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Potential Alternative Energy of Hybrid Coal from Co-pyrolysis of Lignite with Palm Empty Fruit Bunch and the Kinetic Study

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A B S T R A C T

Lignite is classified as a low-rank coal due to its low content of calories. Co-pyrolysis with biomass waste such as palm empty fruit bunches (EFB) here can be used to increase lignite's economic value. The mixture of these two materials can produce an alternative energy source called hybrid coal (HC). This study aims to determine the optimum temperature for co-pyrolysis of lignite and EFB as well as characterize liquid (tar) and solid product (HC). Its kinetic study was evaluated as well. A raw material of 200 grams with a composition of 22.5% (w/w) EFB to lignite was put into a reactor to react at a temperature range of 300-450ºC for 1 hour. To form hybrid coal briquettes (HCB), tapioca adhesive with a concentration of 6% (w/w) was added to the solid product (HC). The results showed that the tar yield increased with increasing temperature from 300 to 450ºC. Similarly, the calorific value of HC increased by 14.50% as also occurred in other physical properties of HC. Meanwhile, the kinetic study revealed that the model was well-fitted to the data, and confirmed the obtained results. Thus, this research can support the development of affordable alternative energy to be implemented in large-scale production.

1. INTRODUCTION

Undeniably, coal still becomes one of the main sources to meet the current energy demand. Most coals, however, are in low grades, leading them to be less prioritized. Lignite is the lowest rank of coal for having less economic value due to the presence of volatile matter and moisture content with low fixed carbon content. This further causes high carbon dioxide emissions leading to inefficient fuel. To increase the added value, a simple and environmentally-friendly process is required.

Meanwhile, the significant increase in plantations and the palm oil industry has brought negative impacts on the production of an abundant amount of waste, including palm empty fruit bunches (EFB). If not managed properly, this biomass waste might cause environmental problems. In fact, the waste is rich in cellulose and other organic compounds in which the appropriate use of the waste can address the energy demand as well as the environmental problems.

To improve the lignite value can be alternatively realized through the combustion process without oxygen such as pyrolysis combined with additional biomass. Hence, this co-processing of biomass with coal eliminates the disadvantages of both materials (Byambajav *et al.*, 2018). Each coal and EFB possesses a complex structure and shows different thermal decomposition, thus resulting in a synergistic effect of the two raw materials (Chen *et al.*, 2020).

The co-pyrolysis process of using appropriate biomass can improve the bio-oil quality resulted as it is possible to obtain a reduction in moisture, oxygen, and acid content and an increase in carbon content (Gouws *et al.*, 2021). Furthermore, the resulting solid product from the process can also be used as briquettes, which are the densification of the biomass mixture decomposing particles through specific variable pressure, temperature, and other processes. Having a uniform shape and size, this densified product makes it simpler and more affordable to store and transport (Bajwa *et al.*, 2018).

Several studies related to the co-pyrolysis of biomass and coal have been carried out (Huang *et al.*, 2019; Ismail *et al.*, 2020; Saeed *et al.*, 2020; Wang *et al.*, 2020), for instance, the co-pyrolysis of lignite and rice husk and sawdust (Sasongko *et al.*, 2017) and co-pyrolysis of lignite and Aspen wood (Byambajav *et al.*, 2018). The co-pyrolysis of lignite and EFB was carried out by Siti et al. to find the effect of the blending ratio on the liquid product. However, in literature, studies on lignite and EFB co-pyrolysis are found limited in number. In turn, this study aims to discover the temperature effect of the co-pyrolysis process and characterize both liquid and solid products.

To analyze and support the results, kinetic studies became a critical part to be applied in large-scale production (Yeo *et al.*, 2017). Furthermore, the kinetic parameters consider the process to operate under optimal conditions, thereby increasing efficiency. This research is expected to describe a new solution of alternative energy based on lignite and EFB as efficient and affordable materials.

2. METHODS
2.1. Materials

EFB (empty fruit bunches) were obtained from PT. Perkebunan Nusantara XIII Pelaihari, Tanah Laut District, South Kalimantan, Indonesia. It contains hemicellulose (18,14%), cellulose (48,85%,) and lignin (22,41%). Meanwhile, lignite was obtained from Asam-Asam, Tanah Bumbu District, South Kalimantan, Indonesia.

2.2. Pre-Treatment of Raw Material

The lignite was pulverized and sifted to 20-50 mesh. The EFB, meanwhile, was cut and washed to remove any dirt particles prior to being dried under the sunlight. It was mashed with a particle size of 50-100 mesh

prior to being dried at a temperature of 105ºC until reaching the constant mass.

2.3. Co-Pyrolysis and Briquetting

A total of 200 grams of a mixture with the composition of EFB/lignite 22.5% was put into the reactor and heated at the temperatures of 300ºC, 350ºC, 400ºC, and 450ºC for 1 hour with 1.5 L/minute of nitrogen gas flow rate. The liquid (tar) and solid product (HC) resulting from co-pyrolysis were then weighed. Furthermore, a tapioca adhesive of 6% was added to HC to form a cylindrical pellet with a diameter of 5 cm with a pressure of 750 psi.

2.4. Characterization

The liquid compound identification was conducted by a Gas Chromatography Spectroscopy Mass (GC-MS) QP2010S SHIMADZU embedded with Column Rastek RXi-5MS, 30 meters in length, ID 0.25 mm, Helium carrier gas, EI ionization, and 70 Ev. The quantification of calorific numbers, meanwhile, was performed using a bomb calorimeter (Gallenkamp Adiabatic Bomb Calorimeter CBA-305) and the proximate analysis was determined following ASTM D3172-07a. SEM was performed for microscopic observation (Hitachi Se3400 N model, Horiba EMAX) using backscattered electrons mode at 5.0 and 10.0 kV.

A wavelength distribution X-ray fluorescence (XRF) spectrometer analysis of materials was performed to analyze the chemical constituents or elements present in the sample using Perkin Elmer 1800 model instrument from 450 cm^{-1} to 4400 cm^{-1} by using a KBr tablet. The X-ray diffraction pattern of the material was recorded by XRD (Bruker AXS). These analyses were conducted using Cu K alpha radiation. The functional groups were detected using FTIR (Nicolet Magna-IR550, Madison). Further, BET analysis was conducted utilizing Micromeritics TriStar II 3020 and thermogravimetric analysis (TGA) was performed on approximately 10 mg of the sample heated at 800°C at a rate of 0.5°C/s under 50 mL/min of nitrogen using a thermogravimetric analyzer.

2.5. Kinetic Study

The kinetic study of EFB and lignite co-pyrolysis was evaluated using TGA data. Commonly, the decomposition rate of a solid is given in the following Eq. (1) (Zhang *et al.,* 2016):

$$\frac{d\alpha}{dt} = k(T)f(\alpha) \tag{1}$$

where α is the mass conversion ratio with $\alpha = (m_0 - m_t)/(m_0 - m_f)$, m_0, m_t, and m_f demonstrate the initial, current, and terminal sample weight, respectively, t refers to time, f(α) is the reaction model and k(T) is the rate constant of Arrhenius' law in Eq. (2):

$$k(T) = A\exp\left(-\frac{E}{RT}\right) \tag{2}$$

where A is the pre-exponential factor, E is the activation energy, R is the ideal gas constant and T is the absolute temperature.

The combination of Eq. (1) and (2) with the assumption of the one-step process of converting raw material to product is described as follows Eq. (3).

$$\frac{d\alpha}{dt} = A\exp\left(-\frac{E}{RT}\right)(1-\alpha)^n \tag{3}$$

where n is the reaction order. First-order reactions are suitable for describing experimental data obtained by TGA (Saddawi *et al.,* 2010):

$$\frac{d\alpha}{dt} = A\exp\left(-\frac{E}{RT}\right)(1-\alpha) \tag{4}$$

Equation (4) can be converted for a constant heating rate β during pyrolysis, $\beta = dT/dt$, hence leading to Eq. (5):

$$\frac{d\alpha}{1-\alpha} = \frac{A}{\beta}\exp\left(-\frac{E}{RT}\right)dT \tag{5}$$

Integration and linearization Eq. (5) resulted in Eq. (6).

$$\ln\left[\frac{-\ln(1-\alpha)}{T^2}\right] = \ln\left(\frac{AR}{\beta E}\right) - \frac{E}{RT} \tag{6}$$

A plot of ln $[-\ln (1 - \alpha)/T^2]$ *vs.* $1/T$ provided the values of *A* from the intercept and *E* from the slope.

3. RESULTS AND DISCUSSION

3.1. Temperature Effect on Tar and Char Yield

In both the pyrolysis and co-pyrolysis processes, the mass of raw materials in the reactor was substantially reduced because the constituent components were decomposed into liquid products (tar), gas, and solids (char). **Figure 1** presents the yield of tar and char (HC) based on temperature variation.

As shown in **Figure 1,** the increase in co-pyrolysis temperature increased tar yield, while the char decreased. Here, temperature affects the co-pyrolysis process because a decomposition process will be more complete with an increasing temperature (Ma *et al.*, 2019). The increase in tar yield at higher temperatures described an increase in decomposition reaction rate. At lower temperatures, heat from pyrolysis can encourage the thermal decomposition of coal to form more liquid products (Chen *et al.*, 2020). At higher temperatures, the heat received by the particles became greater, thus leading to an increase in energy. This caused the breakdown of more polymer chains into smaller molecules. As a result, more products became tar and gas at higher temperatures. The high content of lignin due to its stable structure can lead to higher biochar yields (Muigai *et al.*, 2020).

Lignocellulosic biomass is composed of a cell wall matrix. During pyrolysis, volatile organic compounds left the matrix, but the lignin-rich cell walls were not easily degassed, they remained intact after heat treatment, in contrast to the charcoal and the cell wall that were no longer intact (Abdelsayed *et al.*, 2019). Increasing the temperature in the co-pyrolysis of lignite and EFB can inhibit any secondary reactions (such as re-polymerization and cross-linking reactions) and generates more free radicals (Huang *et al.*, 2019) hence, the char yield decreases.

3.2. Characterization of Tar

The liquid product (tar) resulted from the co-pyrolysis of EFB and lignite was blackish-brown with a pungent odor. It contains an organic phase and a higher water content. To identify the composition of the compound of the tar produced by co-pyrolysis of lignite and EFB, the mixture of compounds was passed through gas chromatography (GC) and then separated into individual components. **Figure 2** presents the results of the GC-MS analysis of tar.
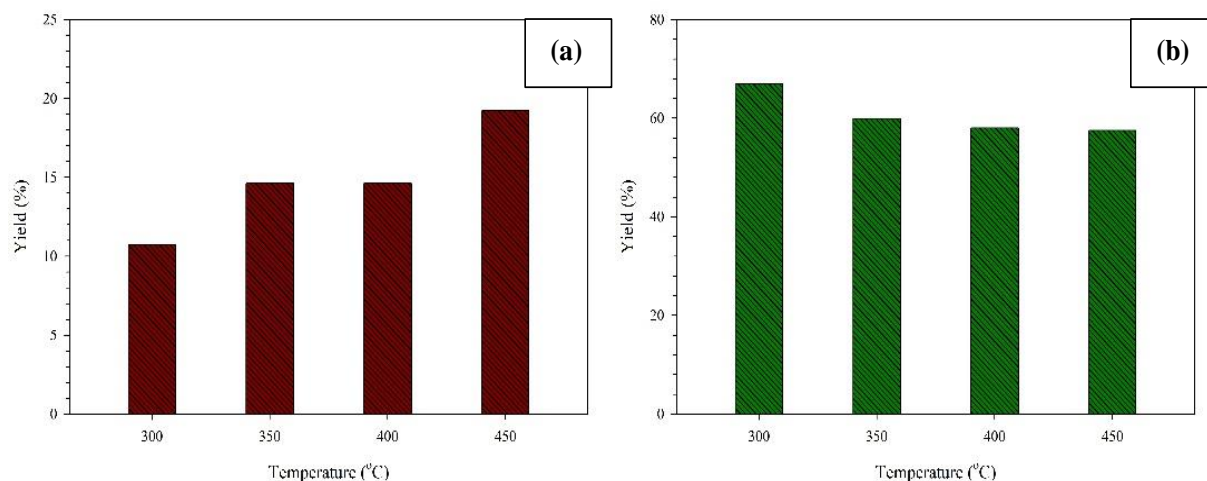
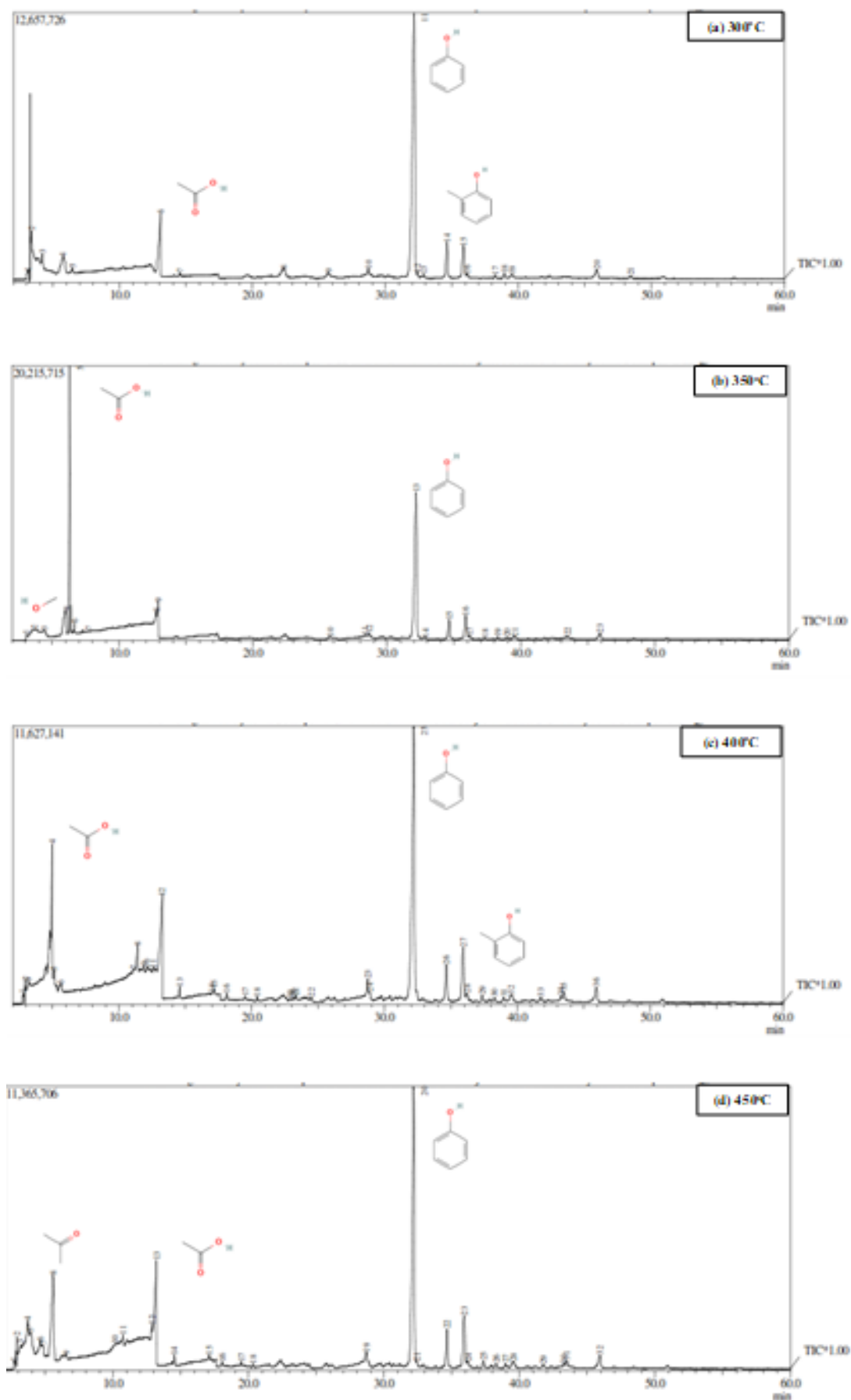**Figure 1.** Relation of (a) liquid (b) solid yield to temperature.

Figure 2. Chromatogram of Tar from Lignite and EFB Co-Pyrolysis

As shown in **Figure 2**, in the coal tar chromatogram, approximately 21-36 peaks were observed indicating the number of compounds contained in the tar product. The major components identified in the tar product are presented in **Table 1**.

Table 1 shows the compounds in tar consisting of phenol, acids, and ketones. The pyrolysis process degraded the hemicellulose in EFB to alcohol and carboxylic acid at low temperatures (200-300°C). This was confirmed by the presence of acetic acid in each variation and the declining value at a high temperature of 450°C. The cellulose was decomposed into carbonyl and heterocyclic compound at medium temperature (300-400°C), but furfural in this study was only observed at 300°C.

The lignin is degraded to monomeric phenolic compounds and light aromatic hydrocarbon at high temperatures (250-500°C) (Huang *et al.*, 2018; Yogalakshmi *et al.*, 2021). Here, the presence of phenol was detected for all temperatures but no benzene was found. Furthermore, phenol followed by acetic acid was found as the largest compound (written in bold) identified in tar. The largest compound of phenol was observed due to the content of lignin contained in the plant and cell walls matrix to stabilize the structure (Muigai *et al.*, 2020). The observation was also found in coal as it was made from plants and decomposed over millions of years (Abdelsayed *et al.*, 2019).

3.3. Characterization of Char (Hybrid Coal)

Solids produced from the co-pyrolysis of lignite and EFB are called hybrid coals (HC) in the form of black powder. The physical properties of lignite, EFB, and HC are shown in **Table 2.** Hybrid coal, which is glued with a starch solution is then called hybrid coal briquettes (HCB) in the form of black pellets with a diameter of 5 cm.

As shown in **Table 2,** increasing the temperature of co-pyrolysis increased the calorific value of hybrid coal. In the temperature range of 200-300°C, biomass underwent degassing and carbonization, thereby increasing the calorific value. Furthermore, at 300-400°C, carbonization began to release carbon monoxide, carbon dioxide, and other short hydrocarbons (Sasongko *et al.*, 2017).

Table 1. Tar compound identified by GC-MS.

Compounds	Chemical Formula	Temperature (°C) Peak (%)			
		300	**350**	**400**	**450**
Diphenylmaleic anhydride	$C_{16}H_{10}O_3$	1.07	0	0.48	0.68
Glyceraldehyde	$C_3H_6O_3$	0	0	0.91	6.35
Methanol	CH_4O	0	**11.68**	0	5.68
Hydroxyacetone	$C_3H_6O_2$	0.34	0	2.95	0.42
Acetic acid	$C_2H_4O_2$	**17.64**	**30.23**	**33.66**	**28.11**
Acetone	C_3H_6O	4.78	7.04	0.93	**11.79**
Furfural	$C_5H_4O_2$	2.63	0	0	0
γ-Butyrolactone	$C_4H_6O_2$	0.54	1.48	1.63	1.32
Phenol	C_6H_6O	**56.16**	**35.16**	**39.44**	**30.73**
o-Cresol	C_7H_8O	4.77	3.39	3.96	3.08
m-Cresol	C_7H_8O	**4.94**	4.48	**6.05**	5.18
3-Ethylphenol	$C_8H_{10}O$	0.81	1	1.35	0.97
Catechol	$C_6H_6O_2$	0	0.36	0.84	0.57
2,6-Dimethoxyphenol	$C_8H_{10}O_3$	1.58	1.4	1.55	1.36

Table 2. Physical properties of raw materials and hybrid coal.

| Condition	Calorific Value (cal/g)	Proximate Analysis (%)			
		Ash	Moisture	Volatile Matter	Fixed Carbon
EFB before pyrolysis	4,157.88	2.971	7.568	67.012	22.449
Lignite before pyrolysis	4,785.15	4.001	25.250	28.272	42.477
EFB after pyrolysis at 400ºC	6,522.10	4.357	4.478	37.266	53.899
Lignite after pyrolysis at 400ºC	6,475.11	14,17	2.44	11.890	71.500
HC at 300 °C	5,964.15	10.358	2.727	28.164	58.751
HC at 350 °C	6,400.76	10.876	2.188	13.257	73.68
HC at 400 °C	6,734.81	7.542	2.272	12.258	77.929
HC at 450 °C	6,828.69	7.385	2.226	12.397	77.993
SNI 13-4931-2010	5,000-6,000	Max 15	Max 12	Max 22	> 30

Furthermore, coal carbonization above 400°C increased the calorific value of hybrid coal more significantly. Here, the calorific value of hybrid coal increased by 14.5% at a temperature of 450°C compared to HC at 300°C. This study also performed individual lignite pyrolysis at a temperature of 400ºC as a comparison in which it produced a calorific value of 6,475.11 cal/g - still lower than that of a mixture of lignite and EFB at the same temperature. It showed that the presence of EFB increased the calorific value of hybrid coal products and the value continued to increase with the increasing temperature.

The calorific value of this hybrid coal greatly affected the quality of the briquettes produced. The calorific value of a briquette describes the value of the heat of combustion produced by briquettes (Ujjinappa & Sreepathi, 2018). Hybrid coal briquettes showed a lower calorific value than the value of HC (**Figure 3a**) but they still met the solid fuel quality requirements.

The increase in calorific value also led to an increase in the fixed carbon content in hybrid coal. This increase then affected the calorific value of HC; at the greater fixed carbon content, the calorific value increased. Similar to the calorific value, it was also observed that the fixed carbon content decreased after becoming HCB (**Figure 3b**).

This was possibly caused by the presence of starch solution formed in the process, thereby increasing the water content. Briquettes with a high water content decrease the calorific value because more energy will be absorbed in water evaporation (Saeed *et al.*, 2020).

The level of fixed carbon is inversely proportional to the number of volatile species in the material (Muigai *et al.*, 2020). As shown in **Table 2**, materials with high volatility levels had lower solid carbon values. Since EFB had the highest volatile matter content, it was thus suggested to be a suitable feedstock for processes with thermochemical transformation such as pyrolysis. The high volatile content also makes biomass a highly reactive fuel burning faster (Shariff *et al.*, 2016). The volatile components of biomass pyrolysis contain abundant OH free radicals, H free radicals, and other trace small molecules with free radicals, which migrate to the surface of coke and enter the matrix of coke (Muigai *et al.*, 2020). The depolymerization and decomposition reaction of charcoal matrix combined with the above-mentioned small free radicals derived from biomass volatiles produce a large number of fragment structures, thereby inhibiting the secondary cracking reactions (Chen *et al.*, 2020).
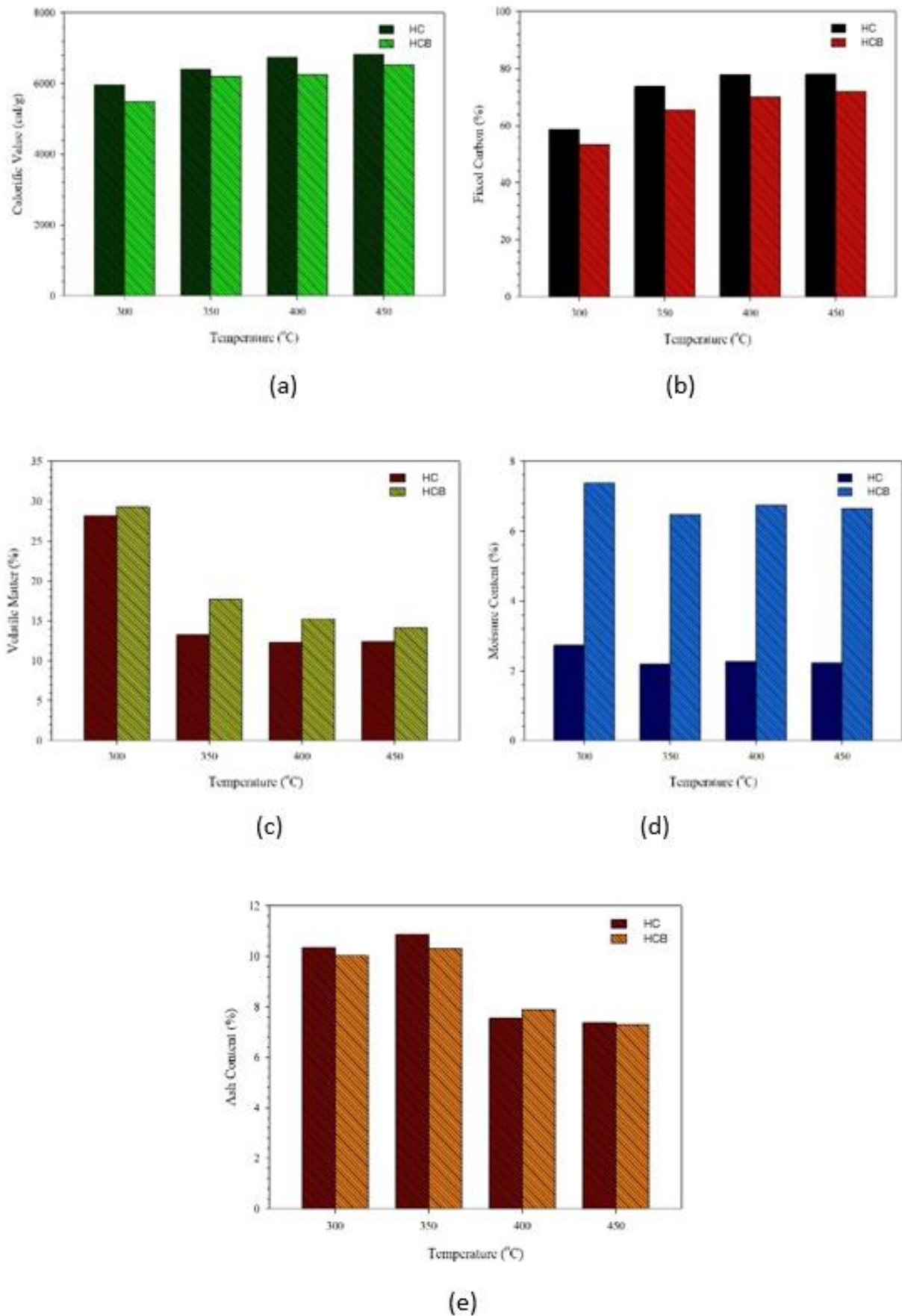
Figure 3. (a) Calorific value, (b) fixed carbon content, (c) volatile matter, (d) moisture content, and (e) ash content of HC and HCB at any temperatures.

The level of volatile matter in HC was determined by the improvement of the carbonization process, time, and temperature of the decomposition process. The higher the temperature and burn time processed, the more volatiles to be wasted, resulting in a low volatile sample during the test (Wang *et al.,* 2020), as seen in **Table 2**. The high volatile matter content in the briquettes caused more smoke but was easier to combust (Ifa *et al.,* 2020). Hence, low volatile matter content is preferable in use for producing less smoke (Kongprasert *et al.,* 2017). In HCB, the volatile matter content, compared to HC, increased by 18.89% (**Figure 3c**)

Along with the volatile matter content, the moisture of hybrid coal decreased with the increasing pyrolysis temperature. The decrease in water content was due to a higher co-pyrolysis temperature allowing more water to evaporate. The water contained in HC affected the quality of the briquettes produced. The moisture content of the briquettes should be as low as possible to produce a high calorific value and then easily ignited for combustion (Saeed *et al.,* 2020). As shown in **Table 2**, the water content in EFB was much smaller than lignite and followed the requirements for water content in pyrolysis raw materials, i.e. below 10% (Muigai *et al.,* 2020). The moisture content of HCB, as shown in **Figure 3d,** increased significantly to 190.63% due to gluing with a starch solution.

The other physic property of HC was ash content that decreased with the increasing co-pyrolysis temperature. It indicated that more complete combustion remained less ash. The ash content indicated the presence of inorganic components in the raw material in the form of metal oxides. High ash content in the fuel leads to corrosion, scaling, and lower heating value (Mohammed *et al.,* 2017), thus the higher the ash content observed, the lower quality of the briquettes

obtained. Low ash content in the biomass feedstock (EFB) as shown in **Table 2** could reduce slagging and fouling in furnaces used in thermochemical conversion processes (Shariff *et al.,* 2016). In general, the ash content decreases after becoming HCB (**Figure 3e**). Other analyses such as SEM, XRF, XRD, FTIR, and BET were performed on hybrid coal at a temperature of 450°C. The selection was made based on the best hybrid coal quality from the previous proximate test. In addition, the characterization was carried out on lignite, EFB, a mixture of the two materials before pyrolysis (22.5% by weight of EFB/lignite). It helped to ease the discussion and the comparison of results with raw materials.

Figure 4 presents the results of SEM analysis for lignite and EFB and their mixtures before and after co-pyrolysis. The lignite surface (**Figure 4a**) showed the presence of minerals through a homogeneously distributed microstructure. The bright part was due to the presence of potassium. EFB fiber (**Figure 4b**) had a rigid surface with a layer of lignin covering the fiber surface. The mixture of the two materials (**Figure 4c**) showed the presence of lignite and EFB simultaneously but not bonded, while after pyrolysis the two materials appeared to bind to each other (**Figure 4d**) where the gaps in the EFB were filled with lignite.

The qualitative analysis of oil palm shells was also characterized using XRF (X-Ray Fluorescent). The concentration of elements contained in lignite, EFB, a mixture of both (22.5% by weight of EFB/lignite), and HC is shown in **Table 3**. Most of the constituent elements of lignite and EFB were the same as the largest component of Fe in lignite and K in EFB. The main element in hybrid coal was Fe. As shown in **Table 3,** the elemental sulfur contained in lignite was lost after undergoing the co-pyrolysis process.
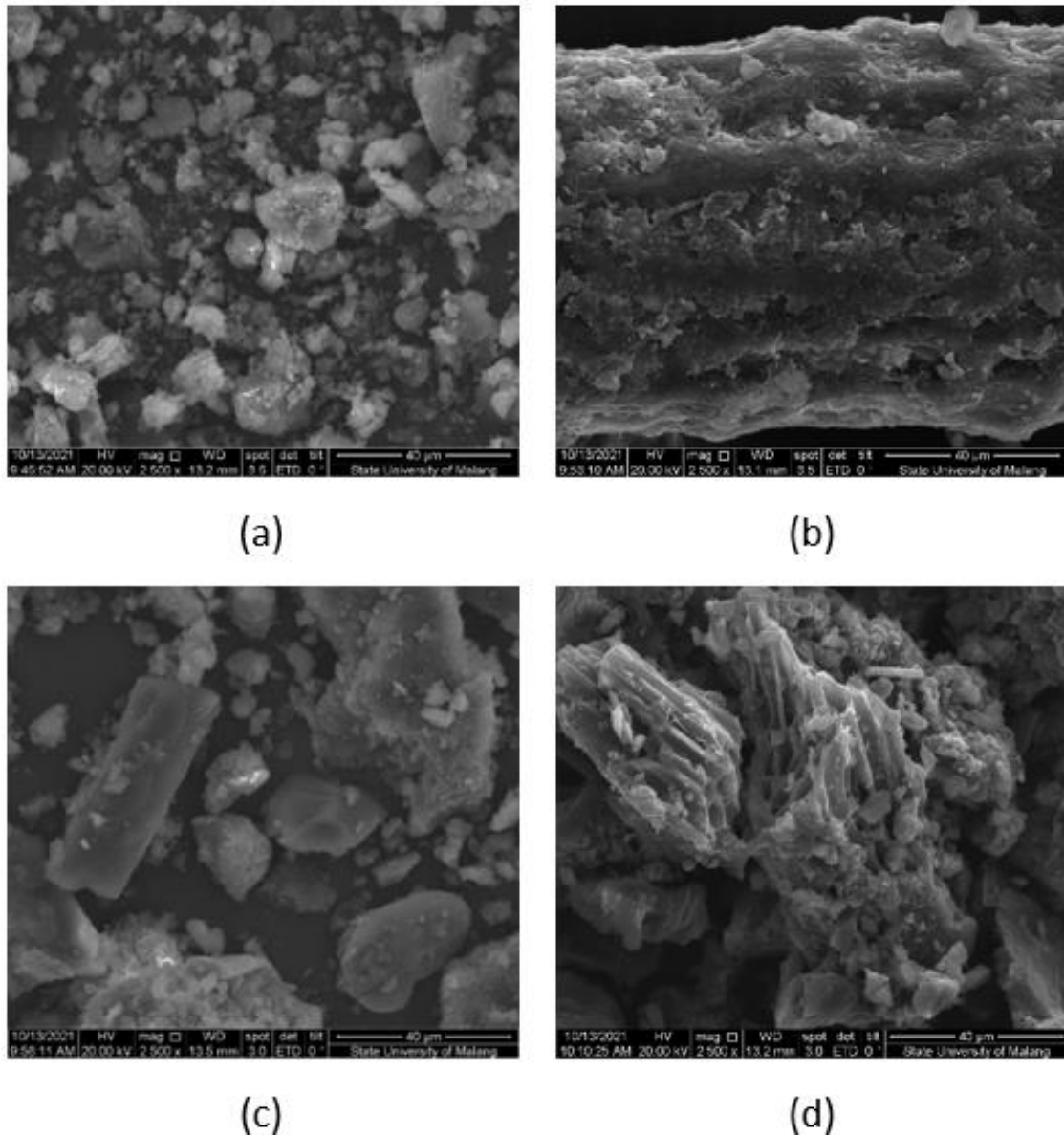
Figure 4. SEM images of (a) lignite (b) EFB (c) 22.5% by weight of EFB/lignite (d) HC.

Table 3. Elements at material according to XRF data.

Element	Concentration (%)			
	Lignite	EFB	25% EFB/Lignite	Hybrid Coal
Si	2.7	6.0	2.4	6.1
P	0.85	2.1	0.68	0.53
S	2.1		2.0	
K	0.22	35.3	0.68	8.21
Ca	4.02	19.3	4.09	6.5
Ti	0.34		0.33	0.78
Cr	0.13	1.7	0.13	0.14
Mn	0.50	0.92	0.46	0.53
Fe	88.0	28.7	87.5	66.9
Ni	0.36	1.3	0.2	0.24
Cu	0.72	1.6	0.64	0.44

XRD analysis was carried out to determine the presence of a crystal structure in the material. The structure was only found in EFB as shown in **Figure 5.** Cellulose crystals were identified at an angle of 2θ between 20°–30° because at that angle there were dominant peaks. The mixture of EFB with lignite still had components in amorphous (hemicellulose and lignin) and crystalline (cellulose) forms, while in lignite and hybrid coal there was no peak indicating a crystal structure of the three main components of biomass, it was only cellulose had crystalline domains, while both hemicellulose and lignin had amorphous structures following the literature (Karimi & Taherzadeh, 2016; Tong *et al.*, 2020).

Wu *et al.* (2019) found that biomass may promote the formation of disordered structures in co-dissociated char, but cellulose in biomass favors the generation of more ordered carbon structures (Wu *et al.*, 2019). The structure of lignite, EFB, mixture of lignite and EFB, and hybrid coal were also studied through FTIR and their spectra as presented in **Figure 6**. Here, the characteristics of the adsorption band changed in the hybrid coal product, where the peaks located at a wavelength of 3450-3600 cm-1 were assigned to the O-H stretch. This indicated the loss of hydrogen and water bonds in lignite and EFB degradation of hemicellulose and cellulose (Martín-Lara *et al.*, 2017).

At a wavelength of 2800-2900 cm^{-1}, there was an enhancement in the wave band in hybrid coal. This was given a stretching vibration of C-H from the alkane section. While, the stretching at a wavelength of 1560-1750 cm^{-1} was caused by the strain vibration of C = O in aldehyde groups and ester groups in cellulose and hemicellulose; and aromatic structures in lignin (Duranay & Akkuş, 2021). The characteristic stretching at a wavelength between 830 – 890 cm^{-1}, was associated with the strain vibration of the C = C portion of the alkene as contributed by the EFB. BET analysis aims to determine the surface area, pore volume, and pore size in raw materials and hybrid coal products.

The results of the BET analysis are shown in **Table 4** in which the surface area of lignite was found larger than the surface area of EFB. In particular, when these two materials were mixed, the surface area was much smaller. However, after pyrolysis, there was an increase in the surface area of the material. High temperatures can remove water molecules, other impurities, and volatile organic compounds (Zhuang *et al.*, 2021). Furthermore, the surface area is affected by pore volume and pore size (Leng *et al.*, 2021). The smaller pore size led to a greater number of pores, thus resulting in a larger surface area. The larger pore volume also led to a larger surface area.
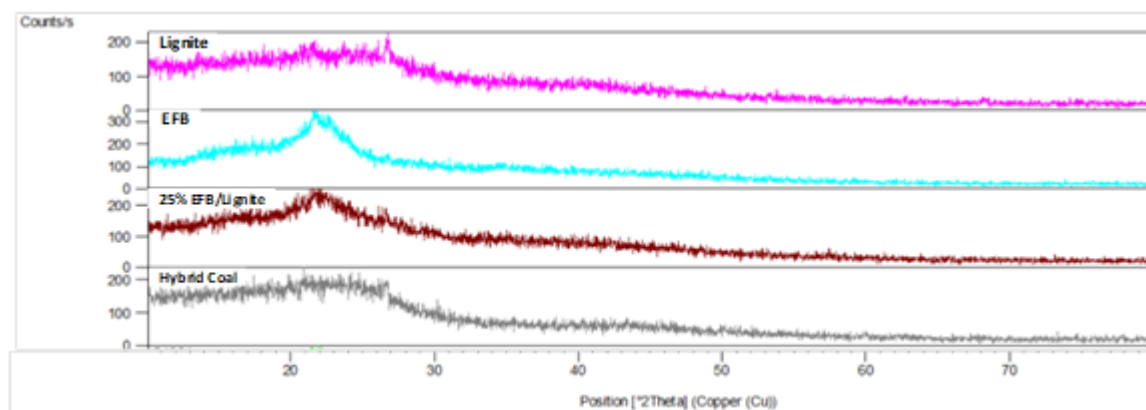
Figure 5. X-Ray Diffraction (XRD) Lignite, EFB, and Hybrid Coal (HC).
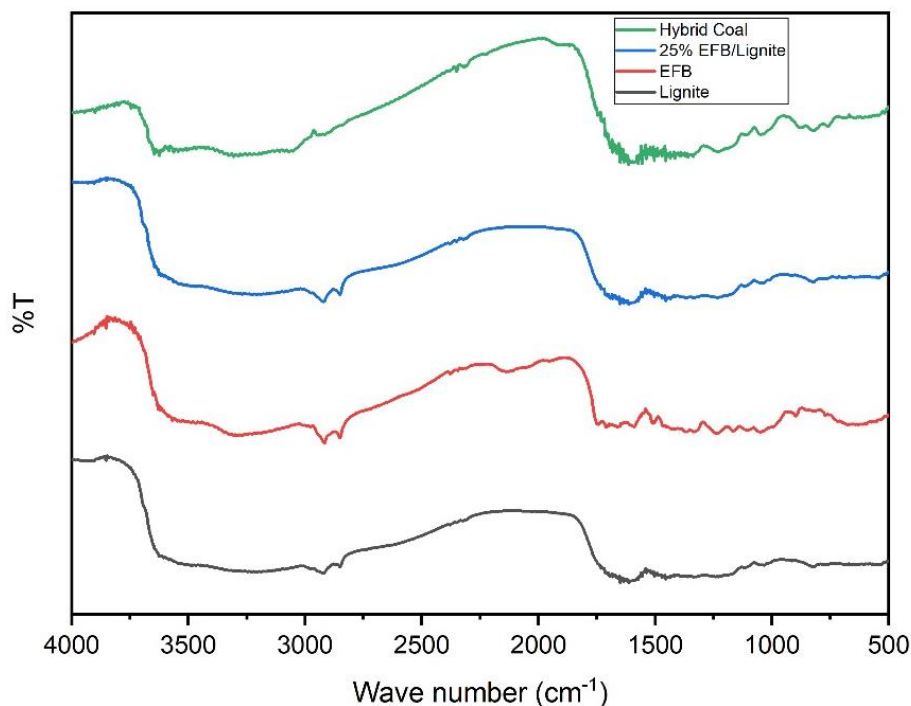
Figure 6. FTIR spectra of lignite, EFB, 22.5% by weight of EFB/lignite, and hybrid coal.

Table 4. BET results for the materials.

| Sample	Surface Area (m²/g)	Average pore size (A)	Pore volume (cc/g)
Lignite	90.828	25.2081	0.1145
EFB	60.617	24.9179	0.0755
22.5% EFB/Lignite	4.766	88.6937	0.0211
Char	38.870	23.6644	0.0459

3.4. Kinetic Study Analysis

Kinetic calculations were performed according to the assumptions and procedures outlined in Method Section. The data were obtained by various compositions of EFB and lignite. **Figure 7** and **Table 5** present the linearization results and the summary of calculation results, respectively. The linearized result in **Figure 7** showed that the model of kinetic study well fitted to the data, thus the model was reliably used.

Table 5 presents the kinetic parameters obtained from the model. From these parameters, it was observed that the produced hybrid coal with the highest EFB resulted in the lowest activation energy, indicating that the energy required for the decomposition reaction was also small, allowing the reaction to proceed faster. Increasing the biomass content in the raw material might cause bonds to break easily, thus reducing the energy required for decomposition.

The apparent activation energy was significantly reduced as indicated by the result of the mixing effect, which increased the biomass fraction of the mixture (Gouws, *et al.*, 2021). Since the thermogravimetric unit is a model of a pyrolysis reactor, it could be concluded from this kinetic study that using more biomass reduced the energy consumption during the pyrolysis reaction since the main step of reaction in pyrolysis was the decomposition reaction, thus biomass such as EFB plays a major role in the process of co-pyrolysis with coal.
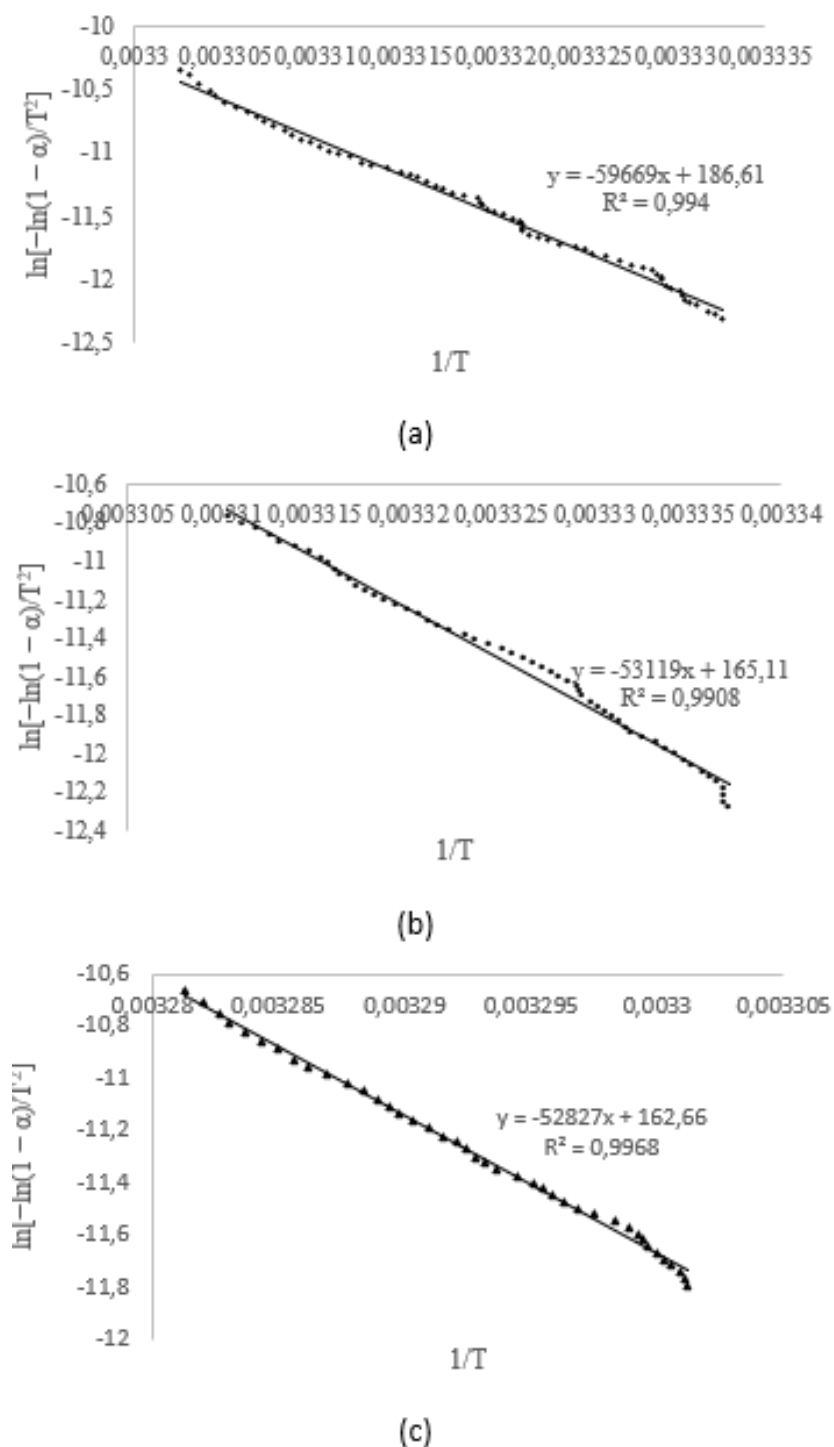
Figure 7. ln [−ln (1 − α)/T^2] vs 1/T for (a) 15% by weight of EFB/lignite, (b) 22.5% by weight of EFB/lignite and (c) 30% by weight of EFB/lignite.

Table 5. Kinetic properties of hybrid coal at various compositions.

Hybrid Coal	Temperature(°C)	E (kJ/mol)	A (s⁻¹)
15% EFB/Lignite	30-800	496,088	$3,29923 \times 10^{85}$
22.5% EFB/Lignite	30-800	441,631	$1,35077 \times 10^{76}$
30% EFB/Lignite	30-800	439,203	$1,15922 \times 10^{75}$

4. CONCLUSION

Co-pyrolysis of lignite and EFB was successfully conducted to produce hybrid coal (HC) and liquid product (tar). The temperature effect in the pyrolysis process led to some significant results. The results showed that the tar yield increased with the increasing temperature. Though the yield of HC decreased, the calorific value of HC increased by 14,5% from a temperature of between 300 and 450°C. Other physical properties of HC were also improved. The largest compounds identified in tar were phenol and acetic acid. The optimum temperature for lignite and EFB co-pyrolysis was 450°C as the greatest tar and the best specifications to produce briquettes were obtained. The resulting briquettes also met the quality requirements as alternative energy. Through kinetic study, the addition of more biomass to coal at the co-pyrolysis process reduced activation energy to the decomposition reaction. The application of co-pyrolysis could increase the value of coal and EFB and thus contribute to alternative energy sources. The use of simple and environmentally friendly technology enables the efficient production of solid fuels to meet the energy demand.

5. ACKNOWLEDGMENT

6. AUTHORS' NOTE

The authors declared that there is no conflict of interest regarding the publication of this article. The authors also confirmed that the paper was free of plagiarism.

7. REFERENCES

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