International Journal of Engineering Research and Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 22, Issue 11 (November 2026), PP 01-12

Co-Torrefaction of Sub-Bituminous Coal and Empty Palm Fruit Bunch: A Process Optimization Study Using Response Surface Methodology (RSM)

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ABSTRACT
This study investigates the co-torrefaction of sub-bituminous coal (SBC) and empty fruit bunch (EFB) biomass as a strategy for enhancing the fuel characteristics of biomass-coal blends for sustainable energy applications. A series of experiments were conducted by systematically varying the EFB mass fraction (20–80%), torrefaction temperature (200–300 °C), and residence time (20–60 minutes). The process optimization was performed using Response Surface Methodology (RSM) with a Box–Behnken design to evaluate both the individual and interactive effects of these parameters on the higher heating value (HHV) and energy yield (EY) of the resulting solid fuel. Statistical analysis revealed that torrefaction temperature exerted the most significant influence on both HHV and EY, whereas the effects of EFB proportion and residence time were comparatively less pronounced. Interaction effects among variables were minimal. The optimal torrefaction conditions—20% EFB content, 200 °C processing temperature, and 60-minute residence time—yielded a maximum HHV of 31.98 MJ/kg and an energy yield of 92.18%. Model validation through experimental data confirmed the predictive accuracy and robustness of the RSM model. The findings demonstrate the technical viability of biomass-coal co-torrefaction as a thermal pre-treatment method to improve the calorific and energy retention properties of solid fuels. This work provides a valuable framework for optimizing co-processing parameters in bioenergy applications and contributes to the advancement of cleaner and more efficient energy systems.

Date of Submission: 27-10-2026 Date of acceptance: 06-11-2026

I. INTRODUCTION

The availability and characteristics of feedstocks play a critical role in shaping global energy production dynamics. Fuel sources are broadly classified into waste-derived and non-waste-derived categories, with waste-based fuels offering greater economic and environmental benefits, particularly in emerging economies characterized by high volumes of biomass waste (Udomsirichakorn & Salam, 2014). The valorization of waste into energy carriers is therefore essential for sustainable economic development and efficient solid waste management. Ensuring sustainable energy systems is heavily dependent on the accessibility, renewability, and environmental footprint of the primary feedstocks, with more abundant and low-impact sources contributing to energy security and resilience.

Various thermochemical energy conversion pathways—such as combustion, pyrolysis, and gasification—have been developed to convert solid fuels like coal, biomass, and other carbonaceous materials into usable energy forms. Among these, gasification offers significant flexibility and can process single or blended feedstocks, enhancing synergetic effects and conversion efficiencies. Parameters such as feedstock composition, reactor design, and operating conditions critically influence the thermochemical performance of gasification systems (Udomsirichakorn & Salam, 2014). Co-gasification, a promising clean coal technology, enables the simultaneous utilization of coal and biomass, producing a synthetic gas (syngas) with a reduced environmental footprint. This integrated approach not only lowers greenhouse gas and tar emissions but also decreases operational costs, contingent on the quality and preparation of the feedstock (Chen et al., 2015).

To improve feedstock properties and overall process efficiency, pre-treatment techniques such as drying, particle size reduction, and torrefaction are employed. While raw biomass is a renewable and carbon-neutral energy source, its direct utilization is limited by inherent drawbacks, including high moisture content, low bulk density, high oxygen-to-carbon (O/C) ratio, and poor mechanical strength or grindability (Raut et al., 2016). These deficiencies often result in operational inefficiencies, including excessive tar formation during gasification, thereby elevating downstream gas cleaning requirements.

Torrefaction is a mild pyrolytic pre-treatment conducted in an inert or oxygen-deficient environment, typically within the temperature range of 200–300°C, aimed at improving the physicochemical properties of

biomass. The process enhances fuel hydrophobicity, energy density, and storage stability while decreasing the O/C and hydrogen-to-carbon (H/C) ratios. Key variables influencing torrefaction outcomes include residence time, process temperature, and feedstock blending ratios. The performance of torrefied biomass is typically evaluated using indicators such as Higher Heating Value (HHV), Energy Yield (EY), and Enhancement Factor (EF). HHV quantifies the total energy potential of the material, EY represents the ratio of energy retained in the torrefied product relative to the raw biomass, and EF provides a comparative measure of energy densification.

Numerous empirical studies have investigated the torrefaction of different biomass types under varying process conditions (Bridgeman et al., 2010; Lu et al., 2012; Ohliger et al., 2013; Wannapeera et al., 2011; Wu et al., 2012). These works consistently highlight the influence of torrefaction temperature and duration on solid yield, energy densification, and fuel reactivity. For example, Park et al. (2012), Pimchuai et al. (2010), and Chen et al. (2011) observed that elevated torrefaction temperatures tend to decrease solid yield and energy yield but enhance fuel quality, as indicated by improved HHV and EF metrics. However, most of these studies did not address process optimization or predictive model development for torrefaction.

To address this gap, researchers such as Nhuchhen and Afzal (2017) and Ozveren et al. (2017) have employed statistical and machine learning models—including Response Surface Methodology (RSM), Artificial Neural Networks (ANN), and Least Squares Regression (LSR)—to estimate the HHV of torrefied biomass. Other contributions, such as those by Bach et al. (2017) and Gul et al. (2017), have utilized LSR and process simulation tools like Aspen Plus to model torrefaction systems. However, these investigations predominantly focused on single biomass types rather than coal-biomass blends.

In a more recent advancement, García Nieto et al. (2019) proposed a hybrid modeling framework integrating Particle Swarm Optimization (PSO), Support Vector Machines (SVM), Random Forest (RF), and Multilayer Perceptron (MLP) techniques to predict HHV values. Despite achieving high predictive accuracy, their study did not extend to co-torrefied fuel mixtures. Moreover, while HHV has often been the primary performance metric in many studies, Energy Yield (EY) has received comparatively less attention, despite its significance in assessing the mass and energy balance of torrefied systems.

Given the limited number of studies addressing the simultaneous optimization of HHV and EY in coal-biomass blends, there exists a research gap in the development of comprehensive models tailored for this purpose. The present study aims to fill this gap by employing Response Surface Methodology (RSM) to identify optimal torrefaction parameters and blend compositions that maximize fuel quality and conversion efficiency. The outcomes are expected to contribute significantly to the advancement of sustainable fuel preparation technologies and support the broader deployment of clean energy systems.

II. MATERIAL AND METHODS

2.1 Materials

Feedstocks:

Sub-bituminous coal (SBC) and empty fruit bunches (EFB) of oil palm were obtained from verified local suppliers in Nigeria. The SBC was sourced from a domestic coal depot, while the EFB was collected from a palm oil processing facility.

Chemicals and Reagents:

Anhydrous calcium chloride ($CaCl_2$) and ultra-high purity nitrogen gas (99.999%) were used throughout the experiments. All chemicals employed were of analytical grade and were utilized without further purification.

Equipment and Instruments:

The torrefaction process was conducted using a programmable Carbolite MFS muffle furnace. Calorimetric measurements were performed using a bomb calorimeter, and elemental composition analyses were carried out with a Vario Micro Cube elemental analyzer. Additional laboratory tools included a precision electronic balance (±0.1 mg accuracy), desiccator, electric drying oven, and silica crucibles. For sample preparation, an MS-800R industrial shredder was employed for EFB size reduction, along with standard sieves and aluminum foil for handling and storage.

2.1 Methods

Sample Preparation

The sub-bituminous coal was pulverized using a mechanical grinder and sieved to achieve a particle size of 1 mm. The EFB was sun-dried for seven days to reduce inherent moisture, shredded using the MS-800R machine, and subsequently sieved to a uniform particle size of 3 mm.

Proximate Analysis
Proximate analysis was conducted to determine the moisture content, volatile matter, ash content, and fixed carbon content of the feedstocks. Each parameter was measured using standard procedures, and all analyses were performed in duplicate using <600 μm particle size fractions.

Ultimate Analysis
Elemental analysis was conducted using a Vario Micro Cube Elementar analyzer. Approximately 2 mg of sample was combusted at 1200 °C after helium flushing to remove atmospheric gases. The resulting gases were reduced, separated via temperature-programmed desorption, and quantified using a thermal conductivity detector. This provided precise CHNS elemental composition of the torrefied samples.

Moisture Content
Determined in accordance with ASTM E871-82. Approximately 1.00 ± 0.01 g of the sample was spread uniformly in a pre-weighed crucible and oven-dried at 105 ± 2 °C for 3 hours. The crucible was then sealed within the oven to prevent rehydration, cooled in a desiccator, and reweighed. Moisture content (%) was calculated based on the weight difference.

Volatile Matter Content
Determined using BS EN 14775:2009. Around 1.00 ± 0.01 g of sample was placed in a covered crucible and heated at 900 °C for 7 minutes in a preheated furnace. After cooling in a desiccator, the sample was reweighed. Volatile matter was expressed as the percentage weight loss on a dry basis.

Ash Content
Following ASTM E870-82, approximately 1.00 ± 0.01 g of sample was weighed into a clean crucible and pre-heated at 250 °C for 1 hour to remove volatiles. This was followed by calcination at 550 ± 10 °C for 2–3 hours. The crucible was cooled and weighed to determine ash content on a dry basis.

Fixed Carbon Content
Calculated by difference using the formula:

$$Fixed\ Carbon\ (\%) = 100 - [Moisture\ (\%) + Volatile\ Matter\ (\%) + Ash\ (\%)] \quad (1)$$

Higher Heating Value (HHV) Determination
The higher heating value (HHV) of the samples was determined via bomb calorimetry. Approximately 0.25 g of dried, homogenized sample was combusted in a high-pressure oxygen atmosphere within a sealed calorimetric chamber. The released heat was absorbed by a known mass of water, and the resulting temperature rise was recorded. The HHV (in MJ/kg) was calculated using the specific heat capacity of water and the measured thermal energy transfer. This parameter is crucial for evaluating the energy potential of biomass-based fuels.

Torrefaction Procedure
Blends of sub-bituminous coal (SBC) and empty fruit bunches (EFB) were prepared in three mass ratios: 80:20, 65:35, and 50:50 (SBC:EFB). Each mixture was homogenized thoroughly before thermal treatment.
Torrefaction was conducted in the Carbolite MFS oven at three discrete temperatures—200 °C, 250 °C, and 300 °C—across three residence times: 30, 45, and 60 minutes. For each condition, twelve pellets (weighing ~2 g each) were individually wrapped in perforated aluminum foil to enable controlled release of volatile gases while minimizing oxidative degradation. To offset initial thermal loss upon oven loading, the furnace was preheated to 20 °C above the target setpoint. Time tracking commenced once the oven returned to the designated torrefaction temperature.
Following treatment, the samples were rapidly cooled to ambient conditions (20–30 °C) under a cloth to prevent post-torrefaction oxidation or combustion. All torrefied samples were stored in airtight containers prior to subsequent analyses.

Performance Evaluation
The performance of the torrefaction process was assessed based on:

Higher Heating Value (HHV): As described above.

Energy Yield (EY):
Calculated using the formula:

$$Mass\ yield\ (MY) = \left(\frac{Mass\ of\ torrefied\ sample}{Mass\ of\ feedstock} \times 100\right)_{daf} \quad (2)$$

$$Energy\ yield\ (EY) = MY \times \left(\frac{HHV\ of\ torrefied\ sample}{HHV\ of\ feedstock} \times 100\right)_{daf} \quad (3)$$

This metric quantifies the proportion of energy retained after torrefaction relative to the original feedstock.

Statistical Analysis

The torrefaction process was optimized using Response Surface Methodology (RSM), a robust statistical and mathematical technique employed for modeling, analyzing, and optimizing processes where multiple independent variables influence one or more response variables (Kaiser et al., 2013). Specifically, a Box-Behnken Design (BBD)—a three-level, three-factor design—was selected due to its efficiency in requiring fewer experimental runs than a Central Composite Design (CCD), while still enabling the estimation of linear, interaction, and quadratic effects of the process variables. The experimental matrix comprised 17 randomized runs, including five central points to improve model accuracy and assess reproducibility. Each run was carried out in duplicate to ensure statistical reliability. The design and analysis were implemented using Design-Expert Software (Version 7, Stat-Ease, Inc., Minneapolis, MN, USA).

Three independent variables were evaluated:

A: EFB blending ratio (% w/w)

B: Torrefaction temperature (°C)

C: Residence time (minutes)

Each factor was coded at three levels: low (−1), medium (0), and high (+1), with actual and coded values provided in Table 1. The responses measured were:

Higher Heating Value (HHV, MJ/kg)

Energy Yield (EY, %)

The relationship between the independent variables and the response functions was modeled using a second-order (quadratic) polynomial regression equation of the form:

$$Y = \beta_o + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \beta_{ij} x_i x_j \quad (4)$$

Table 1: Factors, ranges and levels in BBD experiment.

Independent Variable	Symbol	Coded Level		
		-1	0	1
Temperature (°C)	A	200	250	300
Residence time (min)	B	30	45	60
EFB	C	20	35	50

where Y signifies the expected outcome (HHV of torrefied biomass and EY), β_0 represents the constant term, β_i, β_{ii}, and β_{ij} denote the coefficients for linear, quadratic, and interaction effects, respectively, and xi and x_j relate to the independent variables (EFB ratio, temperature, residence duration).

III. RESULTS AND DISCUSSIONS

3.1 Co-torrefaction properties

The proximate and ultimate analyses of SBC and EFB, as shown in Table 2, highlight significant differences in their composition. EFB exhibits a notably higher volatile matter content due to its organic nature, which aligns with findings that biomass generally contains up to 2.5 times more volatile matter than coal (Yahya et al., 2023). Conversely, EFB has a lower fixed carbon (FC) content compared to SBC, consistent with typical biomass characteristics. Since FC is directly linked to higher heating value (HHV), the reduced FC in EFB may influence its energy potential. These compositional differences suggest that SBC and EFB possess distinct fuel qualities that can impact their efficiency and suitability in thermal conversion processes.

Table 2: Proximate and ultimate analysis of sub-bituminous coal and EFB

	SBC	EFB
Proximate Analysis (wt.%, ar[a])		
Moisture	9.42	7.95
Volatile matter	36.73	83.86
Fixed carbon	42.48	10.57
Ash	9.14	5.43
HHV (MJ/kg)	25.43	19.54
Ultimate Analysis (wt.%, daf[b])		
C	76.53	49.45
H	5.67	6.74
N	1.57	0.74
O[c]	15.84	38.68

3.2 Box-Behnken design and statistical analysis

The experimental matrix was developed using a Box-Behnken Design (BBD) to systematically investigate the effects of three independent variables—EFB-to-SBC blend ratio (20–50 wt.%), torrefaction temperature (200–300 °C), and residence time (30–60 minutes)—on the Higher Heating Value (HHV) and Energy Yield (EY) of the torrefied blends, as detailed in Table 3. The results revealed that both temperature and EFB content exerted significant influence on the response variables. Notably, Run 8 yielded the highest HHV but the lowest EY, whereas Run 6 produced the lowest HHV with the highest EY, underscoring the pivotal role of thermal severity and feedstock composition in energy densification behavior.

Analysis of Variance (ANOVA), presented in Table 4, validated the statistical significance of the quadratic models for both HHV and EY, with p-values < 0.05, indicating that the models are statistically robust. For the HHV response, torrefaction temperature (Factor A) and EFB blend ratio (Factor C) were identified as the most influential parameters, contributing approximately 50.0% and 43.0%, respectively, to the total variation, while residence time (Factor B) accounted for a lesser influence (7.0%). Interestingly, temperature and EFB ratio exhibited inverse effects on HHV: temperature had a positive effect, whereas EFB content negatively influenced HHV. This implies that maximum energy densification can be achieved at elevated torrefaction temperatures and reduced biomass proportions in the blend.

In the case of EY, both linear and quadratic terms were statistically significant, particularly the linear (A) and quadratic (A^2) terms of torrefaction temperature, followed by B^2 and C^2, signifying a nonlinear relationship between the process variables and the energy yield. These results reaffirm the dominant influence of temperature, a finding consistent with existing literature. Conversely, the interaction terms (AB, AC, and BC)

were not statistically significant, indicating that the independent variables predominantly acted in isolation rather than synergistically.

The fitted quadratic models for HHV and EY (refer to Equations 21 and 22) demonstrated excellent predictive performance, with coefficients of determination (R^2) equal to 0.99, indicating that the models explained 99% of the variability in the response data. Furthermore, Pareto charts (Figure 1a–b) graphically substantiated the ANOVA findings, highlighting torrefaction temperature as the most impactful variable for both HHV and EY. The charts exhibit a classic Pareto distribution, reflecting that a limited number of critical factors—primarily temperature—account for the majority of the observed variations in response.

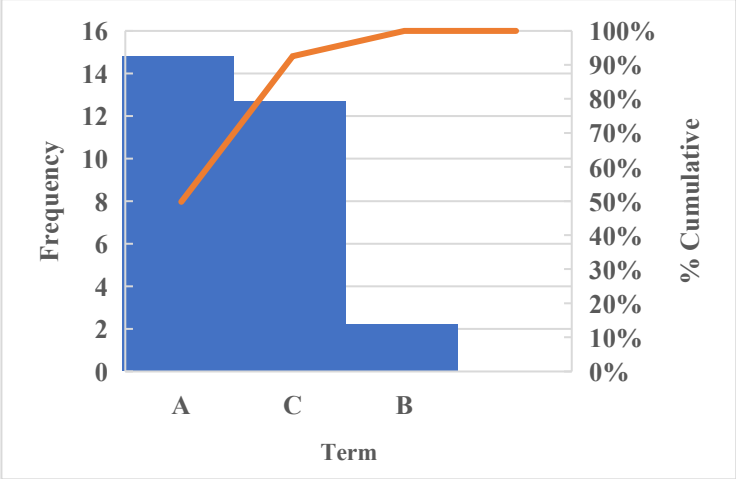
Table 3: Experimental design and responses for co-torrefaction.

Run no.	Temperature (°C)	Reaction time (min)	EFB (%)	HHV (MJ/kg)	Energy yield (%)
1	300.00	30.00	35.00	32.241	59.546
2	200.00	60.00	35.00	30.761	85.539
3	200.00	45.00	20.00	31.453	90.762
4	300.00	60.00	35.00	33.241	68.516
5	250.00	45.00	35.00	31.521	54.928
6	200.00	45.00	50.00	29.073	92.925
7	250.00	45.00	35.00	31.521	54.928
8	300.00	45.00	20.00	33.932	53.003
9	300.00	45.00	50.00	31.552	66.911
10	200.00	45.00	20.00	31.551	90.762
11	250.00	30.00	20.00	32.194	65.538
12	250.00	60.00	50.00	30.814	71.170
13	200.00	30.00	35.00	29.762	92.732
14	250.00	60.00	20.00	33.194	64.654
15	250.00	30.00	50.00	29.813	68.094
16	300.00	60.00	35.00	33.243	68.516
17	250.00	45.00	35.00	31.523	54.928

$$HHV = +19.51 + 1.23A + 0.50B - 1.20C \quad (4)$$

$$EY = +54.93 - 14.19A + 0.62B + 3.08C + 4.29AB + 3.07AC + 0.99BC + 15.29A^2 + 6.61B^2 + 5.82C^2 \quad (5)$$

(a)



(b)

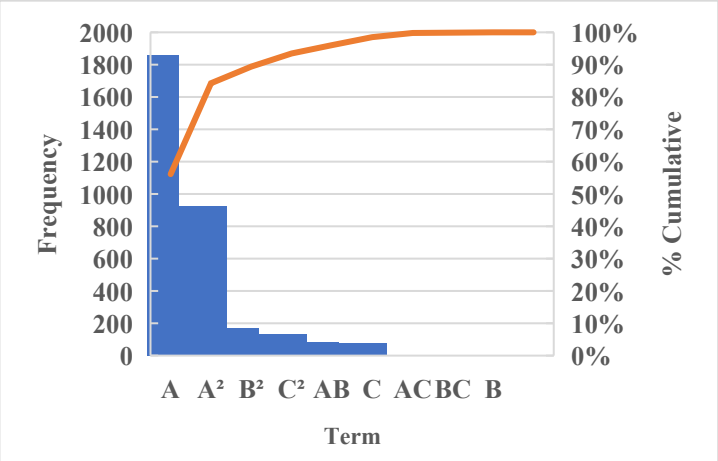


Figure 1: Pareto charts for a) HHV and b) EY.

Table 4: ANOVA results for developed model

Source	Sum of Squares	% Contribution	df	Mean Square	F Value	p-value Prob > F
HHV						
Model	28.45	100	3	9.48	16345.89	< 0.0001
A-Temperature	14.81	50.0	1	14.81	25530.02	< 0.0001
B-Reaction time	2.21	7.0	1	2.21	3812.07	< 0.0001
C-EFB ratio	12.71	43.0	1	12.71	21911.01	< 0.0001
Residual	7.542E-003		13	5.802E-004		
Lack of Fit	2.694E-003		9	2.993E-004	0.25	0.9622

Pure Error	4.849E-003		4	1.212E-003		
Cor Total	28.46		16			
EY						
Model	3251.16	100	9	361.24	81.05	< 0.0001
A-Temperature	1859.45	56.0	1	1859.45	417.21	< 0.0001
B-Reaction time	3.30	0.10	1	3.30	0.74	0.4183
C-EFB ratio	81.52	3.0	1	81.52	18.29	0.0037
AB	85.76	3.1	1	85.76	19.24	0.0032
AC	44.05	1.0	1	44.05	9.88	0.0163
BC	3.92	0.1	1	3.92	0.88	0.3795
A^2	928.59	27.8	1	928.59	208.35	< 0.0001
B^2	172.12	5.0	1	172.12	38.62	0.0004
C^2	133.34	4.0	1	133.34	29.92	0.0009
Residual	31.20		7	4.46		
Lack of Fit	31.20		3	10.40		
Pure Error	0.000		4	0.000		
Cor Total	3282.36		16			

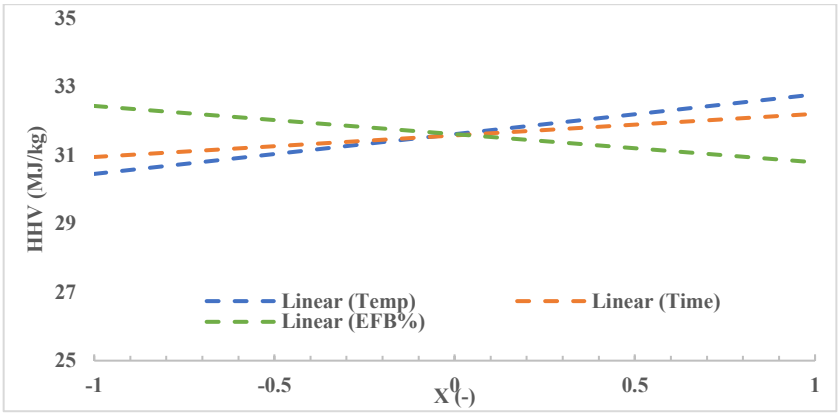
3.3 Effect of independent parameters on co-torrefaction

The main effects of torrefaction temperature, residence time, and EFB blending ratio on the Higher Heating Value (HHV) and Energy Yield (EY) were analyzed by plotting the average response values across the three coded levels of each variable, as shown in Figures 2a and 2b. These main effect plots provided valuable visual insights into the individual (linear) influence of each factor, with the slope of each response curve indicating the relative strength and direction of influence. In Figure 2a, both EFB content and temperature demonstrated significant but opposing effects on HHV. An increase in EFB ratio correlated positively with HHV, while a rise in temperature exhibited a negative correlation. This inverse trend is consistent with the ANOVA results (Table 4) and the regression coefficients in Equation (4). According to the literature (Chen et al., 2021b), elevated torrefaction temperatures facilitate thermal degradation of biomass, leading to the removal of hydrogen, oxygen, and volatile matter, thereby enriching the carbon content and increasing HHV. However, in the present study, the high-temperature conditions were found to reduce HHV, likely due to excessive devolatilization and loss of combustible matter, particularly in biomass-rich blends.

Residence time, on the other hand, exhibited a minimal effect on HHV, as evidenced by the nearly flat slope in Figure 2a and its statistically insignificant contribution in the ANOVA results. Additionally, a decrease in EFB content—implying a higher proportion of sub-bituminous coal (SBC)—resulted in elevated HHV values, which aligns with the known higher calorific value of coal compared to biomass. The slope analysis thereby confirmed EFB ratio and temperature as the dominant factors influencing HHV. In contrast, Figure 2b revealed temperature as the most significant variable influencing EY. The steep negative slope indicated that increased torrefaction temperature led to substantial mass loss due to the volatilization of light organics, thereby reducing the energy yield. This outcome is consistent with the second-order regression model (Equation 5) and the ANOVA findings, both of which identified temperature (both its linear and quadratic components) as the most statistically significant predictor of EY. The EFB ratio and residence time exerted negligible effects, as reflected by their nearly horizontal slopes in Figure 2b.

These observations affirm that torrefaction temperature is the primary operational parameter governing both the energy content (HHV) and energy retention (EY) of the torrefied material. Process optimization should therefore prioritize the careful modulation of temperature to balance energy densification with material preservation.

(a)



(b)

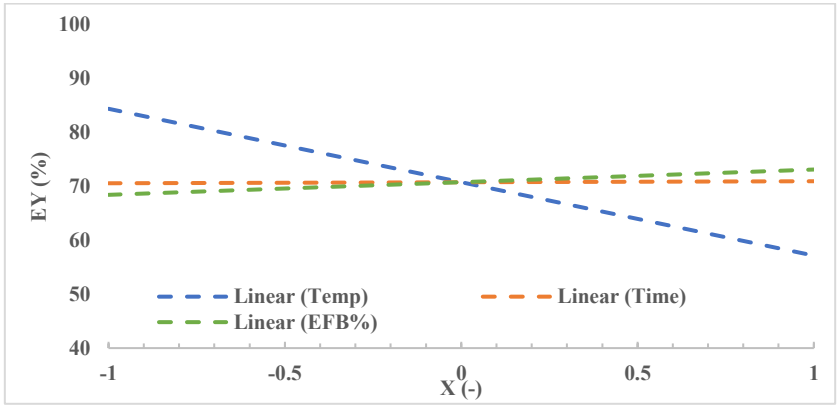


Figure 2: Effect plots of variables for a) HHV and b) EY.

3.4 Optimum conditions

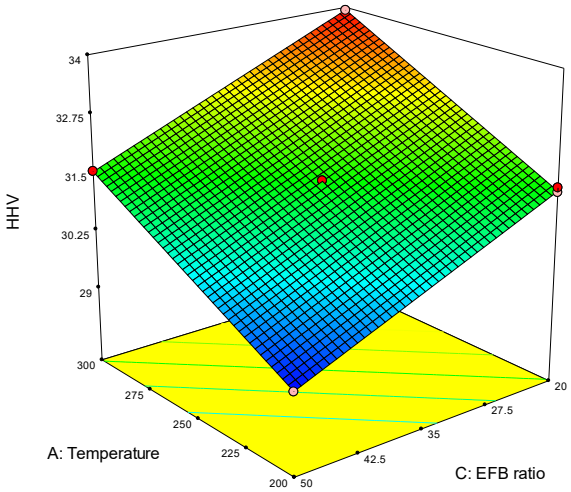
The 3D contour plots, illustrated in Figure 3a-b, revealed that decreasing the EFB content and increasing the torrefaction temperature significantly improved HHV. This trend is attributed to the higher proportion of sub-bituminous coal (SBC) and enhanced devolatilization, which increases fixed carbon content. These findings are consistent with previous studies by Ozonoh et al. (2020) and Seithtanabutara et al. (2023), and align with the impact analysis shown in Figure 1a-b and Table 4.

While HHV increased with temperature, EY was influenced by both HHV and mass yield. As reported in literature (e.g., Martín-Lara et al., 2017), excessive devolatilization at high temperatures reduced mass yield, which in turn diminished EY despite the higher energy density. The optimal performance was achieved by balancing these two metrics—favoring a low EFB ratio and high temperature to maximize both calorific value and retained energy content. Model predictions identified the optimal torrefaction conditions as: 20% EFB ratio, 200 °C, and 60 minutes residence time. Under these settings, the predicted HHV and EY were 31.98 MJ/kg and 92.18%, respectively, with a desirability score of 0.766. Experimental validation, conducted in triplicate, confirmed model accuracy, with deviations between predicted and actual values ranging from 3.54% to 3.63%, as summarized in Table 5.

Table 5: Predicted and experimental results for optimum conditions.

	HHV(MJ/kg)	EY (%)
Experiment	30.86	89.03
Prediction	31.98	92.18
Deviation (%)	3.63	3.54

(a)



(b)

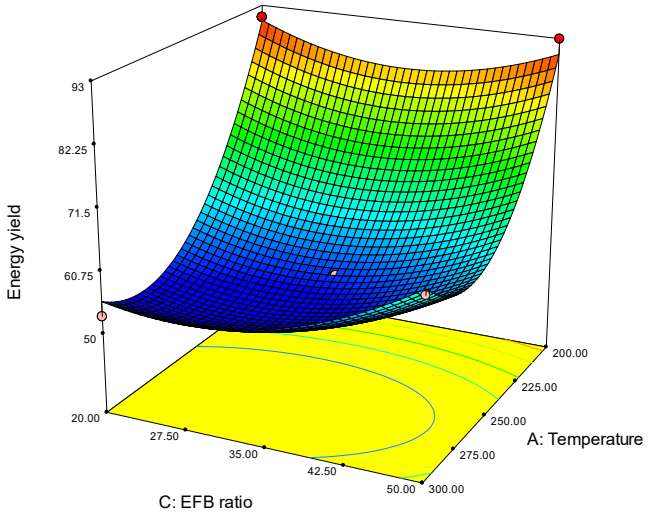


Figure 3: 3D contour plots of HHV and EY with EFB ratio (A), and temperature (B).

IV. DISCUSSION AND CONCLUSION

This study successfully optimized the co-torrefaction of sub-bituminous coal (SBC) and empty fruit bunch (EFB) using the Box-Behnken Design (BBD) under the framework of Response Surface Methodology (RSM). The approach enabled the identification of optimal conditions to maximize Higher Heating Value (HHV) and Energy Yield (EY). The resulting regression models demonstrated strong predictive capability, as indicated by high R^2 values, confirming a reliable fit with the experimental data. Temperature was identified as the most influential factor, significantly affecting both HHV and EY. Optimal performance—HHV of 31.98 MJ/kg and EY of 92.18%—was achieved at 20% EFB ratio, 200 °C, and 60 minutes residence time. Experimental validation closely matched model predictions, reinforcing the accuracy and robustness of the optimization models. These findings hold practical relevance for thermal pretreatment strategies in co-firing and co-gasification, offering valuable insights for enhancing the energy potential of biomass-coal blends across various industrial applications.

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Appendix I

$$\%MC = \left(\frac{initial\ mass\ of\ sample - final\ mass\ of\ sample}{initial\ mass\ of\ sample}\right) \times 100$$

$$\%MC = \left(\frac{initial\ mass\ of\ sample - final\ mass\ of\ sample}{final\ \ mass\ of\ sample}\right) \times 100$$

$$\%Ash = \frac{mass\ of\ residue}{initial\ mass\ of\ sample} \times 100$$

$$Total\ weight\ loss\ of\ moist\ biomass\ = Weight\ loss\ due\ to\ Volatile\ matter\ + Moisture$$

$$Weight\ loss\ due\ to\ VM\ = Total\ weight\ loss\ - Moisture$$

$$\%VM = \frac{mass\ loss\ due\ to\ VM}{initial\ dry\ mass\ of\ sample} \times 100$$

$$FC = 100 - (\%MC + \%VM + \%Ash)$$

$$\%Element = \frac{measured,wt\%element}{100-ash,wt\%-\%Ash} \times 100$$

$$\%O = 100 - (\%C + \%H + \%N + \%S + \%Ash)$$

$$Mass\ yield\ (MY) = \left(\frac{Mass\ of\ torrefied\ sample}{Mass\ of\ feedstock} \times 100\right)_{daf}$$

$$Energy\ yield\ (EY) = MY \times \left(\frac{HHV\ of\ torrefied\ sample}{HHV\ of\ feedstock} \times 100\right)_{daf}$$