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Abstract. This work presents the comparative study between raw biomass and pre-treated biomass co-gasified with coal with the aimed to investigate the reliability of the pre-treated biomass to enhance the gasification performance. Sawdust and wood pellet (the pelletization form of sawdust) and blends of these two feedstocks with sub-bituminous coal, were gasified in an air atmosphere using an external heated fixed-bed downdraft gasifier system. Response surface methodology (RSM) incorporating with the central composite design (CCD) was applied to assist the comparison of all operating variables. The independent variables were investigated within the specific range of coal ratio from 25 to 75%, gasification temperature from 650 to 850 °C and equivalence ratio from 0.20 to 0.30. Meanwhile, the dependent variables were evaluated on the H_2/CO ratio in the syngas, higher heating value of the syngas (HHV_{syngas}) and gas yield (GY). The results revealed the H_2/CO ratio in the syngas, HHV_{syngas} and GY of more than 1.585, 6.072 MJ/Nm^3 and 2.464 Nm^3/kg were achieved, respectively for both co-gasification. From the results, the H_2/CO ratio in the syngas and GY from co-gasification of coal/wood pellet shows a higher value than that of the coal/sawdust. However, for the HHV_{syngas}, co-gasification of the coal/sawdust possess higher value with merely 1% difference from the coal/wood pellet. Therefore, co-gasified coal with wood pellet has the potential to be substitute with the sawdust.

1. Introduction

Rapid industrialization and improvement of living standards on a worldwide scale had greatly increased the global demand for energy for the past several decades. Moreover, over consumptions of fossil fuels make the energy demand at the severe state [1]. Thus, it has ignited the need to search for the alternative energy sources that are renewable, environmentally friendly, sustainable, economically and combat current environmental problems. For the past few years, it has been noted that co-utilization of coal and biomass could be a channel between renewable and non-renewable resource-based energy production especially in the co-gasification [2–4]. Co-gasification of coal and biomass seems to be an appealing technology by producing the end product of syngas that can be used for power generations [5]. Ciferno

and Morano [6] stated that when these two fuels were co-gasified, the fuels had exhibited synergy that provides advantages for all types of emissions, especially greenhouse gas emissions, without deprived the energy content of the product gas. Moreover, the addition of coal in biomass promotes a consistent supply of feedstock and aids in reducing operational costs for commercial enterprises. Meanwhile, for the operations purpose, the biomass could be employed in existing coal operated gasifiers [7,8] thus required only minimum modified especially on the feeding system. Most of the studies are focused on the raw biomass co-gasified with coal [9–12], however, it has been highly discovered limited study of the co-gasification on the pre-treated biomass especially pelletization. Teixeira et al. [13] expressed the opinion that the raw biomass which is existing with low energy density, poor solid flow and massive ash content may resulted to backdraw performance during gasification. Thus, pre-treated of the biomass in the form of pelletized or otherwise densified resulted in better fuel operability in term of handling, transportation, storage, and feeding compared than raw biomass [14,15]. The pelletized biomass is frequently applied in gasification, especially in fixed bed gasifiers where mechanically stable fuel particles of limited size are required for successful operation [16]. Although, it has discovered that pelletized biomass has been utilizing as a co-feed in gasification [17–19] or combustion system; however, according to author's best knowledge, there are only a few studies exploring the gasification performance of pelletized biomass with its parent biomass [20,21]. Hence, this study attempts to investigate the comparative study between pelletized biomass with its raw biomass when co-gasified with sub-bituminous coal.

In addition, presently, no conclusions can be drawn in between the co-gasification of coal with raw biomass or pre-treated biomass either possess better gasification performance at the same. Hence, a comprehensive investigation into the optimization of raw biomass and pre-treated biomass for co-gasification with sub-bituminous coal needs to be performed by applying the response surface methodology (RSM) with various responses and output. Hence, in the present study, sub-bituminous coal (CL), raw biomass-sawdust (SD), pre-treated biomass-wood pellet (WP) have been analyzed in term of proximate analysis, ultimate analysis, and higher heating value to obtain the characteristic for each feedstock for further co-gasification investigations. Furthermore, the co-gasification of biomass and their blend with different coal ratio, gasification temperature and equivalence ratio have been investigating in the externally heated downdraft fixed bed gasifier system. The ratio on the H_2/CO in the syngas, the higher heating value of the syngas (HHV_{syngas}) and gas yield (GY) were obtained through a series of experimental investigations. A central composite design (CCD) incorporating with RSM method was applied to reveal the effects of interaction between the operating variables, unlikely applying traditional method "one-factor-at-a-time". The results indicate the models established through the Design Expert 10 are fitted agreeably with the experimental results for all the output variables that involved.

2. Methodology

2.1. Feedstock preparation and analysis
In this study, the blends of CL/SD and CL/WP were used as feedstock. The coal (CL) sample was collected from the electric utility company in Malaysia through the third party company. Meanwhile, the sawdust (SD) and wood pellet (WP) were obtained from a wood industry located in Penang, north of Malaysia. SD is recognized as the by-product of the woodworking operations. Meanwhile, WP is the pelletization of the SD. Figure 1 shows images of the CL, SD and WP. The feedstock was received prior to the experimental day. The feedstock was prepared for two stage: the first stage is for the use for thermochemical analysis while in the second stage is for co-gasification experiments. The samples were first weighed to obtain the required mass needed throughout the experiment. After that, samples were put into the oven for drying purposes at a temperature of 105 °C for about 24 hours. The main purpose of the drying process was conducted to remove the moisture content from samples. The samples were then be mechanically mixed into different blending ratio (25 %, 50 %, and 75 %). Subsequently, the dried samples were placed into the air-tight container to avoid moisture contact. The characteristic of

the feedstock was performed for proximate analysis as per ASTME1131 [22] procedure using thermogravimetric analyzer (Hitachi STA 7000); ultimate analysis as per ASTM D3176 [23] procedure using elemental analyser (Elementar: vario MACRO cube); and higher heating value (HHV) was determined using a bomb calorimeter (IKA C200).
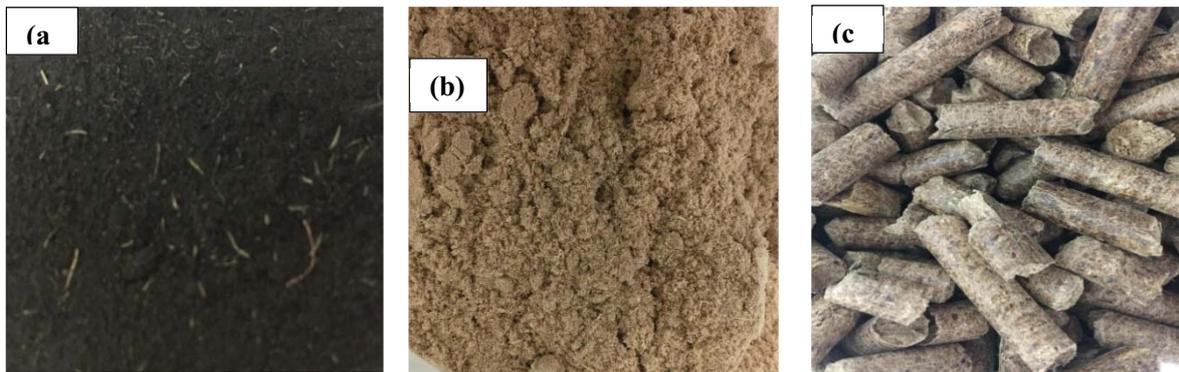
Figure 1. The pictures of coal, CL (a), sawdust, SD (b) and wood pellet, WP (c) that have been used throughout this study.

2.2. Experimental procedure

The co-gasification of CL/SD and CL/WP were performed in a fixed bed downdraft gasifier situated at the biomass laboratory, under Department of Mechanical Engineering, Universiti Teknologi Petronas (UTP), Perak as shown in Figure 2. The gasifier was operated at atmospheric conditions and run 1-2 h for each experiment. In this study, atmospheric air was used as a gasifying agent and supplied to the gasifier using a 1.5 kW air compressor at a pressure of 2 bar. Meanwhile, a rotameter attaches to the gasifier system was used to control the airflow rate. The dimension of the internal diameter and height of the gasifier are 80 mm and 500 mm, respectively. An electric furnace enclosed around the system was functioned to heat the gasifier. The gasifier was flushed with compressed air at the required amount of volume for 10 min before the experiment to achieve a stable state. Then, the gasifier was heated to the desired gasification temperature. Once the gasifier achieved a stable state with the desired gasification temperature and airflow rate, the sample weighed approximately 100 g was then loaded into the gasifier reactor applying drop-chute method. Produce gas flowed into the gas analysis unit (Emerson X-stream X2GP). When the process was completed, the electric furnace and air compressed was switched off, and the gasifier was left to cool to the ambient temperature. The solid residue, which is characterized as char from the experiment, was collected from the gasifier at the opening bottom. The final weight of the remaining char was then weighed using a precision weight balance once it reached the room temperature. The temperature and gas composition readings from the experiment were obtained from the desktop computer for analysis purpose.
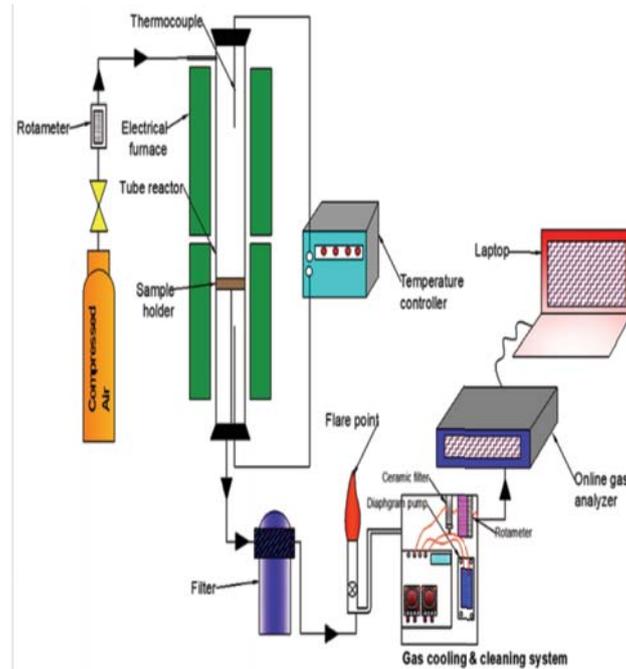
Figure 2. Schematic diagram of the experimental procedure.

From the value of the product gaseous obtained from the gas analysis unit, the H_2/CO ratio in the syngas was calculated as one of the response variables. In addition, the higher heating value of syngas (HHV_{syngas}) was calculated by taking into account the volume percentage of product gaseous (CO, H_2 and CH_4) with their specific HHV [24], expressed in the Equation (1).

$$HHV_{syngas} = (V_{CO} \times HHV_{CO}) + (V_{CH_4} \times HHV_{CH_4}) + (V_{H_2} \times HHV_{H_2})$$ (1)

V, is described as the volumetric percentage for CO, CH_4 and H_2 obtained from online gas analyzer measurements and were each multiplied by their respective HHV with the sum of the multiplication products represented HHV_{syngas}. The HHV for each gas are 12.63 MJ/Nm^3 for CO, 39.82 MJ/Nm^3 for CH_4 and 12.74 MJ/Nm^3 for H_2 as per standard values obtained from the US National Renewable Energy Laboratory (NREL) [25]. Meanwhile, the gas yield (GY) for each experiment is defined as the volume of syngas produced per unit mass of feedstock consumed in gasifier by using nitrogen balance method that has been proposed and applied by several authors as Equation (2) [26–28].

$$GY = \frac{Q_a \times 79\%}{m_{feed} \times N_2}$$ (2)

Where Q_a is the volume flow rate of air varied from 0.12 to 0.24 Nm^3/h, m_{feed} is the mass flow rate of the feedstock in the gasifier system varied from 0.16 to 0.30 kg/h at different blending ratio of the CL with SD and WP, while N_2 % is the volumetric percentage of N_2 in the dry fuel gas.

2.3. Design of experiment
An empirical modelling approach known as Response Surface Methodology (RSM) was chosen for experimental design using Design Expert software (Version 10.0.3, Stat-Ease Inc., MN, USA). In this work, the selected factors were optimized by applying the center composite design (CCD) in RSM. The CCD is an alternative to the full factorial three-level design since it required less number of runs instead stipulate corresponding outcomes. Three input variables studied were coal ratio (A), gasification temperature (B) and equivalence ratio (C) with the ranges of variables are 25-75 %, 650-850 °C, and

0.2-0.3, respectively. Meanwhile, H_2/CO ratio of syngas, higher heating value of syngas (HHV_{syngas}), and gas yield (GY) were measured from the experiment as the output variables. In order to evaluate the result, an ANOVA (analysis of variance) were generate and analyses numerically. It is capable to analyse the individual and combined influence of independent variables on dependent variables. Subsequently, the regression model, significance of terms and lack of fit tests were determine to assess the goodness of fit that indicated whether the proposed models were statistically significant. Meanwhile, the precision of experimental data from the model can be assess through the regression coefficient (R^2) value.

3. Results and Discussions

3.1. Characterization results

The results of proximate analysis, ultimate analysis, and higher heating value are provided in Table 1. The proximate analysis's value of each CL, SD and WP are in the range of data marked by other researcher [29–31]. Moreover, the volatile matter of the SD and WP are almost twice of the CL as reported by [32,33]. The blending of CL/WP has highest percentage of VM compared to the blending of CL/SD due to blending of CL with high VM of WP [34]. Difference in term of FC, SD/CL's blending possess the highest FC than WP/CL due to the high percentage of the FC in SD. Meanwhile, from the ultimate analysis, the C content in CL is much highest at 52.58 % than SD and WP with 44.11 % and 44.28 % respectively. This is due to the nature properties of the CL which formed about 300 million years ago with the right heat and pressure extract out the oxygen and hydrogen and produced carbon-rich combustible mineral. Another essential point, WP denoted much lower N and S content than CL and SD. Overall, it can be seen contribution of CL content in the blending feedstock has the greatest influence carbon content in the blending feedstock [1]. This is due to large amount of carbon are contained in the coal. It can be seen that decreasing order of HHV from CL > WP > SD. The amount of HHV for each CL, SD and WP are also in the range with other researcher [12,35]. Subsequently, the HHV of all the blending ratio fuel are lies between 19.00-17.94 MJ/kg. Furthermore, as expected, increase the blends of CL with SD and WP resulted the increase of the HHV value of the feedstock. It was been supported on the HHV of charcoal mixed with EFB conducted by Monir et al. [36].

Table 1. Proximate, ultimate and higher heating value of coal/sawdust and coal/wood pellet

Samples		Proximate analysis (wt. %)				Ultimate analysis (wt. %)					HHV (MJ/kg)
		MC[a]	VM[b]	FC[c]	Ash	C	H	N	S	O[d]	
100% CL		8.18	39.79	33.81	18.22	52.58	5.90	1.49	1.14	38.90	20.19 ± 0.082
100% SD		11.8	68.05	19.05	1.10	44.11	5.53	2.14	2.70	45.52	17.17 ± 0.089
100% WP		9.19	79.00	10.16	1.65	44.28	6.09	1.05	0.28	48.62	17.46 ± 0.085
Blend of coal & sawdust	75CL / 25SD	12.27	47.89	36.65	3.19	50.46	5.80	1.65	40.55	1.53	18.04 ± 0.206
	50CL / 50SD	10.92	48.23	38.41	2.44	48.35	5.71	1.82	42.21	1.92	18.75 ± 0.099
	25CL / 75SD	9.65	56.86	31.35	2.14	46.23	5.62	1.98	43.86	2.31	17.94 ± 0.084
Blend of coal & wood pellet	75CL / 25WP	9.92	80.85	6.38	2.85	50.50	5.86	1.38	41.33	0.92	19.00 ± 0.389
	50CL / 50WP	9.32	79.13	8.83	2.72	48.43	5.83	1.27	43.76	0.71	18.28 ± 0.641
	25CL / 75WP	9.44	80.74	7.14	2.68	46.36	5.79	1.16	46.19	0.50	18.12 ± 0.112

Moisture content[a], Volatile matter[b], Fixed carbon[c], By difference: O^d= (100 - (C+ H + N + S)).

3.2. Statistical analysis of the experimental results

Table 2 presents the ANOVA (analysis of variance) from both co-gasification experiments to construct empirical prediction models generated by the Design Expert. Subsequently, highest order polynomial was selected for each model in order to maximize the adjusted R^2 where the terms were significant and

to model was not aliased. Therefore, it has been discovered that the quadratic model was chosen for all the operating factors in the co-gasification of CL/SD and CL/WP which shows it is significant to predict the response variables. According to the Table 2, for the co-gasification of the CL/SD, the temperature effect the H_2/CO ratio in the syngas, the coal ratio and equivalence ratio gave influence for both of the HHV_{syngas} and GY. In contrast, for the co-gasification of CL/WP, all the operating variables give effect to the H_2/CO ratio in the syngas and HHV_{syngas}. Except for the GY in CL/WP, only the coal ratio and equivalence ratio shows significant (p-value < 0.05). Furthermore, the p-value for term "lack of fit" in Table 2, which was greater than 0.05 denoted that the "lack of fit" for the whole model for H_2/CO ratio in the syngas, HHV_{syngas} and GY for both co-gasification of CL/SD and CL/WP was insignificant. By all means, the model was fitted with the response data collected and was acceptable for the following experiments. In brief, the R^2 values obtained are close to 1 for all interactions examined, thereupon it indicates that all the model is agreeable for both of the co-gasification. Meanwhile, the adjusted R^2 of the regression model for both co-gasification for CL/SD and CL/WP were shown in excess of or close to 80% denoted that whole model regards as satisfactory to consider the complicated comparative analysis between the co-gasification of the SD and WP with CL in the externally heated downdraft fixed bed gasifier system in atmospheric conditions.

Table 3 exhibits the functionality of different parameter to the three indepedent variables and their interactions obtained from the ANOVA analysis. The actual coefficients aids to predict the actual responses using the original unit. Equally important, the coded coefficients are used in comparing the relative impact for each variable term on the responses. It can be seen from the Table 4 that the major influencing conditions on each dependent variables for both of the co-gasification of SD and WP with CL were determined as temperature for H_2/CO ratio in the syngas and equivalence ratio for HHV_{syngas} and GY. A further comprehensive study on the regression coefficients are elaborated in the following section.

Table 2. Analysis of variance (ANOVA) analysis for co-gasification between CL/SD and CL/WP.

Source	Coal/Sawdust (CL/SD)						Coal/Wood pellet					
	H_2/CO ratio		HHV_{syngas}		GY		H_2/CO		HHV_{syngas}		GY	
	SS	p-value	SS	p-value	SS	p-value	SS	p-value	SS	p-value	SS	p-value
Model	1.5156	0.0008	6.6468	< 0.0001	4.5436	< 0.0001	1.3048	< 0.0001	14.8145	< 0.0001	4.8478	< 0.0001
A-Coal ratio	0.0750	0.0691	0.1946	0.0508	0.0097	0.1884	0.0641	0.0009	0.3992	0.0197	0.0426	0.0018
B-Temp	0.4280	0.0007	2.8690	< 0.0001	0.1393	0.0003	0.3316	< 0.0001	2.5347	< 0.0001	0.0083	0.0928
C-ER	0.0403	0.1663	0.4290	0.0081	4.2792	< 0.0001	0.5822	0.0001	0.5498	0.0087	4.3131	< 0.0001
AB	0.0136	0.4065	1.6965	< 0.0001	0.0378	0.0194	0.2641	< 0.0001	0.0009	0.8973	0.0068	0.1225
AC	0.1105	0.0330	0.0546	0.2672	0.0014	0.6000	0.0568	0.0014	0.9579	0.0016	0.0284	0.0062
BC	0.1677	0.0123	0.2511	0.0304	0.0092	0.1995	0.0005	0.6782	0.2275	0.0629	0.0036	0.2461
A^2	0.3017	0.0022	0.3904	0.0105	0.0148	0.1125	0.0012	0.5462	5.4605	< 0.0001	0.0698	0.0003
B^2	0.0579	0.1038	0.4108	0.0091	0.0014	0.6036	0.0035	0.3018	2.5109	< 0.0001	0.2230	< 0.0001
C^2	0.4754	0.0004	0.6818	0.0020	0.0393	0.0176	0.0004	0.7324	5.0062	< 0.0001	0.2679	< 0.0001
Residual	0.1808		0.3953		0.0489		0.0299		0.5196		0.0239	
Lack of Fit	0.1145	0.2815	0.0899	0.8972	0.0315	0.2638	0.0244	0.0641	0.1681	0.7812	0.0153	0.2726
Pure Error	0.0663		0.3054		0.0173		0.0055		0.3515		0.0086	
R^2	0.8934		0.9439		0.9894		0.9776		0.9661		0.9951	
Adj R^2	0.7975		0.8933		0.9798		0.9574		0.9356		0.9907	
Pred R^2	0.4461		0.8338		0.9352		0.8504		0.8795		0.9708	

Table 3. The empirical correlations develop based on ANOVA for both CL/SD and CL/WP co-gasification as function of actual and coded operating variables.

Samples	Index	Type	Inter	A:Coal ratio	B: Temp	C: ER	AB	AC	BC	A^2	B^2	C^2
Blend of coal & sawdust	H_2/CO	Actual	-0.828	-9.521e-3	3.310e-3	1.670	1.648e-5	0.094	0.029	-2.338e-4	-6.401e-6	-54.169
		Coded	1.25	0.074	0.18	0.050	0.041	0.12	0.14	-0.15	-0.064	-0.14
	HHV_{syngas}	Actual	-12.493	-0.090	0.030	59.04	1.842e-4	-0.066	-0.035	-2.660e-4	-1.705e-5	-64.870
		Coded	5.24	0.12	0.46	-0.16	0.46	-0.083	-0.18	-0.17	-0.17	-0.16
	GY	Actual	0.117	-0.022	-3.559e-3	13.574	2.751e-5	-0.0107	6.792e-3	5.179e-5	9.973e-7	-15.582
		Coded	1.63	0.027	0.10	0.52	0.069	-0.013	0.034	0.032	9.97e-3	-0.039
Blend of coal & wood pellet	H_2/CO	Actual	-1.591	0.0335	2.402e-3	-0.040	-7.268e-5	0.0674	1.653e-3	1.455e-5	1.585e-6	-1.511
		Coded	1.13	-0.069	0.16	0.19	-0.18	0.084	8.266e-3	9.029e-3	0.016	-3.799e-3
	HHV_{syngas}	Actual	-37.13	0.040	0.076	95.645	-4.267e-6	0.2768	-0.0337	-9.948e-4	-4.216e-5	-175.78
		Coded	5.73	0.17	0.43	-0.19	-0.011	0.35	-0.17	-0.62	-0.42	-0.44
	GY	Actual	-10.64	-7.188e-3	0.0196	31.524	1.166e-5	0.0477	-4.259e-3	-1.124e-4	-1.257e-5	-40.66
		Coded	1.91	0.056	0.025	0.52	0.029	0.060	-0.021	-0.070	-0.13	0.10

3.3. The effect of operating variables on H_2/CO ratio in the syngas

Figures 3(a) and (b) present the effect of the indepedent variables and their interactions on the H_2/CO ratio in the syngas for the co-gasification of CL/SD and CL/WP, respectively. The minimum and maximum value for H_2/CO ratio in syngas of the CL/SD are 0.3796 and 1.5837, respectively. In contrast, the minimum and maximum value for H_2/CO ratio in syngas of the CL/WP are 0.7305 and 1.6910, respectively. The maximum value for H_2/CO ratio in syngas of the CL/SD is coal ratio, gasification temperature and equivalence ratio at 75%, 850 °C and 0.30, respectively. This is in contrast to CL/WP that the maximum value for H_2/CO ratio in syngas is at 25% of coal ratio, 850 °C of gasification temperature and 0.30 of equivalence ratio. Meanwhile, the minimum of H_2/CO ratio in the syngas for both co-gasification of CL/SD and CL/WP is at (25%-650 °C-0.30) and (50%-750 °C-0.15), respectively. The influence order of the operating variable for both co-gasification on H_2/CO ratio in the syngas are in the order of Temp.>ER >Coal ratio. The plot marks that the rise up of H_2/CO ratio in syngas by increasing the gasification temperature is noticeable at higher temperature of 850 °C. In monitoring the temperature range from 650 to 850 °C, for both of the co-gasification of CL/SD and CL/WP the H_2/CO ratio in syngas was increased by 26 % and 23 %, respectively. This is expected due to the increasing value of the concentration of H_2 and CO gaseous composition from the both of co-gasification of CL/SD and CL/WP as endothermic reactions in the gasification increasing the gasification temperature [37]. Furthermore, as the blends of CL with WP possess higher VM denoted that increasing of the volatile matter contents in the feedstock eventually enhanced the production of combustible gases at a lower process temperature and hence lead to the decrease of H_2 concentration [37]. This is supported by the Hernandez el el. [38] claims that concurrently rise up the biomass content and temperature in co-gasification led to higher production of hydrogen.. For the operating factors of the equivalence ratio, both of the co-gasification possess similar result that increasing of the equivalence ratio from 0.20-0.30, the CL/SD and CL/WP were increased at 8 % and 29 %, respectively. The increment of H_2/CO is due to the increase of equivalence ratio denoted in higher temperature that resulted to higher feedstock conversion and produced higher fuel quality [39]. Moreover, it can be seen that in CL/SD, the increasing of the coal ratio from 25 % to 75 % the H_2/CO ratio in the syngas is increased by 12 %. This is in contrast from the CL/WP in which the value of the H_2/CO ratio in the syngas was decreased 12 % as the coal ratio is increasing. This can be explained that the low fixed carbon content of the blends of CL and WP reduce the CO production as it is being consumed in the water gas shift reaction [40] resulted the decreased of the H_2/CO ratio as the amount of the coal ratio increased. The result also similar to the study conduct by Brar et al., [19] that reveal increasing the amount of the coal into the hardwood pellet, the H_2 and CO composition of the product gas are reduce. The conversion of fixed carbon was used to determine the rate of gasification and its yield [25]. The lower fixed carbon might resulted the more syngas can be volatile through the gasification process. This is due to the pelletization process that involves thermal treatment eventually modify the feedstock's properties that enhanced the VM and produce low-moisture content of the SD and have aided in improving the biomass as biofuels productions [20,21]. Generally, a higher temperature and equivalence ratio resulted in a high amount of H_2/CO ratio in the syngas from both co-gasification of SD/CL. However, for the coal ratio, CL/SD favor higher coal for the increasing of the H_2/CO ratio. Whereas, CL/WP favor less amount of coal to produce the highest amount of H_2/CO ratio in the syngas.

$$(a) \qquad\qquad\qquad (b)$$
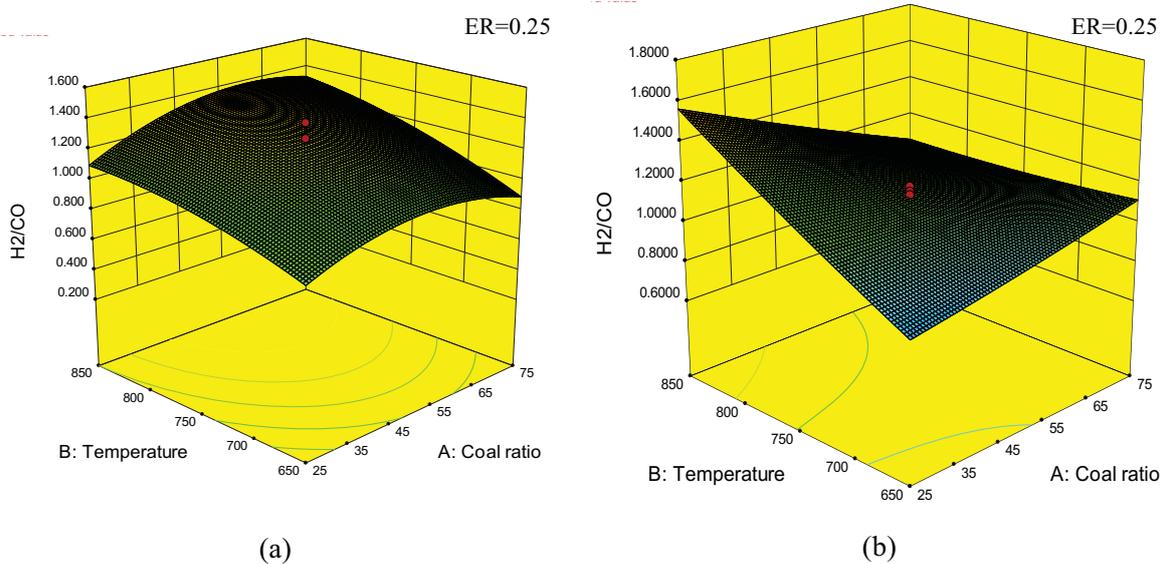
Figure 3. 3-Dimensional response surface plot representing combined effect of coal ratio (25-75 %) and gasification temperature (650-850 °C) at constant ER at 0.25 each for (a) co-gasification of CL/SD (b) co-gasification of CL/WP on H_2/CO ratio in the syngas.

3.4. The effect of operating variables on the higher heating value of syngas (HHV_{syngas})

The effect of the three operating variables on the HHV_{syngas} for co-gasification of CL/SD and CL/WP at constant ER at 0.25 were exhibited in the Figures 4(a) and (b), respectively in the form of 3-dimensional response surface plot. The maximum and minimum value of the HHV_{syngas} for CL/SD are 6.0724 MJ/Nm^3 and 3.7768 MJ/Nm^3, respectively. Complementary to this, the maximum and minimum value of the HHVsyngas for the CL/WP are 6.0160 MJ/Nm^3 and 3.4323 MJ/Nm^3. The maximum value for HHV_{syngas} of the CL/SD are coal ratio, gasification temperature and equivalence ratio is at 75%, 850 °C and 0.20, respectively. This is in contrast to CL/WP that the maximum value for H_2/CO ratio in syngas is at 50% of coal ratio, 750 °C of gasification temperature and 0.25 of equivalence ratio. Meanwhile, the minimum of H_2/CO ratio in the syngas for both co-gasification of CL/SD and CL/WP is at (75% - 650 °C - 0.30) and (50% - 750 °C - 0.35), respectively. Increasing the gasification temperature from 650 °C to 850 °C both of the CL/SD and CL/WP's HHV_{syngas} are increasing at 17 % and 15 %, respectively. It can be noted from Figure 4 that influence of the operating variable for both co-gasification on HHV_{syngas} are in a similar order as H_2/CO ratio in the syngas which are Temp.>ER >Coal ratio. This study confirms that increased of the HHV_{syngas} is associated with higher gasification temperature that enforced the endothermic gasification reactions, resulted in more heat losses of the system, hence improved the gasification process on the syngas production [41,42]. Inversely, the HHV_{syngas} for the co-gasification of CL/SD and CL/WP is decreased by about 7 % with increasing of the ER. As ER related to the airflow rate, high ER contribute to the higher airflow rate leads to the lower heating values for syngas due shorter residence time of the reaction and eventually reduced the gasification process efficiency [43,44]. Moreover, for the term of coal ratio, 4 % and 7 % increasing of the HHV_{syngas} as the amount of the coal increase in the co-gasification with SD and WP, respectively. This can be attributed to the gasification temperature and coal ratio that improve the formation of H_2 and CO eventually increase the HHV_{syngas} [45]. To sum up, the higher temperature and coal ratio, HHV_{syngas} value was increased for both CL/SD and CL/WP. Despite this, increasing of the equivalence ratio, the HHV_{syngas} for the co-gasification of SD and WP with CL will be reduced.
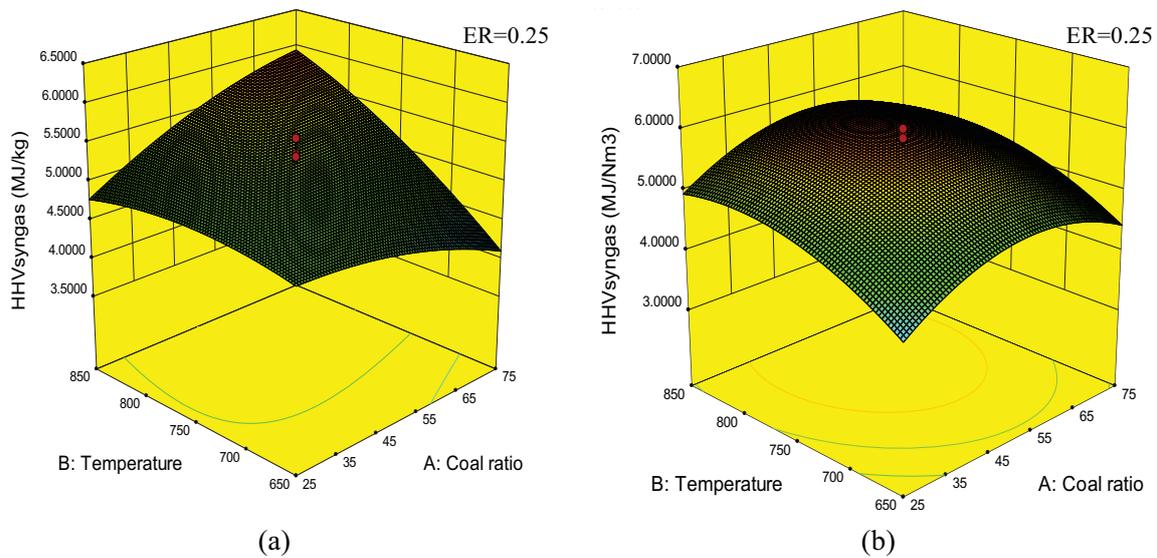
Figure 4. 3-Dimensional response surface plot representing combined effect of coal ratio (25-75 %) and gasification temperature (650-850 °C) at constant ER at 0.25 each for (a) co-gasification of CL/SD (b) co-gasification of CL/WP on HHV$_{syngas}$.

3.5. *The effect of operating variables on the gas yield (GY)*

Figure 5(a) and (b) illustrate the effect of the coal ratio, gasification temperature and ER towards their interactions on the GY for the co-gasification of CL/SD and CL/WP, respectively in the 3-dimensional response surface plot. The minimum and maximum value for GY of the CL/SD are 0.5266 Nm^3/kg and 2.4644 Nm^3/kg, respectively. In contrast, the minimum and maximum value for GY of the CL/WP are 0.4874 and 2.4788, respectively. It has been discovered that both of the maximum value for GY of the CL/SD and CL/WP are coal ratio, gasification temperature and equivalence ratio at 50%, 750 °C and 0.35, respectively. And yet, the minimum of GY for both co-gasification of CL/SD and CL/WP are at 50% of coal ratio, 750 °C of gasification temperature and 0.15 of ER, respectively. The figure indicated that as the ER increase, the GY also increase and occur at higher ER of 0.35. It can be seen that increasing each of the independent variables lead to a positive effect on GY for both co-gasification of CL/SD and CL/WP, the order of influence being: ER>Temp >Coal ratio. In monitoring the ER range from 0.20 to 0.30, for both of the co-gasification of CL/SD and CL/WP the GY was increased by 49 % and 45 %, respectively. It is apparent that a study conducted by Upadhyay et al. [46] on the co-gasification of lignite and sawdust briquette stated that the gas yield is primarily associated with fuel and air consumption rates. Similar studies also inline that high ER resulted to the increasing of GY [47–49]. For the effect on the gasification temperature, increasing the temperature from 650 °C to 850 °C, the GY for CL/SD and CL/WP were increased at 12 % and 3 %, respectively. These results are also attributed by several researchers that state the influence of temperature on GY in co-gasification [40,50]. This is due to increase of the gasification temperature improved the release of gaseous product from the pyrolysis, steam reforming, gasification and cracking reactions inside the gasifier [51]. Therefore, GY increased with the increase of the gasification temperature. It also can be noted that as the coal ratio increase in the SD and WP, the GY are slightly increased by the factors of 3 % and 5 %, respectively. This might be due to the addition of coal possessed lower reactivity and the presence of less volatile matter in coal than in biomass create synergism among the fuels [52]. In brief, for both co-gasification of SD and WP with CL, high GY is favorable the higher coal ratio, gasification temperature and equivalence ratio.
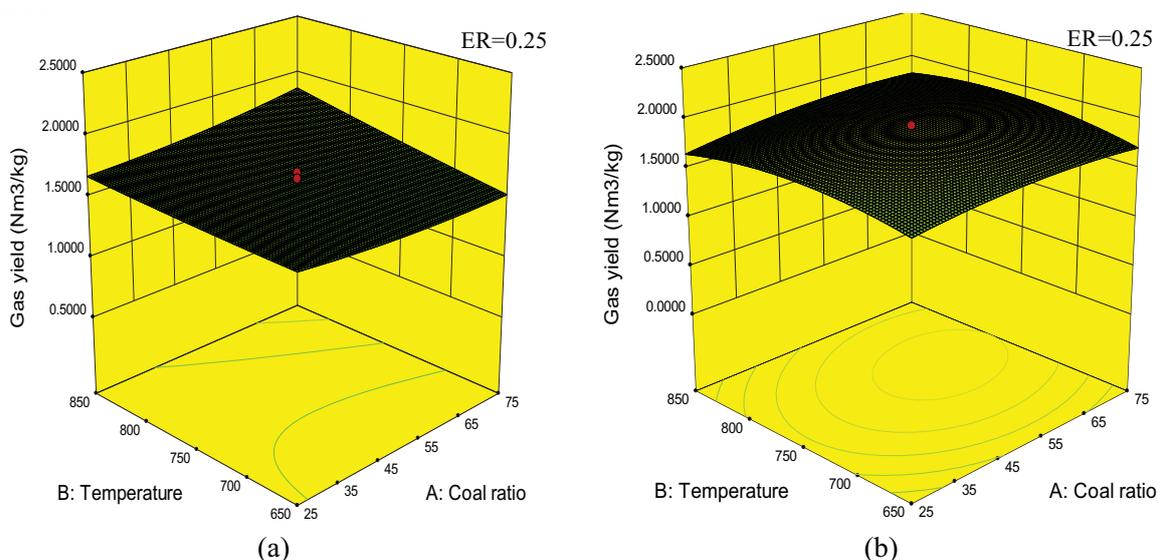
Figure 5. 3-Dimensional response surface plot representing combined effect of coal ratio (25-75 %) and gasification temperature (650-850 °C) at constant ER at 0.25 each for (a) co-gasification of CL/SD (b) co-gasification of CL/WP on GY.

3.6. Process optimization and model validation

The optimization of the coal ratio, gasification temperature, and equivalence ratio for maximum H_2/CO ratio in the syngas, HHV_{syngas} and GY for both co-gasification was performed using Design Expert 10 software by applying numerical optimization method. Table 4 present the process optimization at the desired variables' range and response output. The confirmation runs from the optimized value were conducted triplicate. Table 5 shows the average values for each of the H_2/CO, HHV_{syngas} and GY with standard deviation. An error less than 10 % can be noted between the experimental and predicted results. Based on the model predicted values and the model validation value through additional experiment, it can be concluded that the developed model could accurately predict the output variables.

Table 4. Optimum process variables, model predicted and confirmation values of response

Parameters	Limits
A: Coal ratio	25-75 %
B: Temperature	650-850 °C
C: Equivalence ratio	0.20-0.30
H_2/CO ratio in the syngas	maximize
HHV_{syngas}	maximize
GY	maximize

Table 5. Optimum process variables, model predicted and confirmation values of responses.

Biomass	Coal ratio (%)	Temp. (°C)	ER	Model predicted value			Confirmation run value			Desirability
				H_2/CO	HHV_{syngas}	GY	H_2/CO	HHV_{syngas}	GY	
SD	75	850	0.30	1.488	5.535	2.245	1.58 ± 0.55	5.2683 ± 1.04	1.9762 ± 0.74	0.855
WP	55	816	0.30	1.385	5.333	2.243	1.28 ± 0.31	4.8705 ± 0.65	2.1376 ± 0.54	0.762

4. Conclusions

Comprehensive statistical analyses of the combined effects on co-gasification operating variables (coal ratio, temperature, and equivalence ratio) on different process parameters such as H_2/CO ratio, heating value of the syngas (HHV_{syngas}), gas yield (GY) were performed by applying the response surface methodology (RSM) from a series of co-gasification experiments. These experiments were carried out

in the external heated fixed bed downdraft using air as an oxidizing agent. Gasification temperature was found to be the prominent influential variable for both of the co-gasification between SD and WP. Increasing the gasification temperature, there was an increase in all the response variables (H_2/CO ratio in the syngas, HHV_{syngas}, GY). Moreover, an increase of the ER in the gasification experimental resulted in an increase of the airflow rate, eventually minimize the residence time and in turn the HHV_{syngas} was lowered down. An increase of the coal ratio, gasification temperature and equivalence ratio lead to a higher amount of GY for the co-gasification between CL/SD and CL/WP. Under optimum conditions, the results expressed that maximum H_2/CO ratio in the syngas (1.58 ± 0.55), HHV_{syngas} (5.2683 ± 1.04 MJ/Nm^3) and GY (1.9762 ± 0.74 Nm^3/kg) were obtained at coal ratio at 75 %, gasification temperature at 900 °C, with ER at 0.30 for co-gasification of CL with SD. Meanwhile, for the co-gasification of CL/WP, the optimum conditions at 55 % coal ratio, gasification temperature at 816 °C and ER at 0.30 possess the maximum H_2/CO ratio in the syngas, HHV_{syngas} and GY at (1.28 ± 0.31), (4.8705 ± 0.65 MJ/Nm^3) and (2.1376 ± 0.54 Nm^3/kg), respectively. The confirmation runs revealed good agreement with the predicted values. Hence, the proposed models fitted well with the experimental results for all the output variables involved in this work.

Acknowledgement

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