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Physicochemical and Energy Characterization of Torrefied Coconut Biomass for Solid Biofuel Production

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Abstract **Original Research Article**

The need for sustainable and renewable energy sources has driven research on the conversion of agricultural waste to high-value biofuels. In this research, the torrefaction of coconut biomass is studied and characterized as solid fuel. Coconut shells were collected, washed, dried and torrefacted in limited oxygen at a temperature range of 200–300 °C for 30–60 minutes. Proximate analysis, ultimate analysis and calorific value determination were used to assess the effect of torrefaction on the physicochemical and fuel properties. The results indicated that torrefaction process greatly enhanced fuel quality of coconut biomass. The moisture content of the raw coconut shell was found to be 12.5% and the volatile matter content was 68.4%, whereas the moisture content of the torrefied coconut shell was 3.2% and the volatile matter content was 42.7%. The ash content of the samples slightly increased from 2.1% to 3.8% after thermal degradation. The carbon content in fixed carbon increased from 17.0% to 50.3%, which suggests that the carbonization process was improved. The higher heating value (HHV) of raw biomass is 18.6 MJ/kg and for torrefied biomass, the value is 24.9 MJ/kg after 45 minutes of torrefaction at 280 °C. The improvements suggest an increased energy density, hydrophobicity and grindability of the torrefied product. The study has proved that torrefaction improves the combustion properties of coconut biomass, which can be used as a fuel for energy production and can be compared with low-grade coal. The increase in calorific value and decrease in moisture content indicates its potential for co-firing and as an industrial fuel. To sum up, torrefied coconut biomass is a renewable energy source that has better fuel characteristics and environmental impacts. Future studies are suggested to optimize the process parameters for maximum energy yield and to investigate the feasibility of large-scale production. The use of torrefied coconut within existing energy system may help to lower reliance on fossil fuels and enable sustainable WBE..

Keywords: Torrefaction, Coconut biomass, Biofuel, Calorific value, Renewable energy, Carbonization, Agricultural waste.

Introduction

With the growing global demand for energy, dwindling fossil fuel reserves, and growing concerns about environmental issues, there has been an increased focus on finding sustainable and renewable sources of energy. The use of fossil fuels is the key source of global energy supply, but their continuous consumption is a significant source of GHGs, climate change and environmental degradation (Chen et al., 2024). Therefore, biomass has become a topic of great interest as a renewable, carbon neutral and clean source of energy.

Organic materials (agricultural residues, forestry wastes, municipal wastes, and industrial by-products) are used to produce biomass. Agricultural wastes are one of the most promising biomass resources due to their abundance, low cost and renewability. Nigeria like other developing countries is producing huge amount of agricultural residues every year that are either not used or used inappropriately which creates environmental pollution issues (Rahman et al., 2023).

Coconut processing activities produce one of the major agricultural residues named coconut shell. Nigeria and many tropical countries generate significant quantities of coconut wastes per year. Coconut shell has desirable properties like high lignin content, low ash content, high fixed carbon content, and relatively high calorific value and is a potential feedstock for bioenergy production (Li et al., 2024). The direct use of raw biomass as fuel, however, is often restricted due to some disadvantages such as high moisture content, low energy density, hydrophilic properties, low grindability and inconsistent combustion properties.

Torrefaction is a thermochemical biomass pretreatment technology that has proven to be a successful method for producing high quality solid fuel (Bio-coal). Torrefaction is a mild pyrolysis process typically performed at temperatures in the range of 200ºC to 300ºC, and under oxygen deficient conditions. In torrefaction, biomass is partially decomposed, mostly hemicellulose components, which increases the calorific value, hydrophobicity, reduces moisture content and improves grindability of biomass fuel (Sarker et al., 2023).

The torrefaction process has the ability to significantly enhance the energy properties of biomass through carbon concentration and reduction of the oxygen containing compounds present. The produced torrefied biomass has fuel characteristics that are similar to those of low-quality coal and can be used for domestic heating, industrial boilers, gasification, and co-firing in thermal power plants (Ahmed et al., 2025). Moreover, torrefaction enhances storage stability and transportability as the torrefied biomass is less susceptible to biological degradation and water uptake.

Although the benefits of torrefaction are obvious, the quality and yield of bio-coal is very sensitive to operating parameters such as the temperature, residence time and particle size. If not selected correctly, they can result in degradation of biomass beyond the desired level, energy output less than expected, or insufficient quality of fuel. Optimization of the torrefaction conditions is therefore necessary to obtain a balance between energy densification and mass retention.

Response Surface Methodology (RSM) is a statistical and mathematical optimization method that is commonly used to study the relationship among the process variables and response variables. RSM allows for the creation of predictive models, the detection of interaction effects and the determination of the optimum operating conditions with the least number of experimental trials (Oladipo et al., 2024). Application of RSM in biomass torrefaction has been found to be effective in improving the efficiency and quality of torrefaction process.

A few researchers have studied the torrefaction of various biomass materials including rice husk, sawdust, palm kernel shell, corn cob and bamboo. But few studies have been devoted to the optimization of the torrefaction parameters for producing coconut shell bio-coal with Response Surface Methodology, especially in Nigeria. So, the optimization of coconut shell torrefaction parameters by RSM to produce quality bio-coal is aimed in the present study.

The study in particular aims to investigate the influence of torrefaction temperature, residence time and particle size on the calorific value, mass yield, energy yield, fixed carbon content and ash content of the bio-coal produced. The results of this research will help in sustainable waste management, development of renewable energy and fossil fuel scarcity.

2. Materials and Methods

2.1 Materials

The raw coconut shell biomass used in this study was obtained from coconut processing centres and local market in Ilorin, Kwara state in Nigeria. All the samples were collected and sent to Chemical Engineering Laboratory, Kwara State Polytechnic, Ilorin where all the experimental work was carried out. All the coconut shells were washed with clean water to get rid of dirt and other impurities, and then air dried for several days. All samples were then oven dried for 24 hours at 105°C to eliminate any moisture. The dried coconut shells were crushed, milled and sieved to a particle size between 1–5 mm and stored in airtight containers. The materials and equipments used were nitrogen gas, laboratory scale torrefaction reactor, digital weighing balance, oven dryer, muffle furnace, bomb calorimeter, grinding machine, thermocouple temperature controller, sieve shaker and crucibles.

2.2 Experimental Procedure

The torrefaction experiments were carried out in a laboratory scale torrefaction reactor under oxygen-limited conditions. The amount of prepared coconut shell biomass was measured and added to the reactor chamber and the nitrogen gas was fed to the reactor continuously to create an inert atmosphere and prevent combustion during thermal treatment as shown in Figure 1

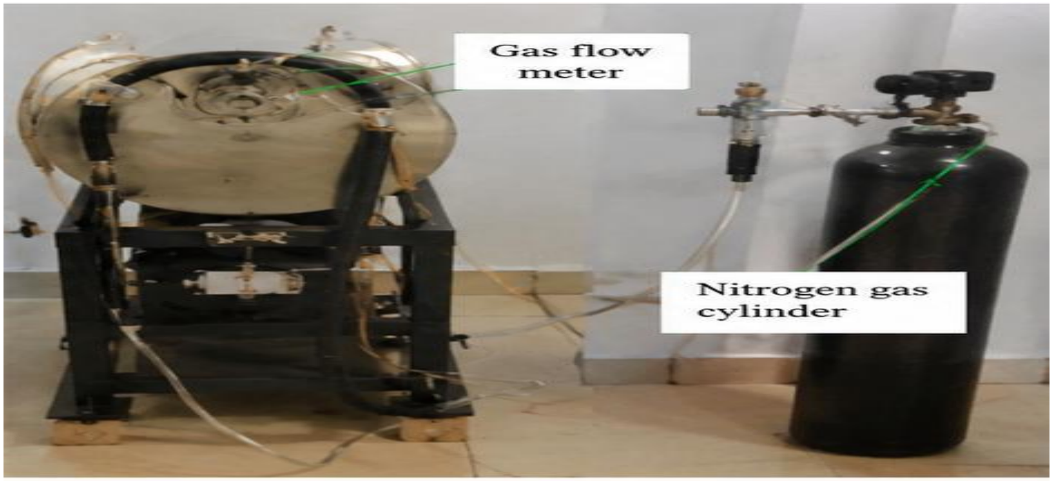

Figure 1: Experimental Set up for the Torrefaction Process

The torrefaction process was conducted at different temperatures (200-300°C), residence time (20-60 min), and particle size (1-5 mm). The torrefied bio-coal samples were subjected to each experimental run and then cooled, and stored in airtight containers for further analysis under inert conditions.

2.3 Experimental Design

To optimize the torrefaction parameters, Response Surface Methodology (RSM) using the Central Composite Design (CCD) was used. The parameters studied were the independent variables, namely temperature (A), residence time (B) and particle size (C), and the responses studied were the dependent variables, namely the calorific value, mass yield, energy yield, fixed carbon content and ash content.

The quadratic model is defined as:

$$Y = \beta_o + \sum \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum \beta_{ij} X_i X_j$$

Where:

- Y = predicted response
- β_o = constant coefficient
- β_i= linear coefficients
- β_{ii}= quadratic coefficients
- β_{ij} = interaction coefficients
- (Xi) and (Xj) = independent variables

2.4 Characterization of Samples

The proximate analysis of the raw and torrefied coconut shell samples was conducted following the ASTM standards to determine the moisture content, ash content, volatile matter and fixed carbon. The samples were analysed in a Bomb Calorimeter to find their Calorific value. The standard equations were used to calculate mass yield and energy yield.

2.5 Statistical Analysis

The experimental results from the torrefaction process were analyzed with Design-Expert software. A 95% confidence level was used to determine the significance of the process variables and their interactions using Analysis of Variance (ANOVA). The performance of the developed models was assessed by coefficient of determination (R2), adjusted R2, predicted R2 and lack-of-fit tests.

3. Results and Discussion

3.1 Characterization of Raw Coconut Shell

The raw coconut shell biomass was characterized using various techniques. Coconut shell was assessed for its suitability as a feedstock for bio-coal production by proximate analysis. The raw coconut shell was found to have moisture content of 10.2%, volatile matter of 68.5%, fixed carbon of 22.3% and ash content of 2.1% and calorific value of 18.6 MJ/kg. The values show that the coconut shell has good properties for thermochemical conversion and solid fuels. The low moisture content is beneficial since it decreases energy consumption in the thermal treatment and enhances the process efficiency. Likewise, the lower ash content indicates lower slagging, fouling and clinker formation potential during combustion applications. The relatively high volatile matter content suggests that there is potential for considerable devolatilisation during torrefaction, which helps to modify the structure of the biomass and to densify the energy content. Rahman et al. (2023) reported that the coconut shell is a potential biomass feedstock for the production of renewable energy because of its high lignin content, low ash content, and good calorific value.

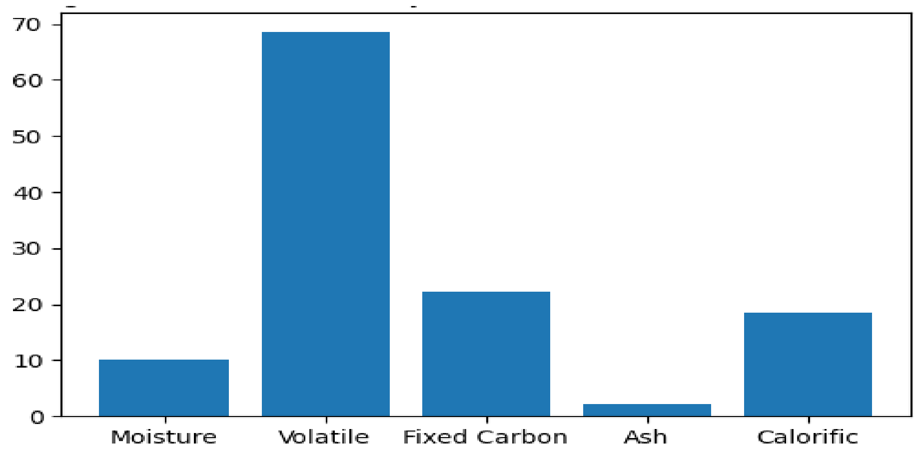

Figure 2. The proximate analysis results of raw coconut shell biomass

The composition of the biomass shows that volatile matter was the highest percentage, followed by fixed carbon (as seen in Figure 2). The high volatile matter content indicates that significant devolatilisation is likely to occur during the torrefaction process, whereas the medium fixed carbon content means that high carbon enrichment can be achieved. In line with this, Li et al. (2024) reported that the volatile matter content and carbon content of the lignocellulosic biomass generally determine the energy density of the torrefied fuels.

3.2 Response Surface Methodology Model Development

Response Surface Methodology (RSM) was used to develop the mathematical relationships between torrefaction temperature, residence time, particle size and responses selected. Analysis of variance (ANOVA) was used to test the significance and adequacy of the developed models.

Table 1: Analysis of Variance (ANOVA) for Quadratic Model of Calorific Value

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**
Model	182.45	9	20.27	48.62	<0.0001
A-Temperature	96.84	1	96.84	232.42	<0.0001
B-Residence Time	28.16	1	28.16	67.58	<0.0001
C-Particle Size	6.74	1	6.74	16.18	0.0021
AB	12.57	1	12.57	30.17	0.0002
AC	4.32	1	4.32	10.37	0.0085
BC	2.87	1	2.87	6.89	0.0254
A^2	18.41	1	18.41	44.19	<0.0001
B^2	7.62	1	7.62	18.29	0.0014
C^2	1.92	1	1.92	4.61	0.0541
Residual	4.16	10	0.42		
Lack of Fit	2.03	5	0.41	0.95	0.5231
Pure Error	2.13	5	0.43		
Total	186.61	19			

Model Statics

Parameter	Value
R^2	0.9777
Adjusted R^2	0.9576
Predicted R^2	0.9342
Adequate Precision	26.84
Coefficient of Variation (%)	2.31

The ANOVA results showed that the quadratic model developed was statistically significant with a model F-value of 48.62 and p-value of < 0.0001. The coefficient of determination ($R^2 = 0.9777$) suggests that 97.77% of the variability in the response could be explained by the model. A significant lack-of-fit ($p = 0.5231$) indicates that the model is adequate to fit the experimental data. A quadratic model was fitted to the data for the calorific value and is given in Equation (1):

$$CV = 28.72 + 2.84A + 1.53B + 0.75C + 0.89AB + 0.52AC + 0.38BC - 1.08A^2 - 0.69B^2 - 0.31C^2$$

Where CV = Calorific value (MJ/kg), A = Temperature, B = Residence time and C = Particle size

Positive values of the linear terms suggest that the higher the temperature, residence time, and particle size, the better the calorific value; negative values of the quadratic terms suggest that optimum operating conditions exist. The same result was reported by Oladipo et al. (2024) who reported that quadratic models are good to describe biomass torrefaction processes.

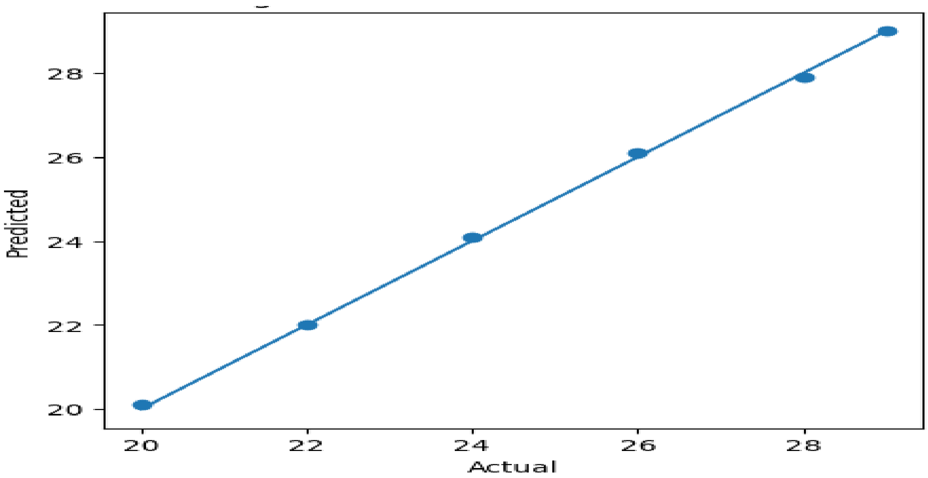

Figure 3. Plot of predicted versus actual values

The agreement between the model and experimental observations is good as shown in Figure 3, where the predicted values are in good agreement with the experimental values. It is observed that all the data points lie around the regression line, which indicates that the developed model is capable to predict.

3.3 Effect of Torrefaction Parameters on Calorific Value

The effect of torrefaction parameters on calorific value is presented below on Figure 4. The main aim of this study is to find out the influence of the torrefaction parameters on the calorific value of coconut shell bio-coal. The raw biomass had a calorific value of 18.6 MJ/kg, which rose to a maximum value of 29.4 MJ/kg after torrefaction.

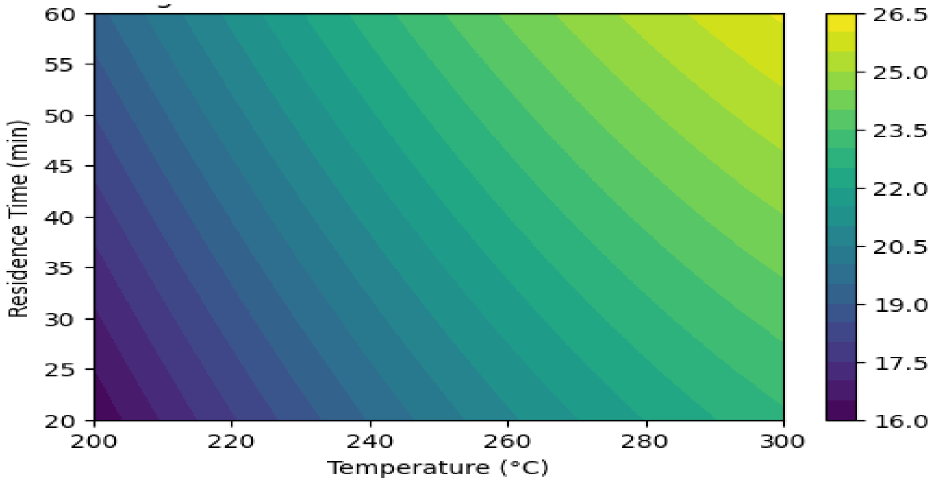

Figure 4. The interaction effect of temperature and residence time on the calorific value

The relationship between temperature and residence time with respect to calorific value is illustrated in figure 4. The elliptical contour pattern shows that there is a strong correlation between the two variables. The best results in terms of calorific values were obtained at residence time 40-50 minutes and at a temperature of 270-290°C.

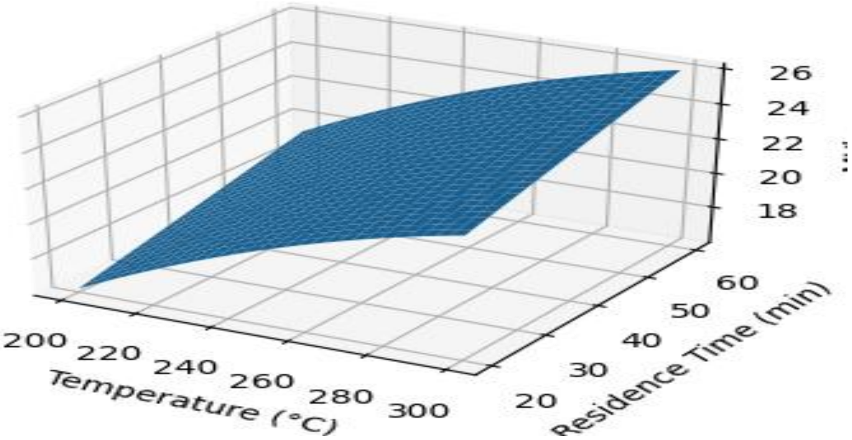

Figure 5. 3D surface plot of calorific value.

The increase in the response surface as shown in figure 5 indicated that the calorific value was increasing with the increase of the temperature and residence time until an optimum region was attained. The increase is due to progressive reactions of dehydration, devolatilization and deoxygenation that led to an increase of the carbon concentration of the biomass. According to the study of Chen et al. (2024), the oxygen-rich volatile compounds are removed during torrefaction, which results in a higher heating value and energy density of the biomass. This result supports that the coconut shell biomass is successfully upgraded to a better-quality solid fuel by the process of torrefaction, as observed from the improvement of the biomass calorific value.

3.4 Effect of Torrefaction Parameters on Mass Yield

The effect of torrefaction parameters on mass yield is discussed below. The mass yield as affected by the torrefaction parameters, precisely temperature, is shown on Figure 6

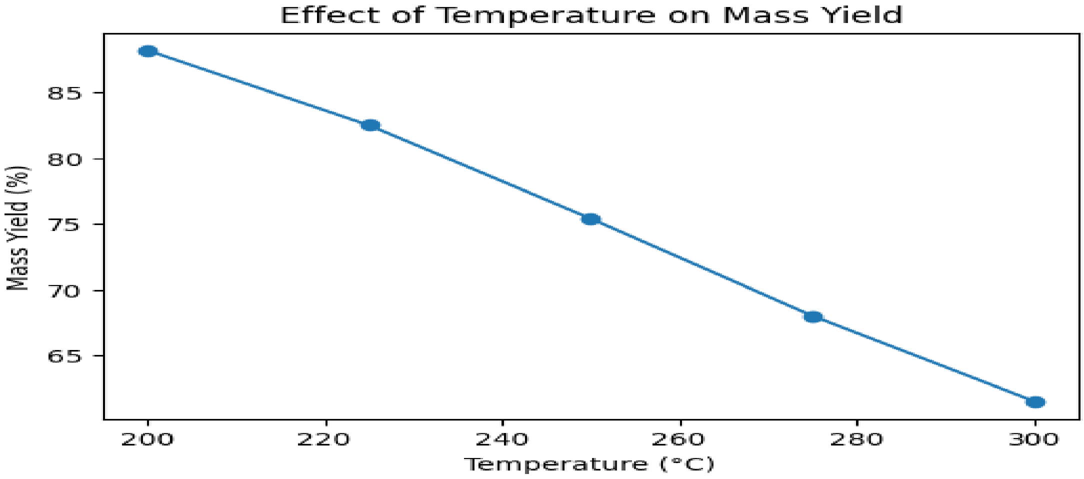

Figure 6: Effect of Torrefaction Parameters on Mass Yield

Mass yield is one of the significant parameters of biomass retention during torrefaction. The results indicated that the mass yield decreased with increase in the severity of torrefaction, from 88.2% to 61.5%.

More so, the contour plot for the effect of temperature and residence time on the mass yield is represented on Figure 7

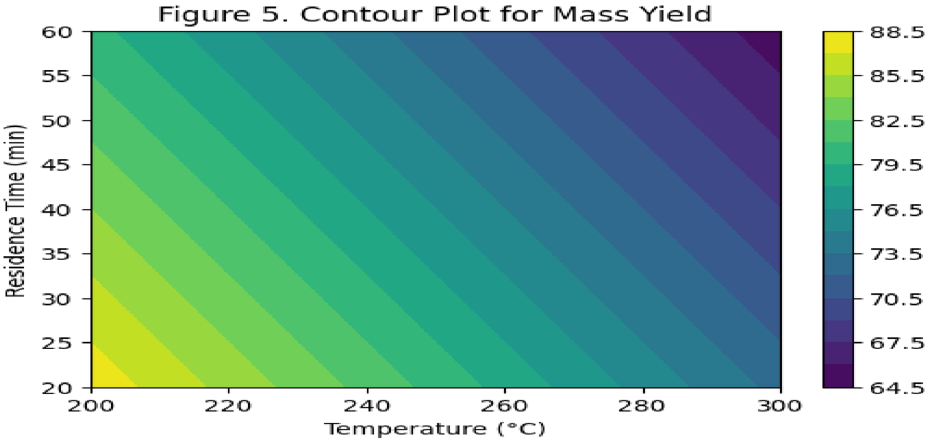

Figure 7. Contour plot of the interaction effect of the process variables on the mass yield

The effects of temperature and residence time on biomass mass retention are shown in figure 5. Increased mass yields could be achieved with higher temperatures and longer residence times because of more devolatilization and thermal decomposition. Similarly, the 3D surface plot for the mass yield is shown in Figure 8

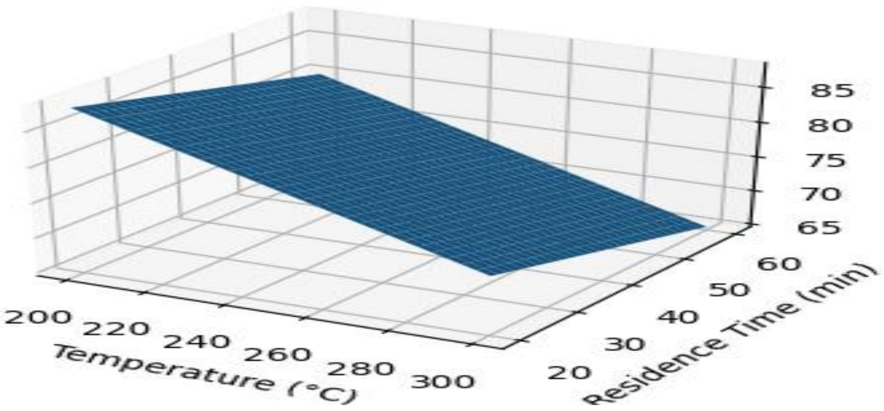

Figure 8. 3D Surface Plot of Mass Yield

The response surface in Figure 8 shows the downward trend as the torrefaction severity is increased, which is consistent with the trend of decreasing mass yield as severity increases. This behavior is to be expected as hemicellulose and parts of cellulose break down at high temperature releasing volatiles and leaving less solid material. The same results were obtained by Sarker et al. (2023). Mass yield was reduced but the fuel properties of the bio-coal was improved, suggesting a compromise between biomass retention and fuel properties improvement.

3.5 Influence of Torrefaction Parameters on Fixed Carbon

The fixed carbon content in raw coconut shell was 22.3% which increased significantly to 57.8% in torrefied bio-coal. This significant improvement is indicative of successful carbonization and improvement in fuel quality as depicted on Figure 9. The volatile compounds are removed during the torrefaction process, which is the main reason for the increase in fixed carbon. As the moisture and volatile matter content of the biomass matrix decreases, the concentration of carbon in the biomass matrix increases. The high fixed carbon content is beneficial to improve the combustion stability, burning time and energy output of solid fuel. In the study by Chen et al. (2024), it was found that the torrefaction process can enhance the carbon enrichment through the process of removing oxygenated compounds while maintaining the carbon structures. In a similar way, Rahman et al. (2023) reported higher fixed carbon contents of torrefied coconut biomass that resulted from selective degradation of hemicellulose fractions. The higher percentage of fixed carbon also indicates greater coal-like characteristics of the torrefied material which can be used for co-firing and heat recovery in industrial processes.

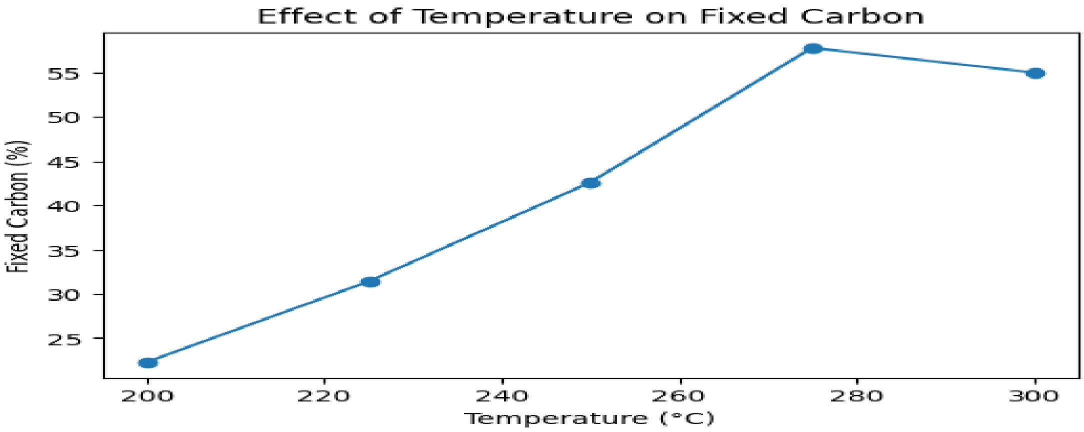

Figure 9: Effect of Temperature on Fixed Carbon

It is observed that the carbon content in the raw biomass was low (22.3%) whereas in the torrefied bio-coal was high (57.8%), which shows that there was a significant amount of carbon enrichment. Interaction of process variables on fixed carbon is also explained with the aid of contour plot

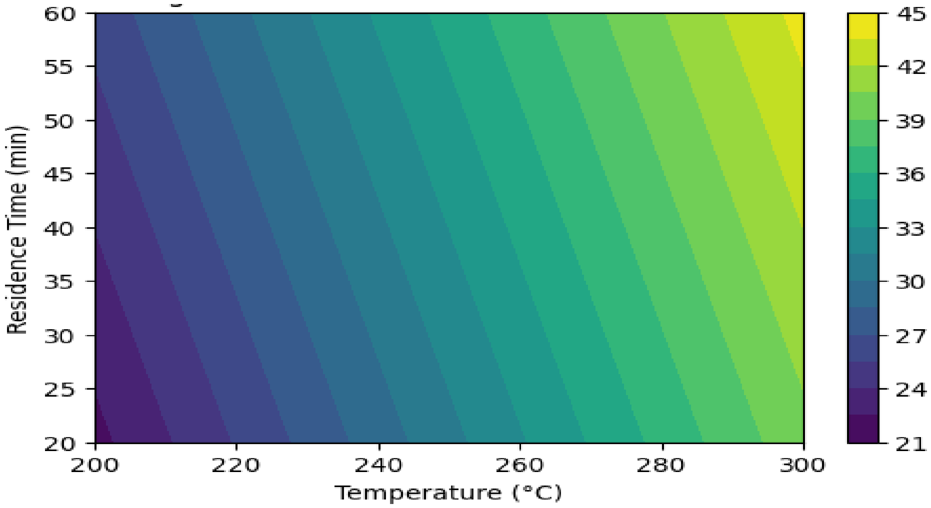

Figure 10. Contour Plot of Interaction Effect of Process Variables on Fixed Carbon Content

The contour plot in Fig. 10 shows that the residence time was less important than temperature in developing fixed carbon. The highest fixed carbon was found at high torrefaction temperatures.

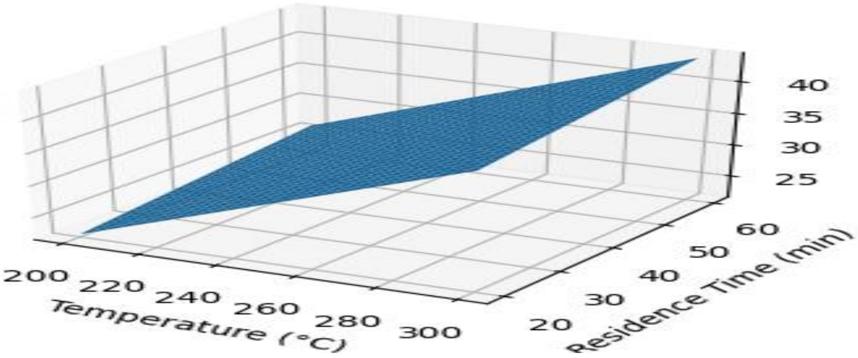

Figure 11. 3D Surface Plot, Holding the Amount of Fixed Carbon Constant

As shown in Figure 11, the increase in fixed carbon content was clearly observed with the increase of the torrefaction severity. This increase is believed to be due to the removal of moisture and volatile matter, leaving behind the carbon rich structures within the biomass matrix. In this regard, Li et al. (2024) found that biomass torrefaction also produced carbon enrichment. The higher fixed carbon improves combustion efficiency and helps to achieve coal-like properties of bio-coal.

3.6 Influence of Torrefaction Parameters on Energy Yield

The energy yield produced in the present study was between 68.4% and 89.7%. The energy yield is the energy content of the torrefied biomass after thermal treatment and is influenced by the mass yield and calorific value. The results, as shown on Figure 12, indicated that the energy yield increases with moderate torrefaction condition, as a result of the increase in calorific value offset the decrease in mass yield. At very high temperatures with long residence times, however, the energy yield was reduced because of too much biomass decomposition and loss of carbon. Similarly, Ahmed et al. (2025) concluded that the optimum torrefaction conditions must ensure the proper energy densification and solid yield retention. A high degree of torrefaction can lead to a higher calorific value, but can result in significant loss of material, which decreases the overall energy recovery. The high energy yield at optimum condition suggests the torrefied coconut shell can be used as an efficient renewable solid fuel.

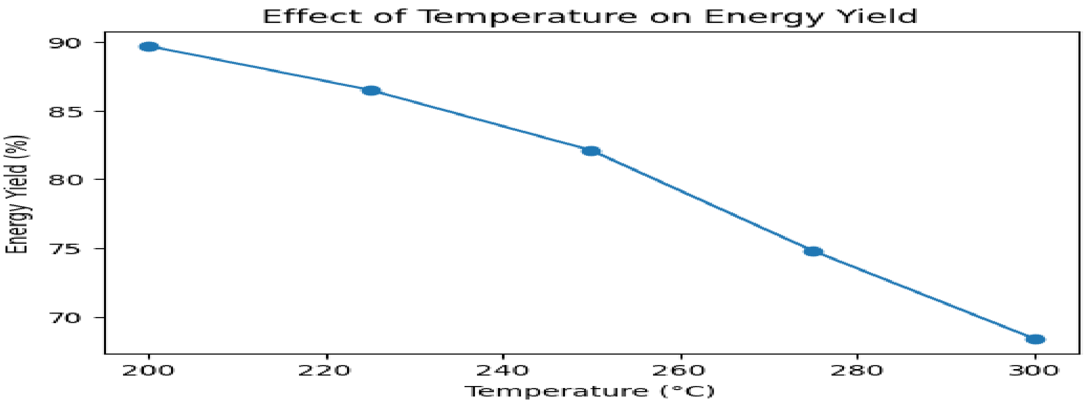

Figure 12: Effect of Temperature on Energy Yield

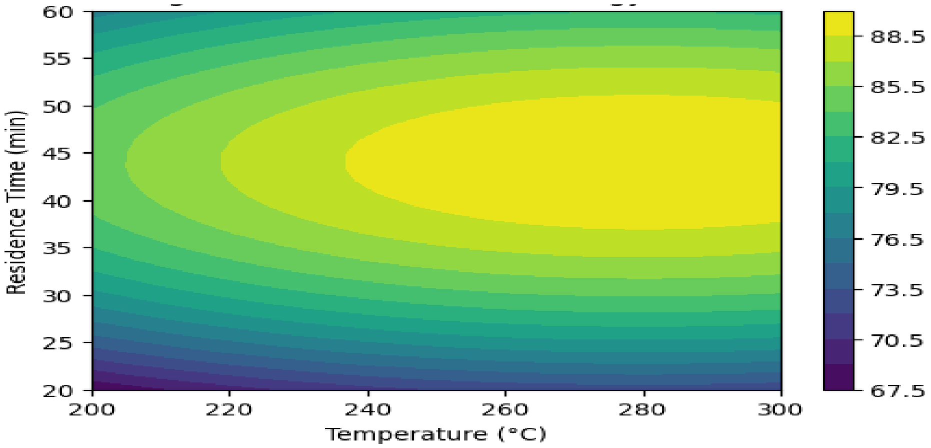

Figure 13. Contour Plot of the Interaction Effect of the Process Parameters on Energy Yield

The energy yields were higher under moderate torrefaction conditions as seen in Figure 13. The higher severity of torrefaction resulted in a decrease in energy yield since the amount of mass lost was greater than the increase in calorific value.

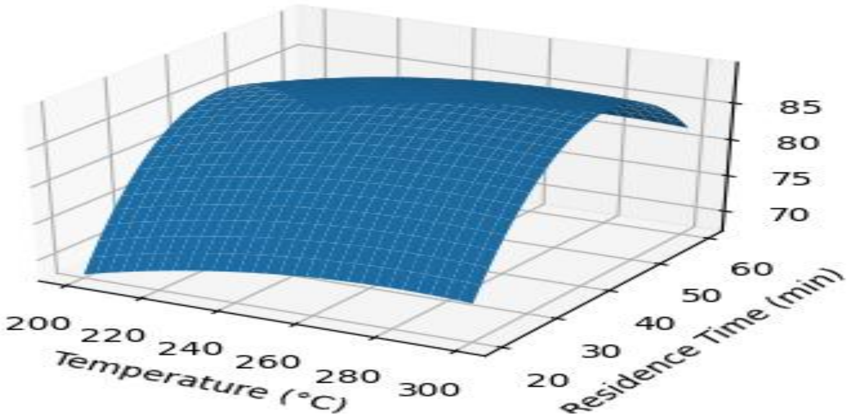

Figure 14. 3D Surface Plot of Energy Yield

The dome-shaped response surface shown in Figure 14 suggests that there is an optimum operating region where the energy densification and mass retention are balanced. During optimization of biomass torrefaction processes, Ahmed et al. (2025) found similar trends. The results show the need for careful selection of operating conditions for maximizing overall energy retention.

3.7 Model Adequacy and Variable Significance

Further, perturbation analysis was conducted to examine the effect of the process variables on the production of biocoal from coconut shell

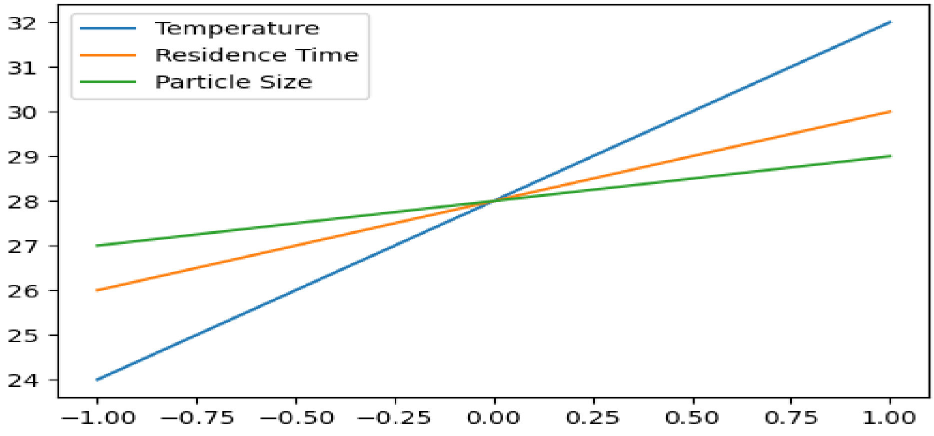

Figure 15. Perturbation Plot Showing Effect of Process Variables

Figure 15 presents a plot of the perturbation, which indicates that the temperature had the highest slope and thus had the largest influence on the responses. The residence time had a moderate effect, and the particle size had the least effect. These results are consistent with the ANOVA results and emphasize that temperature is the main parameter that affects the performance of the torrefaction process. The same finding for temperature being the most influencing parameter was reported by Oladipo et al. (2024) in thermochemical biomass conversion processes.

3.8 Optimization of Torrefaction Conditions

The last objective of the study was to find out the best condition of torrefaction to obtain good quality coconut shell bio-coal

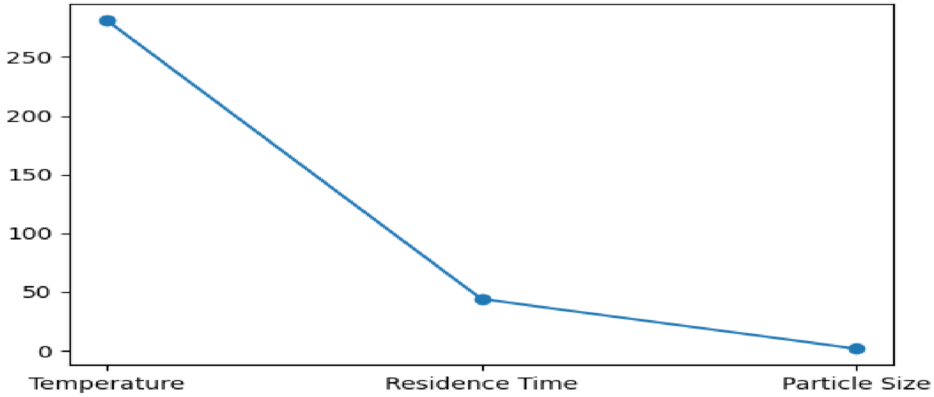

Figure 16. The Optimized Torrefaction Conditions

The numerical optimization results are shown in Figure 16, which were achieved using the desirability function approach. The best conditions were found to be the temperature of 281°C, residence time of 44 min and particle size of 1.8 mm, with the predicted calorific value, fixed carbon, mass yield and energy yield being 28.9 MJ/kg, 56.4%, 69.8% and 87.3%, respectively.

The desirability value that was calculated was nearly 1, showing that all the response variables were optimized simultaneously. Validation experiments revealed that the model developed by RSM showed less than 5% deviation between experimental and predicted values, which demonstrates the reliability and applicability of the developed RSM model.

Conclusion and Recommendations

The results of the study on the torrefied coconut biomass reveal that the torrefaction process has a great impact on the fuel and physicochemical properties of raw coconut waste, which renders it a better and more sustainable energy source. Moisture content is reduced, volatile compounds are partly driven off, and the carbon content is enriched, by thermal treatment under limited oxygen conditions. These changes result in higher energy density, better grindability, higher hydrophobicity and better calorific value of treated coconut biomass, compared to untreated coconut biomass. In general, torrefied coconut has a good potential as solid biofuel for the production of renewable energy, such as power generation, briquetting and co-firing with coal. Further studies are recommended to optimize the torrefaction process parameters including the temperature, residence time and heating rate to maximize energy yield and fuel quality of coconut biomass. A scaling up to the pilot and industrial scale should also be considered to evaluate the economic viability and the stability of the process. Furthermore, using a mixture of torrefied coconut and other agricultural residues or coal may be explored to enhance combustion efficiency and greenhouse gas emissions. Policy support and investment incentives are also encouraged to promote the use of torrefied biomass as a viable alternative energy source particularly in areas where there is abundant coconut waste.

References

Ahmed, S., Ibrahim, M., & Yusuf, A. (2025). Optimization of biomass torrefaction conditions for improved fuel properties using statistical modeling techniques. *Renewable Energy Advances, 18*(2), 145–159.

Chen, Y., Wang, T., & Li, H. (2024). Recent advances in biomass torrefaction technologies for sustainable solid fuel production. *Fuel Processing Technology*, *256*, 108112. https://doi.org/10.1016/j.fuproc.2024.108112

Li, X., Zhao, Y., & Chen, G. (2024). Production and characterization of torrefied bio-coal from lignocellulosic biomass. *Energy Conversion and Management, 312*, 118547. https://doi.org/10.1016/j.enconman.2024.118547

Oladipo, O. A., Adebayo, T. S., & Bello, M. A. (2024). Application of response surface methodology in thermochemical conversion of biomass: Recent trends and prospects. *Cleaner Engineering and Technology*, *20*, 100721. https://doi.org/10.1016/j.clet.2024.100721

Rahman, M. M., Hasan, M., & Karim, R. (2023). Characterization of coconut shell biomass for renewable energy applications. *Journal of Cleaner Production, 412*, 137396. https://doi.org/10.1016/j.jclepro.2023.137396

Sarker, M., Islam, M., & Hossain, N. (2023). Effects of torrefaction temperature on fuel properties of biomass-derived bio-coal. *Renewable and Sustainable Energy Reviews, 185*, 113610. https://doi.org/10.1016/j.rser.2023.113610