Cogasification performance of deashed coal with various biomass

Jenny Rizkiana\textsuperscript{1,2,3*}, Sandy Fajar Maulana\textsuperscript{1}, Ghiffary Azka Nur Aulia\textsuperscript{1}, Nasywa Kamilah\textsuperscript{1}, Reyhan Fitri Ananda\textsuperscript{1}, Naafi Fauzan Mahendraputra Sastrohutomo\textsuperscript{1}, Edo Muhammad Nashiruddin Latif\textsuperscript{1}, Winny Wulandari\textsuperscript{1}, Dwiwahju Sasongko\textsuperscript{1}

\textsuperscript{1} Department of Chemical Engineering, Faculty of Industrial Technology, Institut Teknologi Bandung, Bandung 40132, Indonesia
\textsuperscript{2} Department of Bioenergy Engineering and Chemurgy, Faculty of Industrial Technology, Institut Teknologi Bandung, Bandung 40132, Indonesia
\textsuperscript{3} Center for Catalysis and Reaction Engineering, Institut Teknologi Bandung, Bandung 40132, Indonesia

*Email: jr@che.itb.ac.id

Abstract. Cogasification of lignite and EPFB is present as a production of energy sources that aim to get a synergy effect. However, not all cogasification gives better product quality than fuel parent gasification. In this study, demineralization acted as lignite pre-treatment stage is achieved through HF leaching at 70°C for 4 hours. The mixing ratio varied by lignite to empty palm fruit bunches (EPFB) are 1: 2, 1: 1, and 2: 1 both for non-demineralized lignite (BLM) and lignite demineralized (BLD). The negative synergy effect of two combination is caused by the high content of silica and alumina from the empty palm fruit bunches (EPFB). The lignite demineralization cogasification produces a lower \( \text{H}_2 \) yield than BLM because it also dissolves the mineral content which functions as a catalyst for cogasification synthesis.

1. Introduction

During 2006 to 2016, world energy consumption on average increased by 1.8% per year. World energy consumption reached 13,105 million tons in 2015 and exceeded 13,276.3 million tons in 2016 while the increase in Indonesia was 164.8 million tons and 175 million tons \cite{1} respectively. Until 2015, world coal consumption showed a rising monotonous curve. However, in 2016 there was a decline in the use of coal fuel due to the enactment of rules on reducing \( \text{CO}_2 \) emissions to reduce the adverse effects of the environment. Of course, the use of environmentally friendly technology in processing coal into primary energy sources is very important and urgent to implement. This leads to the development of sustainable renewable energy technologies in realizing energy security and availability, one of which is biomass \cite{2-3}. Indonesia has great potential renewable natural resources, such as palm oil that produces abundant waste, empty palm fruit bunches is the biggest one. Biomass is an environmentally friendly energy source that supplies 14% of the world's energy \cite{4}.

Gasification is a method of converting low rank coal that allows maximum energy extraction with a minimum amount of residue and high carbon conversion \cite{2,5}. Lignite coal has an inhibition effect that is less desirable for processing even though its availability in nature is very large \cite{6}. The disadvantages of biomass gasification are low energy density and high tar production so that the product needs to be treated. The shortcomings and advantages of coal and biomass gasification lead to the solution of
cogasification of coal with biomass which combines high coal energy density and low biomass emissions. When biomass is involved in coal gasification, the rate of production of hydrogen gas signifies the quality of synthesis gas. This occurs due to the presence of alkali and alkaline earth (AAEM) [7]. The presence of AAEM has a synergistic effect on the cogasification process by increasing the overall gasification rate [8]. AAEM in biomass, especially potassium, is a good promoter in the gasification process [9]. Potassium in biomass ash acts as a catalyst to increase coal reactivity and suppress tar formation [10]. Cogasification studies of coal with various types of biomass have been studied. The effects of alkali and alkaline earth synergies in the cogasification of low rank coal were obtained from switch grass [11], straw [12], sawdust [7, 13, 14], corn stalks [15], pine powder [16], wheat powder, and wood waste [17].

The greater the AAEM content in biomass ash, the stronger the catalytic influence. Each type of biomass has different AAEM content. The AAEM content in biomass ash which improves the quality of coal gasification can be deactivated by silica [18]. Therefore, pre-treatment is carried out in the form of coal demineralization through acid leaching such as HNO₃, HF, and HCl. Karaca and Ceylan [19] examined that H₂O₂ solutions were able to reduce mineral content in coal by up to 70%. Ishaq et al. [20] found that demineralization process of coal with HCl and HNO₃ gave 87% mineral content decrease. Demineralization with HF and HNO₃ mixture, Kizgut et al. (2006) [21] explained that the acid leaching method was able to demineralize coal up to 0.12-0.41%-wt. The research conducted by Hacifazlioglu et al. [22], Steel et al. [23], and Vaccaro [24] state that in terms of decreasing mineral content in coal, HCl and HF solutions have very good performance. The dissolution of coal by HF at a temperature of 65°C has been shown to eliminate Al and Si so that it can reduce the yield of ash from 5.3% to 1.37%-wt. Unlike HF, HCl can only dissolve simple compounds such as carbonate and phosphate [23]. Based on those findings, it is interesting to further study the effect of acid leaching to the coal properties and its gasification performance. The purpose of the present study is to examine the effect of pretreatment of HF leaching and mixing ratio on cogasification process of low rank coal with biomass.

2. Experiment

2.1. Materials
Coal and biomass were crushed into sizes smaller than 232μm (48 mesh) and then dried in the oven at 110°C for 14 hours. Determination of ash content in biomass and coal was done through combustion in the furnace at 750°C for 2 hours. Elemental contents in ash were analyzed using EDS while the composition of coal and biomass was determined through proximate and ultimate analysis. The comparative analyses of non-demineralized lignite (BLM), lignite demineralized (BLD), and empty palm fruit bunches (EPFB) are shown in Table 1 and Table 2.

2.2. Coal demineralization by HF leaching method
The 10g of dried coal was dissolved in 250 ml HF solution in Teflon glass. The solution was stirred for 4 hours at a temperature of 70°C. The solution was then neutralized by aqua dm. The filtered solid was dried in an oven for 14 hours at 110°C and then stored in a desiccator.

2.3. Lignit EPFB cogasification
The cogasification process was performed in the fixed bed downdraft reactor for 80 minutes using steam at 90-92°C. The total mass of coal and biomass was 3 grams. The carrier gas (nitrogen) rate is 85 cm³/minute. The furnace used is heated with a heating rate of 6°C/minute until it reached 700°C. The remainder solids after cogasification process was considered as the total mass of charcoal and ash. The gas product was then condensed with a temperature of 14-16°C cooling water. Some gases condensed to form tar were collected in condenser bottle while the non-condensed gas would pass through and collected in a gas bag for every 10 minutes.
Table 1. Proximate and ultimate analysis of the samples.

| Parameter       | BLM   | BLD   | EPFB  |
|-----------------|-------|-------|-------|
| Proximate       |       |       |       |
| Ash             | 9.54  | 1.63  | 8.97  |
| Volatile Matter | 47.38 | 51.53 | 72.18 |
| Fixed Carbon    | 43.08 | 46.84 | 18.85 |
| Ultimate        |       |       |       |
| Sulfur          | 1.07  | 1.07  | 0.14  |
| Carbon          | 64.38 | 64.38 | 46.19 |
| Hydrogen        | 3.74  | 3.74  | 5.52  |
| Nitrogen        | 1.14  | 1.14  | 0.78  |
| Oxygen          | 19.71 | 19.71 | 38.41 |

Table 2. Element content of the samples.

| Element (%) (wt dry basis) | C    | O    | Na   | Mg   | Al   | Si   | S    | K    | Ca   | P    | Fe   |
|---------------------------|------|------|------|------|------|------|------|------|------|------|------|
| BLM                       | 3.13 | 4.34 | 0.26 | 0.2  | 0.41 | 0.37 | 0.07 | 0.02 | 0.02 | 0.05 | 0.67 |
| BLD                       | 0.66 | 0.67 | 0.04 | 0.04 | 0.05 | 0.03 | 0.02 | 0.002| 0.004| 0.01 | 0.11 |
| EPFB                      | 3.34 | 3.8  | 0.24 | 0.27 | 0.27 | 0.25 | 0.07 | 0.04 | 0.03 | 0.05 | 0.59 |

2.4. Lignite EPFB cogasification

The data obtained from the preparation stage, coal demineralization, and the cogasification process were processed, analyzed, and then presented in the graph. Ash content of raw materials was determined by the ASTM method D.3174 and synthetic gas composition was analyzed using gas chromatograph (GC) with a thermal conductivity detector (TCD) connected with 2 types of columns, Porapak Q and Molesieve 5A. Meanwhile, the surface area and size of charcoal were analyzed through isothermal adsorption and so did the proximate and ultimate analysis of three raw materials.

2.4.1. Calculation of coal and biomass ash content. Ash content in coal and biomass was obtained through the combustion process. Coal/biomass mass before and after combustion were used for Equation 1 calculation.

\[
\text{ash content} = \frac{\text{mass ash}}{\text{mass sample}} \times 100\% \quad (1)
\]

2.4.2. Theoretical calculation of cogasification. The synthetic gas and charcoal yield from experimental were compared with predicted calculation. It was assumed there was no interaction between coal and biomass during cogasification [25]. The theoretical gas and charcoal yield were calculated by Equation 2 as follows,

\[
Y_{\text{predict}} = X_{\text{biomass}} \times Y_{\text{biomass}} + (1 - X_{\text{biomass}}) \times Y_{\text{coal}} \quad (2)
\]

with \(X_{\text{biomass}}\) is the mass fraction of biomass, \(Y_{\text{biomass}}\) and \(Y_{\text{coal}}\) are gas yield of biomass and coal.

3. Results and Discussion

3.1. Effect of feed blend ratio on cogasification process
Based on cogasification studies with variations of coal and biomass types, it was found that not all cogasification produced synergy effect. Krerkkaiwan et al. [12] stated that the interaction of biomass and coal in cogasification was determined by the type of biomass and type of coal. This study focused on the effect of adding oil palm empty bunches on H₂ yield from cogasification together with Indonesian lignite coal. To find out the synergy effect of cogasification, the experimental data were compared with the theoretical values calculated from the gasification of each feed: BLM, BLD, and EPFB. If there were differences between them, the synergy effect was indicated exist in cogasification [12]. If the experimental data produced a value greater than theoretical, the synergy effect would be positive whereas if the experimental data value was lower than the theoretical calculation, the synergy effect of cogasification would be negative. The synergy effect in cogasification occurred due to the catalytic effect of biomass ash which caused activation energy decreases [26].

![Figure 1. Product conversion of cogasification EPFB and BLM (a) Liquid, (b) Gas, and (c) Char.](image1)

![Figure 2. Synthesis gas conversion of cogasification EPFB and BLD (a) Liquid, (b) Gas, and (c) Char.](image2)

The main purpose of cogasification was to achieve the catalytic effect of biomass ash in increasing coal char pyrolysis conversion [27]. The pyrolysis char was converted into a gas product in the form of synthesis gas, liquid products consisted of volatile and tar condensates, and solid products as cogasified charcoal. This study focused on increasing the conversion of EPFB and lignite coal mixtures into synthesis gas with high H₂ gas yield. Based on this experiment, the addition of EPFB as a mixture of lignite coal feed, both BLM and BLD, increased percentage of cogasification gas products as shown in Figure 2. The same trend was produced by Patel and Narnaware [28] studies which examined six types of biomass with different mixing ratios to study the cogasification gas products. The six types of biomass provide the same behavior, increase in carbon conversion into gas products along with the increase percentage of biomass in the cogasification feed. This was caused by the synergy effect of biomass ash containing alkali and alkaline earth [27].

The results of the cogasification of EPFB-BLM and EPFB-BLD in Figure 3 show that the conversion of synthesis gas and liquid products produced a negative synergy effect for all mixing variations. Habibi et al. [28] and Krerkkaiwan et al. [12] explained the effect of negative synergy in cogasification due to the ratio of K/Al in feed and heating rate during the pyrolysis process. Habibi et al. [28] stated that the synergy effect occurs when the K/Al ratio in coal mixtures and biomass cogasification was more than 1. This comparison caused K bond Al and Si to form KAlSi₃O₈. The K/Al ratio for EPFB-BLM and EPFB-BLD in this experiment was 0.088 and 0.13, respectively. Although the content of Al and Si in coal has been minimized through leaching of HF acid, the cogasification mixture still had Si and Al content from EPFB with relatively high number. K and Al in carbon fuel were stored in the form of
alu
mina (Al₂O₃) and silicate (SiO₂). Both of these compounds could react with alkali metals to form silica-aluminum compounds (KAlSiO₄, KAl₂SiO₅, CaAl₂Si₂O₈) which inhibited catalytic effect in cogasification. These compounds were formed irreversible reaction so that alkali and alkaline earth metals could not be reused in cogasification [10, 15, and 27]. In addition, effect of slow heating rates during pyrolysis process had caused no synergy effect in cogasification process [29-30].

Based on data from the composition measurement of cogasification synthesis gas EPFB: BLM every 10 minutes, sequence of rate formation of gas H₂, CO, and CO₂ stability respectively occurs in the ratio 1:2, 1:1, and 2:1. Those are showed on Figure 5 and Figure 6.

Figure 3. Profile of synthesis gas and H₂/CO of EPFB:BLM mixing ratio at (a) 1:2, (b) 1:1, (c) and 2:1.

Figure 4. Profile of synthesis gas and H₂/CO of EPFB:BLD mixing ratio at (a) 1:2, (b) 1:1, (c) and 2:1.

Cogasification of BLD had a better pattern of synthesis gas yield and H₂/CO ratio than BLM. This was due to the alkali metal from biomass ash which was active on BLD-EPFB cogasification rather than BLM-EPFB which had high silica and alumina in lignite coal that could deactivate AAEM [15]. Cogasification of BLM-EPFB had high charcoal reactivity [31], so that both mixed cogasification provided an increasing and unstable yield profile. Low reactivity of charcoal BLD caused the mixture of cogasification of BLD-EPFB to have a stable gas yield [32]. The quality of synthesis gas in terms of synthesis gas yield was produced. Good synthesis gas had a large H₂/CO ratio and low CH₄/CO. The more positive synergy effect of coal and biomass cogasification, the better the synthesis gas quality produced (high H₂ yield). All experimental results of H₂, CO₂, CO, and CH₄ were lower than theoretical values, indicating a negative synergy effect. This event was caused by the distribution of the mineral content in the cogasification feed mixture. Based on Table 2, the content of silica and alumina in EPFB was quite large so that it had strong strength in inhibiting the catalytic effect of AAEM from biomass. According to Habibi et al. [28] a low K/Al ratio will have a strong inhibitory effect in cogasification because the K element contained would react with Al to form non-catalytic compounds. The low K/Al ratio and the slow heating rate in the cogasification of the BLM-EPFB and BLD-EPFB cause both of them to have a negative synergy effect.
In general, both the cogasification of EPFB-BLD and EPFB-BLM produced a negative synergy effect in producing CO₂ gas. Figure 7 and Figure 8 explained the most positive synergy effect of CO₂ gas yield from cogasification of lignite-EPFB occurring in mixing feed EPFB and lignite 1:1. The peak of CO₂ yield in the coal-biomass 1:1 mixing ratio was also obtained by the Krerkkaiwan et al. [12]. The increase in CO₂ gas yield when the percentage of biomass in the cogasification feed rose up due to the high oxygen content in the biomass which drove CO₂ oxidation. Mallick et al. [27] said there were two patterns of H₂ production when the percentage of biomass was added in the cogasification feed: increases or decreases. Based on the data of this study as illustrated in Figure 7 and Figure 8, it was agreed that H₂ increased when biomass was added to the cogasification feed. This was caused by an increase in biomass impact on higher H/C and O/C ratio in cogasification feed. The content of H and OH acted as a hydrogen donor species and encouraged the process of breaking aromatic components in coal [12].

The presence of AAEM in biomass which was mixed together with coal as a cogasification feed, increases H₂ and CO₂ with a decrease in CO formed. This occurs due to tendency of water shift gas reaction that converted CO to H₂ and CO₂ [33]. Biomass had more porous charcoal structure and higher charcoal reactivity. With this advantage, steam as gasification media easily diffused and reacted to produce special gas synthesis gases [34].

Although cogasification of raw and demineralization lignite resulted tendency to obtain CO₂ to the same percentage of biomass, the cogasification of lignite demineralization provides a higher theoretical experiment difference, indicating that the H₂ cogasification product of EPFB-BLD was not higher than of raw lignite H₂. Jenkins et al. [32]; Hippo and Walker [35] stated that Ca and Na in low rank coal had a significant effect on reactivity of charcoal while other minerals (K, Na and Fe) did not. A similar study also found that gasification reactivity originated from the content of K, Na, Ca, and coal char [36-38]. Therefore, demineralized coal (BLD) had a lower reactivity than BLM so that the yield of H₂ cogasification of BLD was lower than BLM.

The yield of methane gas in a variety of lignite-EPFB mixtures. Theoretically, the yield of methane was proportional to the addition of lignite in cogasification feed. However, according to the experiment, it was found that methane was only formed during cogasification involving non-demineralized lignite with 1:1 lignite-EPFB ratio while methane was formed at a ratio of 2:1 and 1:2 to the cogasification of lignite demineralization and EPFB. This indicated that methane only applied to a certain ratio for two different types of lignite. Figure 7 and Figure 8 showed that an increase in the amount of biomass leads to an increase in the yield of CO in synthetic gas. This was due to CO consumed in the water gas shift reaction. Yuan et al. [39] explained that the increase in CO along with the increase in the percentage of
biomass caused by the supply of OH radicals was able to attack the aromatic coal chain and react with aliphatic species to form CO.

3.2. Effect of coal demineralization by HF leaching on gasification product

Coal demineralization process was a pre-treatment cogasification phase of EPFB-lignite aimed at minimizing disadvantage minerals in coal ash, silica and alumina. The characteristics of the cogasification charcoal discussed consisted of surface area, pore diameter, and pore volume. Based on BET test with N₂ isothermal adsorption method, data obtained on charcoal cogasification characteristics of the mixture of BLM-EPFB and BLD-EPFB were shown in Table 3 below.

Table 3. Data characteristics of cogasification charcoal.

| Mixed Feed | Char Surface Area (m²/g) | Pore Diameter (nm) | Pore Volume (ml/g) |
|------------|--------------------------|--------------------|--------------------|
| BLM : EPFB = 2 : 1 | 385.994                  | 2.9054            | 0.2804             |
| BLD : EPFB = 2 : 1 | 375.750                  | 2.3668            | 0.2234             |

Based on Table 3, charcoal from the BLM-EPFB cogasification had larger surface area than BLD-EPFB. According to Nunes et al. (2017) [40] and Calahorro et al. [41], HF demineralization of coal was able to reduce the coal surface area since it reduced micropores and mesopores due to the displacement of insoluble inorganic substances from the coal carbon matrix. The transformation of micropores and mesopores into macropores causes lower surface area of BLD than BLM. Based on the experiments in this study, the BLM-EPFB cogasification charcoal had larger diameter and volume pore than the BLD-EPFB. Reduction mesopores and micropores into macropores which resulted in coal pore volume decrease due to HF demineralization found by Nunes et al. [40] and Calahorro et al. [41]. According to Nunes et al. [40] and Calahorro et al. [41], demineralization of HF moved inorganic substances bound to carbon matrix then clogged the micropores and mesoporous coal. Similar to pure sample gasification, the main product of lignite cogasification process along with oil palm empty bunches consists of synthesis gas (H₂, CO, CO₂ and CH₄), liquid products (volatile matter and condensable gases), and charcoal. Figures 11 and Figure 12 showed the distribution of cogasification products for EPFB-BLM and EPFB-BLD based on experiment and theoretical calculations. In general, the three variations in the mixing ratio provided a negative synergy effect on yield of liquid and gas products but not for BLD and BLM carbon conversion.

Based on the experiments, the cogasification conversion of EPFB-BLD and EPFB-BLM had significant differences for liquid, solid and gas products. In liquid products, the synergistic effect of cogasification of EPFB-BLD is more negative than EPFB-BLM, indicating that it is reducing volatile substances and condensed gases. HF is an acid solution with very strong oxidation properties and easily dissolves mineral substances in coal [23]. In case of cogasification that focuses on increasing the gas yield of synthesis, the demineralization process is not good enough because it has a more negative synergy effect than non-pre-treated lignite. Alkali metals that evaporate and stick to the coal surface hold a major effect of charcoal reactivity and catalytic effect in production of gas synthesis [10]. BLD produces a better synergy effect on char conversion because it has a silica content that can help the process of cutting large carbon molecules into smaller products [27]. This behavior occurs in all mixing ratios of EPFB-BLM and EPFB-BLD 2:1, 1:1, and 1:2.
Figures 9 and Figure 10 show comparison of experimental data and theoretical calculations for cogasification synthesis gas EPFB-BLM and EPFB-BLD. In general, the three variations in the mixing ratio provide a negative synergy effect on the yield of H₂, CO₂, CO, and CH₄ for both BLD and BLM. Based on the experiment, the yield of CO and CO₂ gas between the EPFB-BLD and EPFB-BLM cogasification are alike. For H₂ concentration, negative synergy effect of EPFB-BLD cogasification was higher than EPFB-BLM, indicating that demineralization reduced H₂ gas yield. Therefore, demineralization process was not good enough for cogasification pretreatment which aimed to obtain high H₂ yield. Jenkins et al. [32] stated that demineralization of HF was able to reduce the amount of pyrolysis charcoal sevenfold which had an impact on reducing reactivity of lignite charcoal up to 34 times. Overall for the case of low rank coal, demineralization using HF acid solution caused a decrease in reactivity of charcoal [42].

4. Conclusion
Coal pre-treatment by demineralization through HF leaching reduces gasification performance in terms of a decrease in synthesis gas and H₂ yield. An increase in char yield is caused by a drop in coal reactivity significantly that affects the catalytic effect on the overall gasification process.

References
[1] British Petroleum 2017 BP Statistical Review of World Energy 2017 British Petroleum 1–52.
[2] Ahmed I I, Nipattummakul N and Gupta A K 2011 Characteristics of syngas from co-gasification of polyethylene and woodchips Applied Energy 88 165–174.
[3] Fermoso J, Arias B, Plaza M G, Pevida C, Rubiera F, Pis J J, García-Peña F and Casero P 2009 High-pressure co-gasification of coal with biomass and petroleum coke Fuel Processing Tech. 90 926–932.
[4] Saxena R C, Adhikari D K and Goyal H B 2009 Biomass-based energy fuel through biochemical routes: A review Renewable and Sustainable Energy Rev. 13 167–178.
[5] Cormos C C 2012 Hydrogen and power co-generation based on coal and biomass/solid wastes co-gasification with carbon capture and storage Intl. Journal of Hydrogen Energy 37 5637–48.

[6] André R N, Pinto F, Franco C, Dias M, Gulyurtlu I, Matos M. A. A and Cabrita I 2005 Fluidised bed co-gasification of coal and olive oil industry wastes Fuel 84 1635–44.

[7] Xu C, Hu S, Xiang J, Zhang L, Sun L, Shuai C, Chen Q, He L and Edreis E M A 2014 Kinetic models comparison for steam gasification of coal/biomass blend chars Bioresource Tech. 171 253–259.

[8] Ellis N, Masnadi M S, Roberts D G, Kochanek M A and Ilyushechkin A Y 2015 Mineral matter interactions during co-pyrolysis of coal and biomass and their impact on intrinsic char co-gasification reactivity Chem. Eng. Journal 279 402–408.

[9] Hernández J J, Ballesteros R and Aranda G 2013 Characterisation of tars from biomass gasification: Effect of the operating conditions Energy 50 333–342.

[10] Zhang Y, Zheng Y, Yang M and Song Y 2016 Effect of fuel origin on synergy during co-gasification of biomass and coal in CO2 Bioresource Tech. 200 789–794.

[11] Masnadi M S, Habibi R, Kopyscinski J, Hill J M, Bi X, Lim C J, Ellis N and Grace J R 2014 Fuel characterization and co-pyrolysis kinetics of biomass and fossil fuels Fuel 117 1204–14.

[12] Krerkaaiwan S, Fushimi C, Tsutsumi A and Kuchonthara P 2013 Synergetic effect during co-pyrolysis/gasification of biomass and sub-bituminous coal Fuel Processing Tech. 115 11–18.

[13] Xu C, Hu S, Xiang J, Zhang L, Sun L, Shuai C, Chen Q, He L and Edreis E M A 2014 Interaction and kinetic analysis for coal and biomass co-gasification by TG-FTIR Bioresource Tech. 154 313–321.

[14] Yuan S, Dai Z H, Zhou Z J, Chen X L, Yu G S and Wang F C 2012 Rapid co-pyrolysis of rice straw and a bituminous coal in a high-frequency furnace and gasification of the residual char Bioresource Tech. 109 188–197.

[15] Ding L, Zhang Y, Wang Z, Huang J and Fang Y 2014 Interaction and its induced inhibiting or synergistic effects during co-gasification of coal char and biomass char Bioresource Tech. 173 11–20.

[16] Biagini E, Lippi F, Petarra C L and Tognotti L 2002 Devolatilization rate of biomass and coal-biomass blends: An experimental investigation Fuel 81 1041–50.

[17] Vuthaluru H B 2004 Thermal behaviour of coal/biomass blends during co-pyrolysis Fuel Processing Tech. 85 141–155.

[18] Mukherjee S and Borthakur P C 2001 Chemical demineralization/desulphurization of high sulphur coal using sodium hydroxide and acid solutions Fuel 80 2037–40.

[19] Karaca H and Ceylan K 1997 Chemical cleaning of Turkish lignites by leaching with aqueous hydrogen peroxide Fuel Processing Tech. 50 19–33.

[20] Ishaq M, Ahmad I, Shakirullah M, Bahader A and Taj N 2002 Characterization of Khushab coal (Punjab Pakistan) Journal of the Chemical Society of Pakistan 24 240–245.

[21] Kizgut S, Baris K and Yilmaz S 2006 Effect of chemical demineralization on thermal behavior of bituminous coals Journal of Thermal Analysis and Calorimetry 86 483–488.

[22] Hacifazligolu H, Uckan D and Sahin M 2017 Environmental Effects Demineralization of Turkish Tosya lignite coal by boric acid leaching Demineralization of Turkish Tosya lignite coal by boric acid Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 38 2777–81.

[23] Steel K M, Besida J, O’Donnell T A and Wood D G 2001 Production of Ultra Clean Coal - Part II - Ionic equilibria in solution when mineral matter from black coal is treated with aqueous hydrofluoric acid Fuel Processing Tech. 70 193–219.

[24] Vaccaro S 2010 Demineralization and Desulfurization Process to Generate Clean Coal Chem. Eng. Transactions 21.

[25] Rizkiana J, Guan G, Widyatno W B, Hao X, Huang W, Tsutsumi A and Abudula A 2014 Effect of biomass type on the performance of cogasification of low rank coal with biomass at relatively low temperatures Fuel 134 414–419.

[26] McKee D W 1983 Mechanisms of the alkali metal catalyzed gasification of carbon Fuel 62 170–
175.

[27] Mallick D, Mahanta P and Moholkar V S 2017 Co-gasification of coal and biomass blends: Chemistry and engineering Fuel 204 106–128.

[28] Habibi R, Kopyscinski J, Masnadi M S, Lam J, Grace J R, Mims C A and Hill J M 2013 Co-gasification of biomass and non-biomass feedstocks: Synergistic and inhibition effects of switchgrass mixed with sub-bituminous coal and fluid coke during CO2 gasification Energy & Fuels 27 494–500.

[29] Haykiri-Acma H and Yaman S 2007 Synergy in devolatilization characteristics of lignite and hazelnut shell during co-pyrolysis Fuel 86 373–380.

[30] Jones J M, Kubacki M, Kubica K, Ross A B and Williams A 2005 Devolutilisation characteristics of coal and biomass blends Journal of Analytical and Applied Pyrolysis 74 502–511.

[31] Nzhou A, Stanmore B and Sharrock P 2013 A review of catalysts for the gasification of biomass char, with some reference to coal Energy 58 305–317.

[32] Jenkins R G, Nandi S P and Walker P L 1973 Reactivity of heat-treated coals in air at 500 °C Fuel 52 288–293.

[33] Zhang Z, Pang S and Levi T 2017 Influence of AAEM species in coal and biomass on steam co-gasification of chars of blended coal and biomass Renewable Energy 101 356–363.

[34] Xu Q, Pang S and Levi T 2011 Reaction kinetics and producer gas compositions of steam gasification of coal and biomass blend chars, part 2: Mathematical modelling and model validation Chem. Eng. Science 66 2232–40.

[35] Hippo E and Walker P L 1975 Reactivity of heat-treated coals in carbon dioxide at 900 °C Fuel 54 245–248.

[36] Fernández-Morales I, López-Garzon F J, López-Peinado A, Moreno-Castilla C and Rivera-Utrilla J 1985 Study of heat-treated Spanish lignites: Characteristics and behaviour in CO2 and O2 gasification reactions Fuel 64 666–673.

[37] Fung D P C and Kim S D 1984 Chemical reactivity of Canadian coal-derived chars Fuel 63 1197–1201.

[38] Miura K, Hashimoto K and Silveston P L 1989 Factors affecting the reactivity of coal chars during gasification, and indices representing reactivity Fuel 68 1461–75.

[39] Yuan S, Dai Z H, Zhou Z J, Chen X L, Yu G S and Wang F C 2012 Rapid co-pyrolysis of rice straw and a bituminous coal in a high-frequency furnace and gasification of the residual char Bioresource Tech. 109 188–197.

[40] Nunes K G P, Engel K M, Osório E and Marcílio N R 2017 Demineralization of Brazilian coals for use in gasification and oxy-fuel combustion processes, aiming to reduce CO2 emissions Energy and Fuels 31 8560–71.

[41] Calahorro C V, Cano T C and Serrano V G 1987 Effect of acid and heat treatments on surface area and porosity of a Spanish coal with high mineral matter content Fuel 66 479–485.

[42] Laurendean N M 1978 Heterogeneous kinetics of coal char gasification and combustion Progress in Energy and Combustion Science 4 221–270.