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Use of Response Surface Methodology to Measure the Impact of Operating Variables on the Co-gasification of Oil Palm Biomass

Hadiza Aminu Umar[1,2,*], Shaharin Anwar Sulaiman[1], Mior Azmanbn Meor Said[1], Afsin Gungor[3], Rabi Kabir Ahmad[1]

[1] Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia

[2] Department of Mechanical Engineering, Bayero University, Kano, Nigeria

[3] Department of Mechanical Engineering, Akdeniz University, Antalya, Turkey

Abstract: Co-gasification of biomass is a thermochemical technique for harnessing the chemical energy of biomass in order to produce low carbon energy. In this study, co-gasification of oil palm trunks and fronds was carried out to examine the effects of particle size, blending ratio, and temperature using a downdraft gasifier in the presence of air as the medium. Response surface methodology (RSM) was used to optimize syngas (H_2+CO) and methane (CH_4) yield from the combined effects of particle size, blending ratio, and temperature using the Box-Behnken design (BBD). A temperature range of 700–900ºC, a blending ratio of 20–80% wt., and a biomass particle size of 1.18–4mm were used. The results indicate that temperature had the greatest influence on syngas yield, followed by particle size and then blending ratio. The optimum input parameters were as follows: temperature of 900 ºC, blending ratio of 50/50% wt., and particle size of 2.59 mm. These parameters resulted in optimum yields of 48.60% volume of syngas and 17.1% volume of methane.

Keywords: co-gasification, optimisation, oil palm trunk, syngas, methane.

使用响应面方法来测量操作变量对油棕生物质共气化的影响

摘要：生物质的共气化是利用生物质的化学能以产生低碳能的热化学技术。在这项研究中，进行了油棕树干和叶状体的共气化，以在空气为介质的情况下，使用向下气流式气化炉检查粒径，混合比和温度的影响。使用盒子-贝肯设计（生物多样性公约），使用了响应面方法（RSM）从粒径，混合比和温度的综合影响中优化了合成气（氢气+一氧化碳）和甲烷（通道 4）的产率。使用温度范围为 700–900 摄氏，混合比例为 20–80％重量。，生物质粒径为 1.18–4 毫米。结果表明，温度对合成气收率的影响最大，其次是颗粒大小，然后是混合比。最佳输入参数如下：温度为 900 摄氏，混合比为 50/50％重量。，颗粒尺寸为 2.59 毫米。这些参数导致了 48.60％体积的合成气和 17.1％体积的甲烷的最佳收率。

关键词：共气化，优化，油棕树干，合成气，甲烷。

1. Introduction

The overdependence on fossil fuels, rapid population boom, industrialization, and the need to modernize living conditions have pushed the world into a search for renewable, affordable clean energy [1]. Biomass, which can be harnessed through gasification, is a promising source of this energy. Gasification is a thermochemical process that involves the conversion of carbonaceous fuels to gases through the application of elevated temperatures (700–1,000 °C) within a

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About the authors: Hadiza Aminu Umar, Department of Mechanical Engineering, Universiti Teknologi PETRONAS, Seri Iskandar, Malaysia; Department of Mechanical Engineering, Bayero University, Kano, Nigeria; Shaharin Anwar Sulaiman, Mior Azmanbn Meor Said, Department of Mechanical Engineering, Universiti Teknologi PETRONAS, Seri Iskandar, Malaysia; Afsin Gungor, Department of Mechanical Engineering, Akdeniz University, Antalya, Turkey; Rabi Kabir Ahmad, Department of Mechanical Engineering, Universiti Teknologi PETRONAS, Seri Iskandar, Malaysia

controlled amount of an oxidizing agent to produce syngas. Co-gasification involves the gasification of more than one feedstock at a time in a single gasifier. It is conducted to harness the synergistic effect that may exist between the feedstocks, thereby improving the yield. It eliminates the problem of disrupted feedstock supply due to seasonal availability and natural disasters like rain, flood, and drought conditions. It is also an effective way for several researchers to obtain syngas from other biomass types. Most importantly, it avoids process breakdown by providing additional resource alternatives, and it prevents storage challenges and high conveyance costs. Malaysia is endowed with abundant biomass, and palm oil provides one of the most abundant sources. The country is among the top producers of palm oil, which presents a chance to utilize palm oil biomass for clean energy [2]. Biomass sources include oil palm trunks (OPT) and oil palm fronds (OPF), both of which are forms of plantation waste. Empty fruit bunches (EFB), palm kernel shells (PKS), and mesocarp fibers (MF) from industrial waste provide additional sources. Research has shown that most of these palm biomass sources have been used in gasification and co-gasification studies [3],[4],[5],[6]; however, OPT is scarcely used. It is often perceived as incapable of undergoing thermochemical reactions. Therefore, its potential in co-gasification studies is quite unclear in terms of its syngas and methane yield. In addition, there are no previous studies on its yield optimization. Conducting such a study will fill the gap and clear up the uncertainties surrounding OPT co-gasification performance.

1.1. Literature Review

Most co-gasification studies have been conducted with different biomass types for which different parameters have been studied. Peng et al. [7] co-gasified wet sewage sludge (WSS) and forestry waste (FW) blends and found that altering the blending ratio increased the gas yields. Seggiani et al. [8] co-gasified sewage sludge with wood pellets in an updraft gasifier and discovered that less sewage sludge was needed in the blending ratio and that slagging and clinker were formed as the level of sewage sludge increased. Xiao et al. [9]used pig droppings and wood cutlets in their investigation and reported that operating variables influenced producer gas yield. Sewage waste was co-gasified with woody biomass, producing syngas with a calorific value of 4.5 MJ/Nm3 and a gas volume of 30% [10]. Kaewpanha et al. [11] ascertained the influence of a catalyst containing alkali and alkali earth metals in yielding remarkable syngas with high contents of hydrogen and carbon monoxide during gasification of Japanese cedar and seaweed. In a simulation study, Buragohain et al. [12] emphasized the importance of blending ratio and temperature in obtaining high carbon monoxide (CO) content and lower heating values. Aigner et al. [13] confirmed that high temperature was more effective in tar reduction than blending ratio changes.

Optimization of input parameters to improve responses is a top priority in processing industries; likewise, optimization of co-gasification enhances producer gas. The response surface methodology (RSM) has also been used by several researchers to optimize co-gasification processes. Using the RSM, Fermoso et al. [14], investigated the effects of temperature, O_2 levels, and steam concentration on hydrogen, carbon monoxide, and syngas production, hydrogen-to-carbon monoxide ratio, and cold gas and carbon conversion efficiency. The results indicate that temperature was the most important variable. Yusup et al. [15] also used RSM to investigate the effects of temperature, biomass particle size, steam to biomass ratio, adsorbent to biomass ratio (A/B), and superficial velocity on H_2 volumetric content and yield. In terms of the H_2 volumetric content, the A/B was the most influential factor, whereas temperature and particle size were marginally significant. The factors affecting H_2 yield were as follows (from most to least significant): temperature, biomass to mass ratio, A/B, and biomass particle size. Hou et al. [16] used RSM in combination with Taguchi to investigate the effects of oxygen to coal ratio (O/C), pressure (P), and stream to coal (S/C) ratio on syngas fraction. The O/C had the highest influence, whereas P had no effect, and S/C had a slight effect on the syngas fraction. Nam et al. [17] studied the role of temperature, modified equivalent ratio, and O_2 content on gasification products. The authors combined the Box-Behnken design (BBD) and central composite design (CCD) for optimization and reported the strength of influencing factors in the following order: temperature > oxygen concentration > equivalent ratio. Silva et al. [18] gasified forest residues and used RSM to optimize the syngas yield and gas efficiency. H_2 yield was found to improve with steam–to-biomass ratio; however, it decreased with more O_2. It was further observed that alternating the operating variables will reduce costs without compromising the gas yield and efficiency of the system.

The reported literature shows that there is limited usage of palm wastes in cogasification studies. Furthermore, there are few reports of studies on the role of input variables and their mutual effects on syngas and methane through the use of response-surface methodology -based (RSM) design and analysis of variance (ANOVA analysis). This work aimed to study the production of syngas and methane during co-gasification of OPT and OPF. The mutual interaction effect of the temperature, blending ratio and particle size was explored via RSM and Box Behnken design (BBD). The input variables were optimised for maximum syngas and methane gas yield. Based on the authors' knowledge, such investigation has not been covered in the published literature. There exists a wide gap in the study of oil palm trunk biomass, especially in the field of thermochemical conversion.

2. Materials and Methods

2.1. Feedstock Collection, Preparation and Characterization

OPF and OPF were the feedstock used for the research work. The raw biomass was sourced from a nearby plantation Federal Land Consolidation and Rehabilitation Authority (FELCRA) that specializes in oil palm cultivation, situated in Seri Iskandar Perak, Malaysia. The size of feedstock was reduced and sun-dried for a period of seven consecutive days. Further drying was achieved in the oven to remove extra moisture at a temperature of 105°C for 24hrs. Both feedstocks were later granulated, and some of the granulated samples were further grounded to a very fine texture and sieved to 250 µm for the purpose of physicochemical analyses. Leco CHNS-932 model analyser was utilised in carrying out the ultimate analysis, in accordance with ASTM D3176-09[19] standard. Proximate analysis was conducted using a LABSYS EVO analyser, as per ASTM E1755-01 procedure [20]. The heating value was determined with an Ac-350 bomb calorimeter to determine the higher heating value according to D4809-00 [21]. Moisture content was also determined according to ASTM E871-82 standard procedure [22]. Table 1 gives the proximate analysis and calorific values, while Table 2 gives the ultimate analysis of the feedstock. Feedstock characterization is an essential step in the gasification process, as the results obtained reveal the chemical composition, and help to determine the efficiency and calorific value of the fuel. The remaining granulated samples were then sieved to three different sizes of 1.18, 2.59 and 4 mm. Samples were mixed mechanically to form blends in preparation for the co-gasification experiments. Homogeneity of the blends was ensured by mixing the same sizes together, and weight proportion corresponded with the blending ratio. The blends used for the study were OPT20:OPF80, OPT50:OPT50, and OPT80:OPF20.

Table 1 Proximate analysis and calorific value of the fuel blends

Analyses	**OPT20: OPF80**	**OPT50: OPT50**	**OPT80: OPF20**
Proximate (wt.%)			
MC	3.06	2.85	2.64
FC	25.78	25.93	26.08
VM	65.34	64.19	63.04
ASH	7.02	8.07	9.12
Calorific Value			
HHV (MJ/kg)	17.47	17.44	17.42

Table 2 Ultimate analysis of the fuel blends

Ultimate Analysis (wt. %)	**OPT20: OPF80**	**OPT50:OPT50**	**OPT80: OPF20**
C	45.01	44.39	43.76
H	6.33	6.31	6.28
N	0.53	0.62	0.7
S	0.19	0.29	0.39
O	47.94	48.41	48.87

2.2. Experimental Design

The experimental matrix was developed by using Box-Behnken Design (BBD) technique of Response Surface Methodology (RSM), using Stat-Ease Design Expert 11® software. The application of RSM helps to avoid large number of experiments that are done based on one factor at a time. It aids in generating 3-dimensional graphs that show the interaction between operating variables and the responses. The RSM in conjunction with BBD was utilized to fully understand the mutual reaction between the operating variables (input parameter) and the response (output parameter). It also predicts the optimum variables that will generate the desired responses (results). The advantage of BBD is that it does not give experimental runs beyond the limit boundaries and also does not combine factors of the same levels at once [23]. The input variables for this study are temperature (A), blending ratio (B), and particle size (C) of three different levels. Table 3 presents the ranges of the operating variables, which include 700-900ºC, blending ratio 20-80%, and particle size 1.18-4mm. The effect of these input variables on the responses syngas ($CO+H_2$) and methane are shown in Table 4. The experimental levels were selected based on experimental setup limitations, literature, and preliminary experimental results [24]. A total of seventeen runs were generated from a 3factor-3level Box Behnken factorial design. Among the total runs, five, which represented the central point, were replicated to assess errors resulting from the experiments.

Table 3 Levels of operating parameters used for the Box Behnken Design (BBD)

Parameters	**Symbol**	**Levels**		
	Coded	**-1(Low)**	**0 (Medium)**	**+1 (High)**
Temperature (ºC)	A	700	800	900
Blending ratio (wt %)	B	OPT20:80 OPF	OPT50:50OP F	OPT80:20OPF
Particle size(mm)	C	1.18	2.59	4

Table 4 Experimental plan showing obtained results base on BBD

Std.	**Run**	**Tempt ºC**	**Blending Ratio (wt.%)**	**Particle size (mm)**	**Syngas ($CO+H_2$) (vol.%)**	**CH_4 (vol.%)**
1	1	800	OPT50: OPF50	2.59	43	17
4	2	800	OPT50: OPF50	2.59	35	16
11	3	800	OPT50: OPF50	2.59	36	14

7	4	900	OPT50: OPF50	4.00	38	07
10	5	700	OPT50: OPF50	1.18	18	04
6	6	900	OPT20: OPF80	2.59	44	13
9	7	900	OPT80: OPF20	2.59	47	11
3	8	700	OPT20: OPF 80	2.59	21	05
14	9	900	OPT50: OPF50	1.18	38	14
15	10	700	OPT80: OPF20	2.59	23	05
2	11	700	OPT50: OPF50	4.00	24	06
8	12	800	OPT80: OPF20	1.18	20	03
16	13	800	OPT20: OPF80	4.00	24	03
12	14	800	OPT20: OPF80	1.18	23	04
5	15	800	OPT50: OPF50	2.59	37	14
17	16	800	OPT80: OPF20	4.00	20	02
13	17	800	OPT50: OPF50	2.59	36	14

2.3. Co-Gasification Facility and Operational Method

The facility utilized for the current work is shown in Figure 1. An electrically heated gasifier with a dow-draft configuration was utilized to carry out the co-gasification experiment. Attached to the gasifier is a PID microcontroller used for setting and controlling the temperature. An air compressor, controlled through a rotameter, is also connected to the setup for air supply. The experiment starts by connecting the gasifier, air compressor, and PID microcontroller to the main power supply. The temperature of the gasifier is gradually set stepwise until the required temperature is attained. Meanwhile, the required air amount of 2.5 L/min is supplied to the gasifier. As soon as the required temperature is attained, the gasifier top lid is opened, the premixed biomass is quickly poured, and the lid is closed.

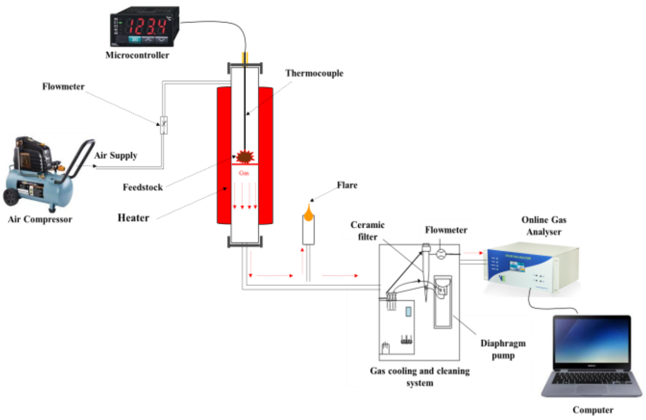


Fig. 1 Equipment utilized for OPF/OPT blend co-gasification

After a few seconds, the generated gas travels through the connecting pipe to the gas cooling and cleaning system. The produced gas temperature is lowered and particulates removed before being admitted into the gas analyzer. The analyzed gas is displayed on the computer monitor, connected to the analyzer via LAN intranet cable. Readings were automatically recorded every second and saved. The gasifier was turned off and left to cool down to collect char and ashes.

2.4. Response Variable Analysis

This study intended to generate maximum syngas ($CO+H_2$) and CH_4 as combustible gases for power production from the co-gasification process. Hence optimization of the response variables was conducted to maximize the yields of the combustible gases.

2.5. Statistical Analysis

The statistical tool used for this analysis is the analysis of variance referred to as ANOVA. The ANOVA was used to define the results of the interaction of the variables amongst themselves and their effect on the responses. Three tests were used for the analysis: lack of fit test, regression model, and significance of terms. They assist in evaluating the significance and reliability of a model. Probability values of P and F control the significance of terms. The P-value determines how close the results are to actual experimental results, thus indicating significance, and is required to be $P \leq 0.05$ (confidence level 95%). On the contrary, the F-value is required to be higher, and it examines the variables across and within the model. Hence lower P-value and higher F value are determinants of a good model. The lack of fit aids in evaluating the effects of operating parameters on the response variables [25]. It stands for the difference between calculated and anticipated values, which involves systematic error [26]. For an acceptable model, it is required to have a non-significant lack of fit.

The regression model (R^2) measures the accuracy of experimental results and lies between zero and unity. The more the value is nearer to unity, the more accurate the model is. The term Adj-R^2 measures the predicted data variation. The difference between Adj-R^2 and Predicted R^2 is the referee of the model that should be ≤ 0.2 [26]. A great difference between Adj-R^2 and Predicted R^2 occurs from non-significant model terms. An interesting characteristic of ANOVA is the generation of 3-D graphs, which display the interaction of variables and the corresponding effects on the responses. The graphs help in analyzing the responses of points that were not conducted experimentally [15].

3. Results

3.1. Biomass Characterization

The results of the proximate analysis were shown in Table 1. Such analysis provides the contents of fixed carbon (FC), whose high amount is required for making biochar. Also, it gives the volatile matter, which is very important in terms of gas generation. Others obtained from the proximate analysis are ash and moisture content (MC) of the fuel. The feedstock's moisture content was between 2.85-3.06%. All the moisture content was within the agreeable range (15-20%) for a successful gasification process. Moisture content >30% is not desired as it lowers the oxidation zone temperature, thereby affecting the syngas quality and process performance. Generally, biomass has high VM and low FC, as shown in the results. All the feedstocks have exhibited high VM content of more than 60% with FC less than 30%; high VM is required for high syngas yield while moderate FC is required for hot char provision to sustain the gasification process. Too much FC may hinder syngas yield due to difficulty in conversion, while too little may not sustain the gasification process. The highest VM content was seen in OPT20:OPF80 (65.34 wt.%), followed by OPT50:OPT50 and OPT80:OPF20. The highest FC was seen in OPT50:OPF50 (25.93 wt.%), followed by OPT20:OPF80and OPT80:OPF20. The ash content in biomass is required to be low as it minimizes the frequency of ash removal, slagging, and fouling problems, which is an indication of high-quality fuel. All the feedstocks in the current study had low ash content, with OPT20:OPF80 having the lowest 7.02 wt. % followed by OPT50:OPT50 and OPT80:OPF20. The heating value of a feedstock is equivalent to the heat energy dissipated during its combustion. Therefore, the more a fuel's heating value, the more its energy dissipation tendency during thermo-conversion. That is the reason why fuels with high calorific value are preferred in thermochemical conversion procedures.The calorific value of biomass usually lies within 15-20 MJ/kg, and all the results obtained in this study fall within the range. The results obtained from the ultimate analyses of OPT and OPF, on weight % on a dry basis, are shown in Table 2. On a general note, the elemental compositions of all the feedstock were almost the same. The similarity may be due to their origin from the same parent plant. The carbon content of the biomass from the current study ranged from 43-45 wt. %. The carbon content of OPT20:OPF80was the highest (45.01 wt.%) compared to OPT50:OPT50 (44.39 wt.%) and OPT80:OPF20 (43.76 wt.%). Compared to hydrogen content, the higher percentage of carbon content led to an increment in the calorific value resulting from higher energy of the C-C bond compared to the C-H bond. The high carbon content of samples indicates their good potential as a gasification fuel, as it aids char formation during volatilization reaction. The proportion of nitrogen and sulfur in the biomass is also an essential factor during the gasification reaction. These elements tend to react with oxygen at elevated temperatures to form NOx and SOx, which are toxic to both the environment and thermal plants. As such, a lower proportion of nitrogen and sulfur is required for fuel to be environmentally friendly. In the tested samples, the nitrogen and sulfur levels were low between 0.5-0.7 wt. % and 0.19-0.39 wt. % respectively.

3.2. ANOVA Analysis and Regression Equation Development

A statistical relationship was obtained from the RSM and BBD technique, which is a combination of the process variables (temperature, particle size, and blending ratio) to develop a statistical relationship in the form of an equation. The result showed that the quadratic model was the best fit for the experimental data. Similarly, other researchers reported the same case for regression analysis on gasification experiments [1, 15, 25, 26]. The model equations aid in predicting the response of the given levels of the variables and in determining the corresponding influence of the factors by examining their coefficients. They depict the relationship between the input factors and their interactive effect on the responses. The regression analysis developed a second-order polynomial equation for syngas and methane.

$$Syngas\ (CO + H_2) = 17.52892 - 0.203363 \times TEMPT + 0.573641 \times BR + 35.35147 \times PS + 0.000083 \times TEMPT \times BR - 0.010638 \times TEMPT \times PS - 0.005910 \times BR \times PS + 0.000205 \times TEMPT^2 - 0.006333 \times BR^2 - 5.00478 \times PS^2 \quad (1)$$

$$CH_4 = -140.42495 + 0.220913 \times TEMPT + 0.741667 \times BR + 28.75547 \times PS - 0.000167 \times TEMPT \times BR - 0.015957 \times TEMPT \times PS + 1.13760E - 16BR \times PS - 0.000088 \times TEMPT^2 - 0.006250 \times BR^2 - 3.20658 \times PS^2 \quad (2)$$

ANOVA was carried out to examine the relevance of the model and variables for syngas and CH_4, as presented in Table 5. The P-values were found to be low for both cases, 0.0013 for syngas and <0.0001 for CH_4, while higher F-values were obtained, 13.26 for syngas and 33.29 for CH_4, which confirms the relevance of the model. The relevance of the model terms is indicated by the P-value <0.05. For the two models, the R^2 values were close to unity 0.9446 (syngas) and 0.9772 (CH_4), indicating that the model predicted the data approaching actual data. Furthermore, adequate precision determines the noise–signal ratio, which is required to be more than 4. In both cases, the ratio was found to be high, 10.149 for syngas and 14.411 for CH_4, which illustrates sufficient signal. This model can be used to predict several points within the design. The Adj R^2 values 0.8733 (syngas) and 0.9478 (CH_4) were also very close to the R^2 measured. These indicate sufficient consistency between anticipated and obtained data from the experiment. Figure 2 shows the correlation plot of actual and predicted syngas (H_2+CO) and CH_4 data values. The lack of fit for both cases was insignificant.

Non-significant lack of fit is good; we want the model to fit. Table 5 presented the ANOVA results. When a lack of fit that is not significant is obtained, then there is a minimum systematic and random error for both data obtained from experiments and models. The resultant influence of input factors on syngas and CH_4 was dependant on the P and F values of the models. Temperature happened to be the most significant variable, followed by sample size and blending ratio.

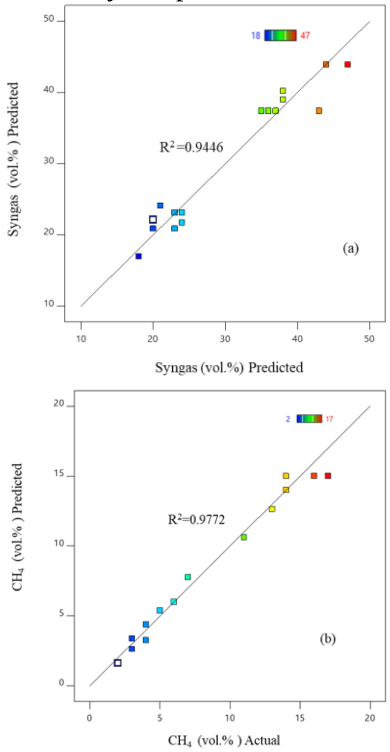


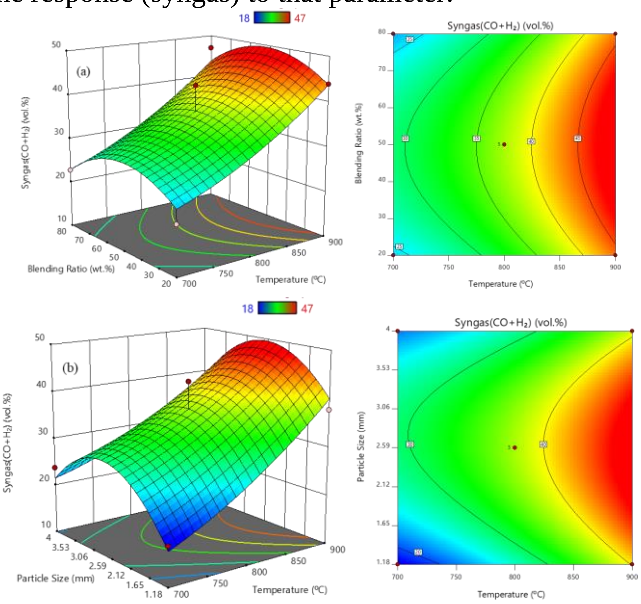
Fig. 2 Plots of actual vs. predicted of (a) syngas and (b) methane responses

Table 5 Experimental design with output response base on BBD

Source	Syngas (H_2 +CO) vol.%		CH_4vol. %	
	F-value	P-value	F-value	P-value
Model	13.26	0.0150	33.29	< 0.0001
A-TEMPT	68.79	0.0033	53.35	0.0002
B-BR	0.0419	0.9095	1.37	0.2808
C-PS	0.5138	0.8205	4.18	0.0801
AB	0.0210	1.0000	0.6829	0.4358
AC	0.7549	0.1774	13.83	0.0075
BC	0.0210	0.8724	0.0000	1.0000
A^2	1.48	0.0924	2.20	0.1814
B^2	11.48	0.0251	90.98	< 0.0001
C^2	34.97	0.0033	116.86	< 0.0001
Lack of Fit	1.37	0.6326	0.375	0.7767
Pure Error	-		3.2	
Cor Total	-		448.94	
R^2	0.9446		0.9772	
Adj R^2	0.8733		0.9478	

3.3. Response for Syngas Generation during Co-Gasification of OPT-OPF at Varying Input Factor Interaction

The mutual interaction of operating variables, i.e., temperature, particle size, and blending ratio on syngas, was investigated using the 3-D response surface plots of RSM, as shown in Fig. 3. In the analysis of the interaction between the three variables, one is kept constant at its middle value, while the others are investigated. The interaction of temperature and blending ratio at constant particle size is shown in Fig. 3a. It is seen that as the temperature increases from 700-900°C, the (CO+H_2) yield raised from 23.69-49.35 vol. % at a particle size of 2.59mm and blending ratio of OPT50:OPF50.The increased syngas is due to thermodynamic equilibrium improvement of Boudourd and water gas shift reactions, both favored by high temperature. In Fig. 3b, the mutual interaction of temperature and particle size is shown, with the blending ratio at a constant value. More syngas was obtained at a smaller particle range (1.18-3.0 mm) as high temperatures facilitate faster reactions in smaller particles. The maximum syngas was obtained to be about 49. 42 vol.% at 900 °C, 2.59 mm and 50 OPT/50 OPF. However, the interaction between particle size and blending ratio showed a marginal effect in Fig. 3c. Maximum syngas was obtained as 37 vol.%, at 50 OPT/50 OPT and 2.59 mm. Among the three variables the temperature had more effect, followed by particle size and blending ratio, which had marginal effect. This is depicted by Pareto graph analysis in Fig. 4a. In Fig. 4b, however, a perturbation plot is shown, which compares the effects of the input parameters on the syngas. In the perturbation plot, steep slope or deflection around a factor indicates the sensitivity of the response (syngas) to that parameter.



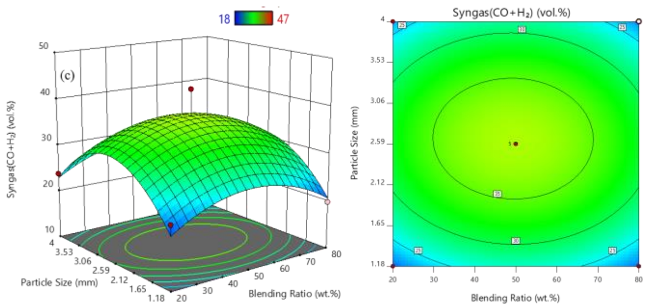


Fig. 3 3-D surface and contour plots of syngas production showing the combined effects of temperature (700-900°C), blending ratio (20-80 wt.%), particle size (1.18-4 mm)

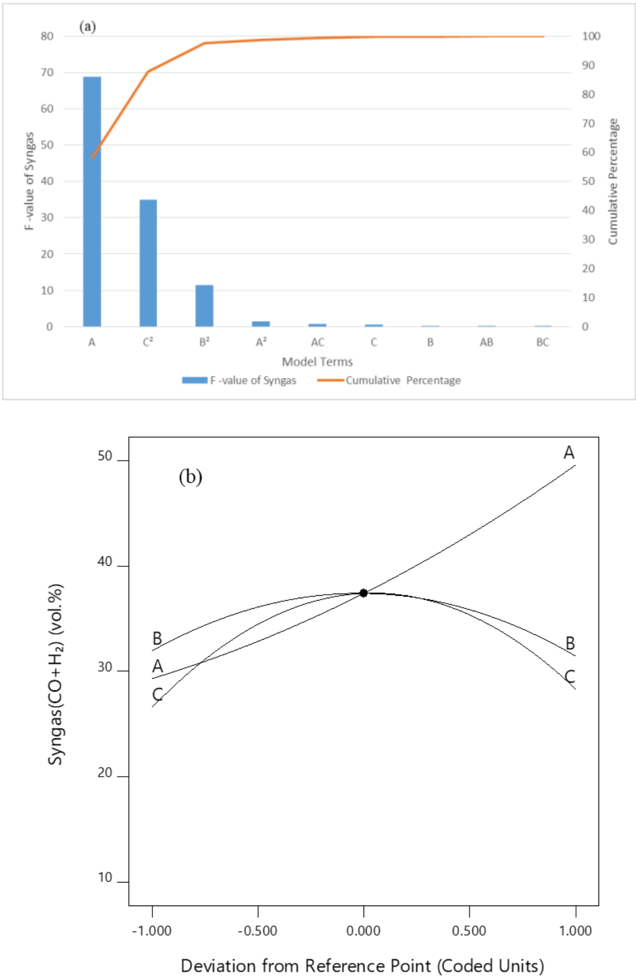


Fig. 4 (a) Pareto graphic analysis (b) and perturbation plot of model terms (A; temperature, B; blending ratio and C; particle size for syngas production)

3.4. Response for Methane Generation during Co-Gasification of OPT-OPF at Different Variables Interaction

Methane (CH_4) production during cogasification of OPT and OPF shows the combined interaction of the variables, as shown in Fig. 5. The combined effects of temperature, blending ratio, and particle size are represented in 3-D response surface and contour diagrams. Figs. 5a and b show that the methane yield raises with a hike in temperature for both cases. In Fig. 5a, mutual interaction of blending ratio and temperature led to a maximum CH_4 yield of 17.25 vol% at 900 °C and 50OPT/50OPF. In Fig. 5b, mutual interaction of particle size with temperature is shown, which yielded a maximum CH_4 as 17.61 vol% at 900 °C at 2.2 mm. Such high CH_4 yield was obtained due to relatively smaller particle size, which improved methanation reactions ($C + 2H_2 \rightarrow CH_4$, $CO + 3H_2 \rightarrow CH_4 + H_2O$, and $2C + 2H_2O \rightarrow CO_2 + CH_4$). In Fig. 5c, marginal results were obtained resulting from the mutual effect of particle size and blending ratio interaction. Maximum yield was 15 vol%, at particle size 2.4 mm and 50OPT/50OPF blending ratio. The Pareto and perturbation charts in Fig. 6 show the effects of the factors on the CH_4 yield.

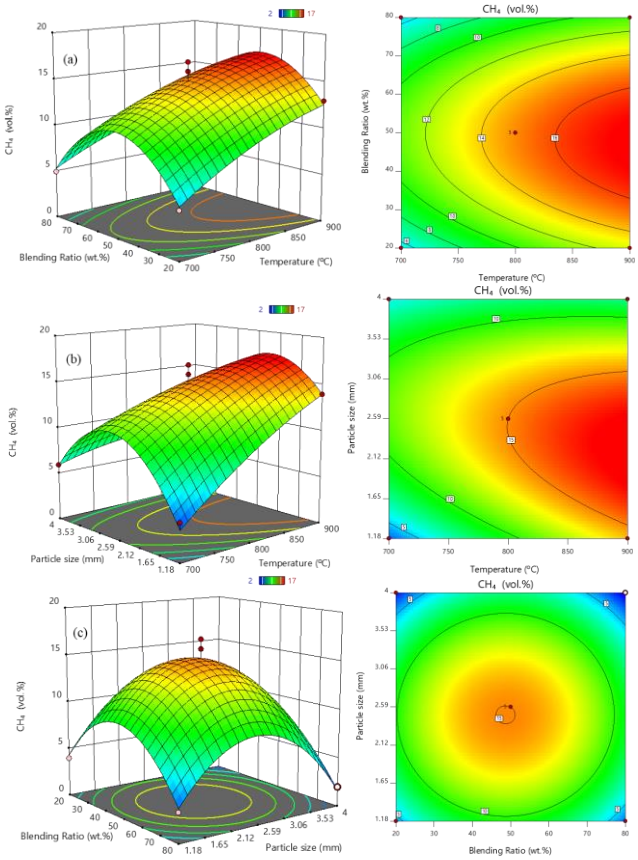
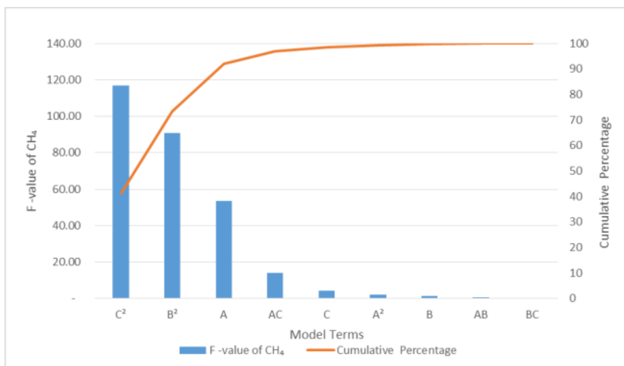


Fig. 5 3-D surface plots of methane production showing the combined effects of temperature (700-900°C), blending ratio (20-80 wt.%), particle size (1.18-4 mm)



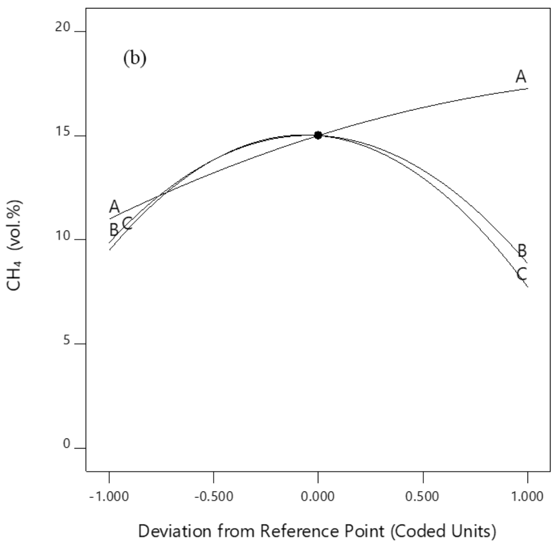


Fig. 6 Pareto graphic analysis (a) and perturbation plot of model terms (A; temperature, B; blending ratio and C; particle size for Methane production)

3.5. Process Optimization and Model Confirmation

The optimization of temperature, blending ratio and particle size for maximum syngas (H_2+CO) yields and CH_4 formation was conducted using the optimizer feature of Design Expert 11 software. Optimization was carried out taking into consideration the upper and lower limits of the input factors as shown in Table 6. For the purpose of confirmation, experiments were conducted using the optimized values and were repeated thrice. The experimental and predicted results were in agreement.

Table 6 Process optimization within the variables ranges for the desired output

Parameter	Response	Goal	Lower limit	Upper Limit
Temperature, A		In Range	700 °C	900 °C
Blending ratio, B			20 wt.%	80 wt.%
Particle size C		2.59mm	1.18 mm	4 mm
	(H_2 + CO)	Maximize	18	47
	CH_4		2	17

With the given specifications in Table 6, the optimization feature in Design Expert 11 suggested solutions for the optimization pathway. Table 7 shows the recommended solutions obtained from the software, and the solution with the maximum yield was selected from among eight others. Confirmation runs based on the optimized parameters were conducted, and experiments were repeated thrice. The average values of CO + H_2 and CH_4 yield obtained with standard deviations are shown in Table 8. Confirmatory run results were compared with the predicted values showing agreement, therefore validating the model and reliability of the outcome. The percentage error was also calculated and found to be less than 10%, showing positive reliability of the experiments.

$$\text{Error}=(\text{Experimental}-\text{Predicted})/\text{Experimental}\times 100$$

Table 7 Solutions obtained from Design Expert 11 on the numerical optimization of OPT/OPF co-gasification results

	Tempt (°C)	BR wt.%	PS mm	H_2 + CO	CH_4	Desirability
1	900	50	2.59	48.60	17.10	1.00
2	888.17	49.17	2.59	47.92	17.10	1.000
3	891.35	43.51	2.59	48.10	17.07	1.000
4	889.79	46.93	2.59	48.09	17.12	1.000
5	890.62	47.16	2.59	48.21	17.15	1.000
6	888.31	46.87	2.59	47.88	17.11	1.000
7	891.68	49.73	2.59	48.41	17.14	1.000
8	889.83	45.90	2.59	48.05	17.13	1.000

Table 8 Optimum process variables, model predicted and confirmation values of responses co-gasification results

Conditions	Predicted values (vol. %)	Experimental values (vol. %)	Error %
T = 900°C PS =1.18 mm BR=OPT50/50OPF	Syngas 48.60	Syngas 49.37	1.6%
	CH_4 17.01	CH_4 17.88	4.5%

4. Conclusion

The co-gasification of OPT/OPF was conducted in a downdraft gasifier in the presence of air as the oxidizing agent. The characterization results proved OPT to be an adequate biomass for the co-gasification process as all blends yielded remarkable results. The influence of temperature, blending ratio, and particle size yield on H_2+CO and CH_4 from co-gasification was investigated and analyzed statistically and graphically through response surface methodology—Box–Behnken design. According to the statistical analysis (ANOVA), temperature had more of an influencing affect followed by the particle size and blending ratio. The 3D surface and contour plots showed maximum syngas and methane yield was obtained by mutual interactions of temperature with particle size and temperature with blending ratio, respectively. Under optimum conditions at a temperature of 900°C, blending ratio of OPT50:OPF50, and particle size of 2.59 mm, the yields predicted were 48.60 vol% syngas, and 17.01 vol% methane. The confirmation runs showed good agreement with predicted data. Results concluded that co-gasification of OPT/OPF is a promising thermochemical way of obtaining syngas and methane for various energy applications. Practical application of the present study may be seen in remote areas where access to electricity is a major problem. Gasification of oil palm trunks and fronds can be undertaken to obtain syngas which can be used for combined heat and power generation in households. Syngas is a fuel that can be used in internal combustion engines, turbines and even cooking stoves.

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