggets offer high energy output, low emissions, and significant environmental benefits by reducing agricultural waste and deforestation. It is recommended that future research explore additional biomass materials and assess the commercial scalability of this technology to promote broader adoption in energy-deficient regions

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Keywords: Palm kernel shell (pks), Moisture content, Calorific value, Biomass, Fuel nuggets.

I. Introduction

Demand for energy and fossil fuels is growing day by day, contributing to a rise in “greenhouse gas emissions” into the environment and additionally the deleterious effects of environmental pollution and global warming (Ngusale et al. 2014; Kpalo et al, 2020). The production of fuel nuggets from agricultural waste materials offers a sustainable solution to both energy generation and waste management challenges. Fuel nuggets, commonly referred to as fuel briquettes or biomass briquettes, are compacted blocks created from a variety of organic materials, including agricultural waste, wood chips, sawdust, charcoal dust, and other biomass (Sanchez et al., 2022). They serve as an alternative fuel source to conventional fossil fuels such as coal or wood logs. The production of fuel nuggets from agricultural waste materials is a promising solution to address both environmental concerns and energy demands. Agricultural residues such as straw, corn Stover, rice husks, and nut shells are abundant biomass resources that can be converted into densified fuel nuggets. This project aims to explore the feasibility of producing high-quality fuel nuggets from agricultural waste, emphasizing sustainable energy production and waste management. By converting agricultural residues into valuable fuel sources, this project contributes to reducing greenhouse gas emissions, promoting renewable energy utilization, and enhancing agricultural sustainability. The findings from this study can serve as a foundation for scaling up production and implementing similar projects in agricultural regions globally.

Biomass, particularly agriculture residues seem to be the most promising energy resources for developing countries (Patomsok, 2008). Rural households and minority of urban dwellers depend solely on fuel woods (charcoal, firewood and sawdust) as their primary source of energy for the past decades (Onuegbu et al., 2010). Of all the available energy resources in Nigeria, coal and coal derivatives such as smokeless coal briquettes, bio-coal briquettes and biomass briquettes have been shown to have the highest potential for the use as suitable alternative to coal/fuel wood in industrial boiler and brick kiln for thermal application and domestic purposes. Global warming has become an international concern. Global warming is caused by greenhouse gasses which carbon dioxide is among the major contributors. It was shown that increase emissions of CO₂ have been drastically reduced owing to the fact that the rate of deforestation is higher than a forestation effort in the country (Yahaya and Ibrahim, 2012). In counties like Japan, China, India etc., it was observed that agricultural wastes (agro residues) can be briquetted and used as substitute for wood fuel. Every year, millions of tons of agricultural waste are generated (Wang et al., 2017). These are either not used or burnt inefficiently in their loose form causing air to the environment. The major residues are rice husk, corn cob coconut

shell, jute stick, groundnut shell, cotton stalk, etc. these wastes provide energy by converting into high density fuel nuggets. These nuggets are very cheap, even cheaper than coal briquettes. Adoption of nuggets technology will not only create a safe and hygienic way of disposing the waste, but turn into a cash rich venture by converting waste into energy and also contributing towards a better environment (Zubairu and Gana, 2014).

The global usage of renewable and nonrenewable energy sources is on the rise. Over time, the growing energy demands have been efficiently met. Each country's community needs an alternative energy source to reduce fossil fuel usage, which is environmentally friendly and sustainable in the long run. Renewable energy sources like solar, biomass, wind, and geothermal are plentiful. Solar energy, derived from the sun, provides the planet with essential energy. By using solar panels, we can directly convert sunlight into electricity for homes and businesses. Wind turbines harness wind power to generate electricity, while geothermal energy from within the earth can also be used for electricity generation. (Sirajudin et al., 2013).

In developing countries like Nigeria, there is a growing need for renewable energy resources for domestic cooking. Non-renewable sources such as kerosene and liquefied petroleum gas (LPG) are failing to meet local demands, and their high costs are pushing people to switch to renewable options. Energy is crucial for the nation's growth, significantly contributing to the social and economic well-being of its people. Nigeria's goal of becoming one of the world's top twenty economies by 2020 may remain unachieved if energy issues are not properly addressed. Currently, a global energy scarcity crisis affects Nigeria as well (Oladeji, 2012).

The inefficient management and disposal of agricultural waste materials pose a challenge to sustainable agriculture and environmental protection. At the same time, many regions, especially in developing countries, face energy shortages and rely heavily on traditional fuels like firewood and charcoal, which contribute to deforestation and air pollution. The use of fuel wood for cooking has health implications especially on women and children who are disproportionately exposed to the smoke apart from environmental effects. The smoke causes acute lower respiratory infection (ALRI) particularly pneumonia in children (Smith and Samet, 2000; Ezzati and Kammen, 2001).

The justification for researching the production of fuel nuggets from agricultural waste is multi-dimensional, including environmental, economic, social, health, and technological advantages. This study tackles waste management challenges and offers a sustainable energy solution, aligning with international objectives for sustainable development, energy security, and environmental conservation. Its potential positive effects on communities and the environment underscore the study's relevance and importance in promoting sustainable practices and enhancing quality of life. The study addresses the issue of waste management, minimizing Pollution: waste into fuel briquettes, the study aims to minimize this environmental pollution. Deforestation Prevention, income generation, employment opportunities, cost-effective energy Source and affordable Fuel: Fuel nuggets typically produce less smoke and harmful emissions compared to traditional biomass fuels. This can lead to improved indoor air quality and better respiratory health for users, especially women and children who spend significant time near cooking fires.

II. Materials and Method

Raw materials

The materials for this study are shown in figure 1. These materials were sourced locally and tested to ensure that they meet all the necessary standards.

- 1) Palm kernel shell (pks) was sourced from Ihiagwa market, Owerri Imo state.
- 2) Corn cobs was collected from Jattu market Uzairue, Auchi, Edo state.
- 3) The plastic straw was sourced from Umuchima, Owerri Imo state.



Fig. 1. Palm Kernel Shell Samples



Fig. 2. Corn Cobs Sample

Apparatus used for the experiment

Triple beam balance, model: MB-2610g, manually hydraulic press, mold (13 by 8cm), muffle furnace, Design expert software, Bomb calorimeter, Oven, Sample mixing apparatus, Gas cylinder, Thermometer, Ball mills.

III. Methodology

In the current study, palm kernel shell and corn cobs were employed as two input factors and plastic straw as the remaining third factor for a “face-centered central composite design” (FCCCD) (Ali et al. 2023). The low and high values of each factor are denoted by $+\alpha$ and $-\alpha$ as shown in Table 3.1. A minimum 30% pks, 20% corn cobs and 5% straw was employed for this experiment as it is expected that such an amount of biomass feed stocks shows better physical and thermal properties of fuel nuggets (Li et al. 2017).

Table 1: Design of Experiment

Factor	Name	Low level	High level	-alpha	+alpha
A	PKS	43.5025	57.2675	38.81	61.96
B	CC	31.4942	45.6458	26.67	50.47
C	straw	8.18873	14.9613	5.88	17.27

Design Expert software version 11 was used to generate the design of experiment according to Table 1 which enabled the development of mathematical models to predict responses, analyze factor interactions, and determine optimal conditions efficiently, thereby reducing the need for extensive trial-and-error experimentation. RSM also determined the ANOVA table and constructed the predicted vs actual graph which showed the relationship between the effect of pks and corn cobs on the fuel nugget. It streamlines the design of experiments (DOE). It was used to build quadratic equations, examine response surfaces using 3D plots and contour diagrams, and assess factor interactions with the software's statistical analysis and modeling capabilities. By determining which factor values enhance or reduce a response or accomplish desired goals, it also makes optimization easier. Design Expert improves experimental study decision-making by expediting data processing and interpretation.

Using Design-Expert software version 11, 15 experimental runs were designed in a randomized manner in order to optimize the calorific value and are presented in table 2.

Table 2 Design Expert Experimental Runs

Run	PKS (%)	Corn cobs (%)	Polymeric straw (%)
1	48.6590	39.6341	11.7073
2	50.0000	38.8889	11.1111
3	51.4175	41.8815	6.7010
4	57.9944	28.0521	13.9535
5	47.3684	36.8421	15.7894
6	52.1485	37.6953	10.1562
7	41.4594	50.4661	8.0745
8	48.0216	34.7121	17.2663
9	42.8571	47.6190	9.5238
10	40.0000	46.6667	13.3333
11	38.8079	45.1378	13.9535
12	61.9567	29.9687	8.0745
13	52.9412	41.1765	5.8824
14	60.0000	26.6667	13.3333
15	57.1429	33.3333	9.5238

The palm kernel shell and corn cobs were collected, cleaned and dried in order to remove any form of impurities. Then the palm

kernel shell was ground to a 1mm sieve size and the corn cobs to a 5mm sieve size using a grinder while the plastic straw were shredded into small pieces using a shredder. The palm kernel shell and corn cobs powder were mixed in the different ratio as shown in table 2 as obtained using the design expert software to create a uniform blend while the plastic straw was mixed with it to blend properly. It was then poured into the mold and heated to a temperature of 125°C for the plastic straw to melt across the mixture and then a pressure up to 150Mpa to the mixture to bind the particles together and form the solid nuggets. The nuggets were then dried in order to remove excess moisture after which it was cured in a control environment to allow the binder to fully set and harden. The fuel nuggets were packaged and sent for proximate analysis and performance to ensure they meet the desired standard.

IV. Results and Discussion

Characterization Results Vs Predicted RSM

Table 3 summarizes the characterization results of the locally made fuel nugget from (palm kernel shell, corn cobs and plastic straw) and this table consist of the calorific values (CV), moisture contents (MC), ash contents (AC), volatile matter (VM), combustion efficiency (CE) and bulk density (BD). We see from this table that the calorific value ranges from 16.66 to 24.12 MJ/Kg, moisture content (2.87 to 9.99%), ash content (0.9 to 5.82), volatile matter (11.78 to 31.63%), combustion efficiency (83.57 to 92.9%) and bulk density (1.12 to 1.63g/cm³). While table 4 presents the predicted values of the analyses. The difference between the predicted and actual values was less than 0.2 and this shows that the response surface model is well calibrated ensuring accurate predictions and reliable conclusions. This is often validated through statistical measures, such as R-squared or lack-of-fit tests, to confirm that the model's performance is consistent.

Table 3: Result of Fuel Nuggets Analysis

Run	CV (MJ/kg)	MC (%)	AC (%)	VM (%)	CE (%)	BD (g/cm ³)
1	17.15	8.88	2.68	17.48	83.72	1.62
2	17.76	5.57	5.81	20.12	84.11	1.29
3	20.12	7.29	3.45	20.48	87.95	1.53
4	21.96	2.87	3.50	27.53	91.04	1.26
5	18.61	8.76	5.47	11.78	84.56	1.63
6	20.58	5.31	4.83	21.66	85.07	1.35
7	19.24	7.09	5.82	20.12	86.41	1.50
8	18.23	7.40	2.73	29.15	88.01	1.25
9	17.11	5.70	1.36	31.63	87.23	1.27
10	16.66	9.99	1.42	28.97	85.03	1.39
11	18.34	6.78	3.39	16.84	83.57	1.32
12	24.12	5.46	2.75	18.25	93.88	1.47
13	21.50	6.29	1.80	24.78	91.79	1.43
14	22.12	6.87	0.90	24.54	92.90	1.22
15	20.47	6.77	2.24	21.57	87.69	1.12

Table 4: Predicted Values of The Fuel Analysis.

Run	CV (MJ/kg)	MC (%)	AC (%)	VM (%)	CE (%)	BD (g/cm ³)
1	16.96	8.93	2.60	17.56	83.43	1.63
2	17.73	5.55	5.77	19.98	83.84	1.31
3	20.10	7.27	3.41	20.50	84.15	1.56
4	21.76	2.91	3.42	27.82	84.57	1.28
5	18.67	8.59	5.39	11.85	85.00	1.59

6	20.63	5.13	4.75	21.52	85.48	1.32
7	19.36	7.38	5.77	20.24	86.27	1.50
8	18.04	7.23	2.88	29.22	87.34	1.26
9	17.44	5.81	1.31	31.49	87.48	1.23
10	16.69	10.01	1.45	28.95	87.66	1.39
11	18.50	6.89	3.54	16.88	88.14	1.31
12	24.25	5.57	2.90	18.11	90.76	1.46
13	21.48	6.08	1.96	24.64	91.81	1.45
14	22.17	6.92	0.5845	24.61	92.92	1.18
15	20.24	6.75	2.40	21.61	94.07	1.18

Response Surface Methodology

RSM analysis yielded optimum results for CV, MC, AC, VM, CE and BD at 19.264 MJ/kg, 7.757%, 4.046%, 25.053%, 87.051% and 1.447g/cm³ respectively. The output response function of the model is listed in the form of P values, F values, and lack of fit (LOF) represented in ANOVA tables. Table 5 and 3.8 presents the fit summary of the fuel performance and efficiency models for all the analyses. Four models were employed as sources (linear, two factor interaction [2FI], quadratic and cubic). In all the cases, the quadratic model is the best-fitted model because the predicted R² is close to 1, and it is in reasonable agreement with the adjusted R². The difference between the predicted R² and adjusted R² is less than 0.2.

Response 1: Calorific Value

Table 5: Fit Summary

Source	Sequential p-value	Adjusted R ²	Predicted R ²	
Linear	0.1340	0.2178	-0.0886	
2fi	0.1418	0.4356	0.4199	
Quadratic	<0.0001	0.9861	0.8956	Suggested
Cubic	0.5517	0.9896	0.7711	Aliased

Table 6: ANOVA For Quadratic Model

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	66.28	9	7.36	111.67	< 0.0001	sig
A-pks	3.52	1	3.52	53.33	0.0008	
B-cc	1.55	1	1.55	23.47	0.0047	
C-st	20.61	1	20.61	312.47	< 0.0001	
AB	0.5304	1	0.5304	8.04	0.0364	
AC	3.08	1	3.08	46.63	0.0010	
BC	15.85	1	15.85	240.33	< 0.0001	
A ²	0.9610	1	0.9610	14.57	0.0124	
B ²	15.40	1	15.40	233.58	< 0.0001	
C ²	8.83	1	8.83	133.96	< 0.0001	
Residual	0.3297	5	0.0659			
Cor Total	66.61	14				

The Model F-value of 111.67 implies the model is significant. The ANOVA table showed that the quadratic model is suitable for analyzing the experimental data

Graphical Response of Surface Methodology: Plots of expected versus actual responses of the analysis were shown in Figure 4 and 6 as straight-line graphs. The collection of points through the line of best fit shows that the models correctly anticipated the experimental data. A diagnostic tool for evaluating a model's dependability is the predicted versus real plot. The three-dimensional (3D) plots that display the interactive impact of the parameters under consideration on the effectiveness of the fuel nugget characteristics as shown in Figure 3 and 5. The quadratic model is supported by the parabolic curves that are present in all of them.

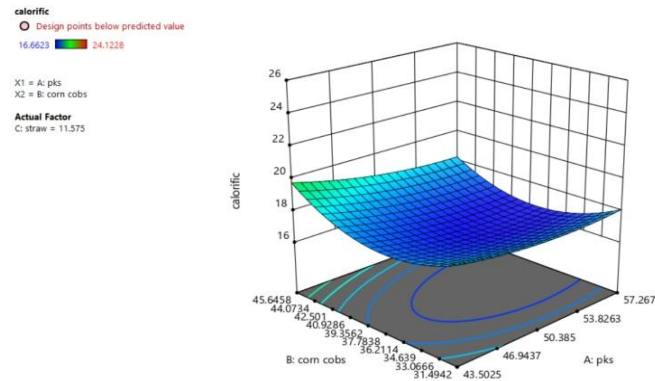


Fig. 3. 3D response surface of PKS and CC on calorific value.

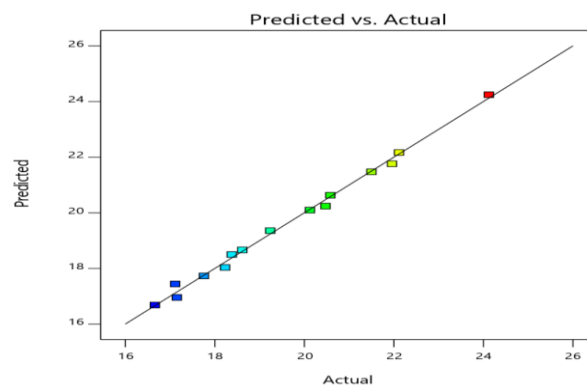


Fig 4. Comparison of actual and predicted values of the responses for calorific value

TABLE 7: FINAL EQUATIONS IN TERMS OF ACTUAL FACTORS

Calorific value	=
+97.67211	
-0.409517	A
-2.82381	B
-3.00156	C
-0.005287	AB
-0.026603	AC
+0.058742	BC
+0.008412	A ²
+0.031862	B ²
+0.105356	C ²

$$Y = +97.67211 + (-0.409517A) + (-2.82381B) + (-3.00156C) + (-0.005287AB) + (-0.026603AC) + 0.058742BC + 0.008412 A^2 + 0.031862B^2 + 0.105356 C^2 \dots\dots\dots(1)$$

Response 2: Moisture Content

Table 8: Fit Summary

Moisture content	=
-77.35177	
+0.854219	A
+2.99380	B
+1.67601	C
+0.001927	AB
+0.002632	AC
+0.006838	BC
-0.009373	A ²
-0.042305	B ²
-0.090673	C ²

Table 9: ANOVA For Quadratic Model

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	41.23	9	4.58	87.85	< 0.0001	sig
A-pks	0.1363	1	0.1363	2.61	0.1669	
B-cc	5.96	1	5.96	114.25	0.0001	
C-st	0.1114	1	0.1114	2.14	0.2037	
AB	0.0705	1	0.0705	1.35	0.2975	
AC	0.0301	1	0.0301	0.5775	0.4816	
BC	0.2148	1	0.2148	4.12	0.0982	
A ²	1.19	1	1.19	22.88	0.0050	
B ²	27.15	1	27.15	520.75	< 0.0001	
C ²	6.54	1	6.54	125.48	< 0.0001	
Residual	0.2607	5	0.0521			
Cor Total	41.49	14				

Adjusted R²=0.9824

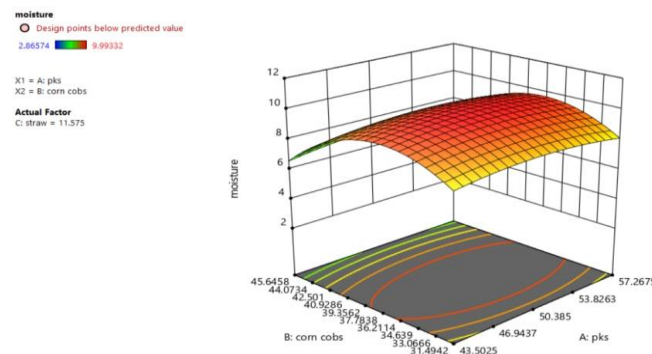


Fig. 5. 3D response surface plot of PKS and CC on moisture content

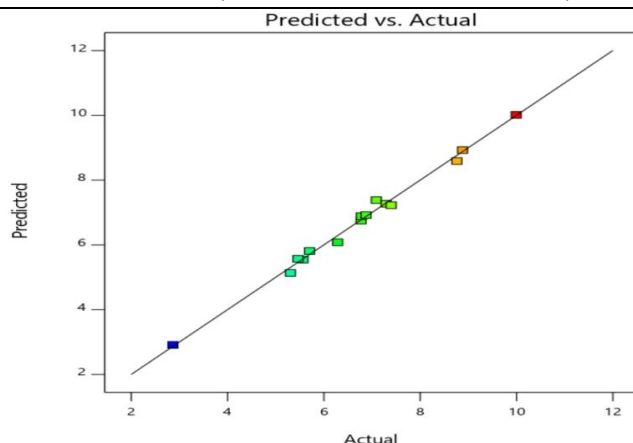


Fig. 6. Comparison of actual and predicted values of the responses for moisture content

Table 10: Final Equations in Terms of Actual Factors

Moisture content	=
-77.35177	
+0.854219	A
+2.99380	B
+1.67601	C
+0.001927	AB
+0.002632	AC
+0.006838	BC
-0.009373	A ²
-0.042305	B ²
-0.090673	C ²

$$Y = -77.35177 + +0.854219A + 2.99380B + 1.67601C + 0.001927AB + 0.002632AC + 0.006838BC + (-0.009373A^2) + (-0.042305B^2) + (-0.090673C^2).....(2)$$

Optimization Using Numerical Approach

Table 11: Criteria for Optimization

Name	Goal	Lower limit	Upper limit	Lower weight	Upper weight	importance
A: pks	Minimize	43.5025	57.2675	1	1	3
B: corn cobs	Minimize	31.4942	45.6458	1	1	3
C: straw	Minimize	8.18873	14.9613	1	1	3
Calorific	Maximize	16.6623	24.1228	1	1	3
Moisture	Minimize	2.86574	9.99332	1	1	3
Ash	Minimize	0.8972	5.81511	1	1	3
Volatile	Minimize	11.7765	31.6312	1	1	3
combustion	Maximize	83.5677	93.8763	1	1	3
Density	is target= 1.37316	1.1206	1.62571	1	1	3

Optimal Solution: 40 Solutions Found

Number	pks	corn cobs	straw	calorific	moisture	ash	volatile	combustion	density	Desirability	
1	48.639	31.494	8.189	19.264	7.757	4.049	25.047	87.049	1.447	0.500	Selected

Summary of The Characterization and Optimization

The study optimized fuel nuggets from palm kernel shells (PKS), corn cobs (CC), and plastic straws (PS), evaluating calorific value, moisture content, ash content, volatile matter, combustion efficiency, and bulk density. Key findings:

Calorific Value (CV): Quadratic model ($R^2 = 0.9861$) showed high accuracy. PKS and CC significantly increased CV due to high fixed carbon and low moisture, enhancing energy density. Interaction and quadratic terms (A^2 , B^2 , and C^2) indicated non-linear effects. **Moisture Content (MC):** Quadratic model ($R^2 = 0.9824$) highlighted CC's role (F-

value= 114.25) in reducing moisture below 10%, improving combustion efficiency due to its porous structure.

Ash Content: Quadratic model ($R^2 = 0.9811$) showed PKS significantly reduced ash content, with interaction terms (AB, AC) also influential. Lower ash improved fuel quality and reduced maintenance needs.

Volatile Matter (VM): Near-perfect model fit ($R^2 = 0.9986$) indicated PKS, CC, and their interactions increased VM, enhancing ignitability but requiring balance to control emissions.

Combustion Efficiency: Optimized PKS-CC blends achieved up to 93.88% efficiency, reducing emissions and increasing heat output.

Bulk Density: Higher PKS content increased density, improving compaction, burn time, storage, and transport efficiency.

Overall, PKS and CC blends produced high-quality, efficient, and commercially viable fuel nuggets with low moisture, low ash, and high energy output.

V. Conclusion and Recommendation

Conclusion

Fuel nugget is a sustainable energy production method that has the potential to replace coal, fuel wood, and charcoal. In this present work, fuel nugget was fabricated by the mixture of palm kernel shell, corn cobs and polymeric straw. A total number of 15 fuel nugget samples have been fabricated with different combinations of crop residues and solid biomass based on the faced-centered central composite design (FCCCD) approach. The fuel nugget sample with 61.96% palm kernel shell (pks), 29.97% corn cobs and 8.0745% straw has achieved the maximum CV of 24.12 MJ/kg and has a thermal efficiency of 93.88%. In the same manner, the fuel nugget sample made from 60% pks, 26.67% corn cobs and 13.33% straw yields a minimum AC and MC of 0.9% and 4.87% respectively. When investigated by the bomb calorimeter. Based on the ANOVA and RSM statistical analyses, the biomass composition has a great influence on the fuel nugget properties (CV, MC and AC). The optimum values of CV, MC and AC determined by RSM were 19.264 MJ/kg, 8.19% and 4.1%.0%, respectively. Fuel nuggets with higher CC content showed reduced moisture content, as low as 2.87%, which directly improves combustion efficiency and energy release. Lower moisture levels (<10%) are ideal for efficient burning and reducing emissions during combustion. The ash content varied from 0.90% to 5.81%, with the lowest ash content observed in nuggets containing higher PKS content. Low ash levels are advantageous as they minimize residue buildup and reduce equipment maintenance.

Recommendations

Government should in its effort of diversification consider the use of alternative fuel sources such as renewable energy; this will reduce over dependence on crude oil.

Community members should organize themselves to identify channels of collecting their waste and partner with public and private organizations for recycling the waste in to wealth.

Corporate investors should be given licensed of operation in to alternative fuel sources, to enable diversification of the economy to be holistic.

A formulation with approximately 60% PKS, 30% CC, and 10% PS provides the best balance between high calorific value, low moisture, and high combustion efficiency. This composition ensures a calorific value above 24 MJ/kg, moisture content below 5%, and combustion efficiency exceeding 90%.

Adoption of these fuel nuggets can significantly reduce deforestation and reliance on traditional wood fuels. Farmers and entrepreneurs should be encouraged to invest in fuel nugget production, as it offers both waste management and economic opportunities.

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