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Characterization and Combustion Kinetics of Binderless and Bindered Dry Cow Dung Bio-Pellets

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ABSTRACT. The effect of molasses addition as a binder in the manufacturing of cow dung bio-pellets on their characteristics and combustion kinetics has been studied. The bio-pellets characterization included the physical and mechanical properties as well as the proximate analysis and calorific values. Thermogravimetric analysis (TGA) was carried out using a macro-TGA apparatus under non-isothermal conditions and an oxidative atmosphere to study the thermal decomposition characteristics. Then, the first-order Coast and Redfern method was used to determine the kinetic parameters of bio-pellet combustion. It was found that the ash content of bio-pellets tended to decrease, while the volatile matter and fixed carbon tended to increase with the addition of molasses. Nevertheless, the density, the axial compressive strength, and the calorific values of bindered bio-pellets were decreased due to the higher amounts of water in the raw mixtures. The thermogravimetric analysis provided information that the combustions of cow dung bio-pellets took place in three stages of decomposition The bindered bio-pellet began to decompose at lower temperatures than the binderless bio-pellet with a higher weight loss percentage. According to the comprehensive combustion characteristic index (S), the combustion performance of both binderless and bindered bio-pellets was similar. The addition of molasses as a binder tended to reduce the ignition temperature and activation energy for all stages of bio-pellet combustion.

1. INTRODUCTION

The availability of cow dung as a type of biomass waste is abundant in Indonesia. According to the Central Bureau of Statistics (BPS) of Indonesia, the number of cows population in 2021 reached 18,623,289 heads, with a percentage of beef cattle at 96.89% and dairy cows at 3.11% [1]. The number of cows populations is likely to continue to increase in the coming years. Furthermore, a cow generates dry dung of about 7 kg/day on average [2], thus the potential of dry cow dung in Indonesia is calculated to reach 130.4 million kg/day in 2021. Various methods of the utilization of cow dung have been applied, such as composting, biogas production, and direct burning. However, the volume of untreated cow dung in Indonesia is still high [3]. The untreated cow dung is generally just piled up in the yard and then dried naturally. The piles of cow dung possibly reduce the quality of environmental health [3] and emit methane as the greenhouse gases that cause global warming [4].

Among the methods of cow dung utilization, the thermochemical conversion is capable of reducing large amounts of this waste in a shorter time [5]. Pyrolysis, gasification, and combustion are the optional technologies in thermochemical conversion. The pyrolysis of cow dung produces combustible gas, bio-oil, and char which have potential as an energy carrier as well as sources of chemicals and other useful materials [3,5]. The gasification of cow dung is also promising in the hydrogen-rich syngas production [6]. Meanwhile, direct combustion is a proven technology for heat and electricity generation [4].

Currently, with the high price of fuel oil, small and medium enterprises tend to switch to biomass pellet fuel to meet their heat needs. An example is the medium-scale tofu industry in Boyolali, Central Java, Indonesia which has switched to using wood pellets as fuel for steam generation. However, the availability of wood pellets is also limited by the availability of sawdust as raw material. Therefore, it is necessary to look for alternative local biomass resources that have potential as fuel. Central Java province has the second largest population of dairy cows and beef cattle in Indonesia [1], and Boyolali Regency has the largest population of dairy cows in Central Java [7]. Thus, the cow dung waste produced is attractive to be used as an alternative solid fuel with a calorific value of 10.9 MJ/kg on a dry basis [8].

The calorific value of cow dung is low compared to rice straw (14.0 MJ/kg), rice husks (12.3 MJ/kg), and sawdust (24.8 MJ/kg) [8]. The proximate analysis of cow dung shows that the content of moisture, ash, volatile matter, and fixed carbon is between 3.1-7.8, 25.3-41.2, 43.56-54.55, and 5.41-12.4 %wt in air-dried basis (adb), respectively [8-10]. The nature of dry cow dung with a less volumetric energy content, small bulk density, hydrophobic character, and a high ash content are drawbacks of its direct utilization as fuel [11]. Overcoming the drawbacks, a densification (pelletization) process is a method to increase the homogeneity and energy density, resulting in improved fuel characteristics [12]. Mixing with other biomass that has better properties [13] or the addition of a binder can also improve the quality of pellets. Despite water-soluble carbohydrates, starch, protein, oil, and cellulose commonly used as binders, a sugary material such as molasses as natural waste can be used in bio-pellet manufacturing [12]. The study reported that the addition of molasses had an impact on reducing ash content, decreasing bulk density, and had no significant effect on the durability of mixed biomass pellets [14]. The addition of molasses strengthens the wheat straw pellets and has no significant effect on quality and processability [15]. The molasses binder decreased the ignition temperature and maximum mass loss rate of food waste hydro-char pellets, and it had the potential for the preparation of solid biofuel [16].

The use of molasses as a binder in cow dung pellets has not been widely reported in previous studies. Also, the reports regarding the comparison of the characteristics of binderless and bindered cow dung pellets, as well as their thermal characteristics and combustion kinetics have not been widely reported. This research aims to study the effect of molasses addition as a binder in the manufacturing of cow dung bio-pellets on their characteristics and combustion kinetics. In this study, analysis of binderless cow dung bio-pellets is performed as a comparison. The bio-pellets characterization includes the physical and mechanical properties as well as the proximate analysis and the heating values. Thermogravimetric analysis (TGA) is carried out using a macro-TGA apparatus under non-isothermal conditions and an oxidative atmosphere to study the thermal decomposition characteristics. Then, the first-order Coast and Redfern method is used to determine the kinetic parameters of bio-pellet combustion.

2. MATERIALS AND METHODS

2.1 Materials Preparation

The raw cow dung was obtained from dairy farming in the village of Mundu, Klaten, Central Java, Indonesia. The cow dung was then naturally dried for about 30 days. The dried cow dung was then ground and sieved using a Tyler mesh -20+40, producing dry cow dung powder with a size ranging from 0.841 – 0.400 mm. Molasses as a binding agent was obtained from a home industry of alcohol manufacturing in the village of Sembung, Sukoharjo, Central Java, Indonesia. After being separated from solid impurities, the dark brown viscous molasses contained 82.8%w of total sugar and 17.2%w of water. The molasses was then diluted with some water to make it easier to mix with cow dung powder.

2.2 Bio-pellet Manufacturing

The mixtures of cow dung powder and molasses were prepared and well mixed with the following variation (molasses: water: dry cow dung powder): BLP (0 g : 0 g: 250 g); BDP-5 (12.5 g: 62.5 g: 237.5 g); BDP-10 (25 g: 125 g: 225 g); BDP-15 (37.5 g: 187.5 g: 212.5 g). The code BLP refers to binderless bio-pellet and the code BDP refers to bindered bio-pellet, while the numbers of 5, 10, and 15 after the dash refer to the weight fraction of molasses in the raw mixture. Before pelletization, the mixture of BDP-5, BDP-10, and BDP-15 was dried in an oven at 60 °C for 3 days. The final mixture of raw material has a water content of 15.53, 18.10, 20.82, and 21.35%w for BLP, BDP-5, BDP-10, and BDP-15, respectively. The bio-pellet was then produced by pressing such mixture by a hydraulic press machine under a tonnage of 5 tons for 1 minute using a pellet mold with 10 mm in diameter and 40 mm in length.

2.3 Bio-pellet Characterizations

The physical characterizations were carried out on the dimensions and density of the bio-pellets using a screw millimeter and an analytical balance. Meanwhile, the mechanical property of the bio-pellet was related to its axial compressive strength. The Universal testing machine QC-503B1 with a maximum tonnage capacity of 10 tons was used to measure the axial compressive strength of bio-pellets as the ASTM E-910 procedure. The proximate analysis was performed to measure the contents of moisture, ash, volatile matter, and fixed carbon of bio-pellets as ASTM D-3173, ASTM D-3174, and ASTM D-3174 procedures. The fixed carbon content was calculated by difference. Furthermore, the higher heating value (HHV) of bio-pellets was also measured using a bomb calorimeter according to ASTM E-711.

2.4 Thermogravimetric Analysis

Thermogravimetric analysis was carried out in a macro-TGA apparatus to determine the thermal characteristics of bio-pellets by measuring weight loss over time during thermal decomposition. In each experiment, approximately 15 g of bio-pellet samples were loaded into the macro-TGA. The bio-pellets were then heated from ambient temperature to 700 ºC with a heating rate of 10 ºC/min in the presence of atmospheric air. The thermogravimetric (TG) curve or the weight loss curve (%w) and the derivative TG (DTG) curve or weight loss rate curve (%/min) were then obtained from this analysis. In this study, thermogravimetric analysis was only performed on the combustion process of BLP and BDP-15 samples.

2.5 Combustion Kinetics

The thermogravimetric (TG) curve was then used to study the combustion kinetics of BLP and BDP-15 samples. The kinetics of bio-pellets combustion were performed by assuming the global combustion reaction according to the first-order Coast-Redfern method which is common and feasible for biomass combustion [17]. The resulting kinetic parameters of activation energy (E) and pre-exponential factor (A) were then used for comparison. The kinetic formula and derivation of the kinetic equations based on the first-order Coats-Redfern method are presented in the next section.

3. RESULTS AND DISCUSSION

3.1 Bio-pellet Characteristics

The bio-pellet products are shown in Fig. 1, the bindered bio-pellet (BDP-15) shows a darker appearance due to the addition of molasses as a binder. Apart from the visual appearance, there are no significant differences between the BAP and BDP-15 at first glance. Thus, it is necessary to carry out the standard measurements of bio-pellets to study their characteristics. The results of physical and mechanical characterization of bio-pellet as well as the results of proximate analysis and heating value measurements are presented in Table 1.

It is found that the hydraulic pressing produces bio-pellets with a uniform length-to-diameter (L/D) ratio within a range of 1.06 – 1.09. The measurement of the pellet weight from twelve samples in each variation provides information that the average weight per pellet for BLP (1.12 g/pellet) is a little bit heavier than BDP bio-pellets (1.04-1.06 g/pellet). The lower average weight per pellet in BDP bio-pellets is probably caused by the formation of pores in the raw material due to the water released during heating in the oven. These pores may persist during hydraulic pressing causing a reduction in bio-pellet weight and having an impact on reducing the pellet density. The average density of BLP bio-pellet is 1.17 g/cm^3. The lower average density is obtained for BDP bio-pellets and tends to decrease gradually with the increasing molasses weight percentage [14].

Figure 1. Bio-pellet products: (a) Binderless bio-pellet (BLP); (b) Bindered bio-pellet (BDP-15)

The mechanical strength of bio-pellets is represented by the axial compressive strength values shown in Table 1. The higher axial compressive strength indicates that bio-pellets do not fracture or crumble easily when stacked or dropped. As shown in the table, the BLP bio-pellet has the highest axial compressive strength of 328.32 N/mm^2. Increasing the amount of molasses and water in the raw mixtures of BDP-5, BDP-10, and BDP-15 reduces the axial compressive strength significantly to 195.70, 120.89, and 97.23, respectively. The high amount of water in the raw mixture causes the pellets to expand after the ejection from the mold due to higher residual stress [4]. This causes a low axial compressive strength of BDP bio-pellets which is associated with increased fracture properties.

The results of the proximate analysis show that the moisture content of BLP bio-pellet is 14.31%w(ar). Meanwhile, the moisture content increases with the increase of molasses in BDP bio-pellets, and it reaches 19.48%w(ar) in BDP-15 bio-pellets. This highest moisture content is responsible for the lowest heating value of bio-pellet [11]. The BLP bio-pellet has the highest HHV of 17.34 MJ/kg. This value falls to 16.40 MJ/kg or decreases by 5.4% in BDP-15 bio-pellet with an increase in moisture content of 36% compared to BLP bio-pellet. On the other hand, the ash content of bio-pellets tends to decrease with the addition of molasses [14]. However, in BDP bio-pellets, the addition of a higher amount of molasses tends to increase the ash content. The addition of molasses tends to slightly increase the volatile matter and fixed carbon content compared to BLP bio-pellets [14].

Table 1. Bio-pellets characteristics

Characteristics	Unit	BLP	BDP-5	BDP-10	BDP-15
Diameter (average)	Mm	10.40	10.48	10.56	10.66
Length (average)	Mm	11.36	11.14	11.31	11.51
Weight per pellet (average)	G	1.12	1.06	1.04	1.05
Density (average)	g/cm^3	1.17	1.11	1.04	1.02
Axial compressive strength	N/mm^2	328.32	195.70	120.89	97.23
Proximate analysis:					
Moisture (M)	%w (ar)	14.31	17.33	17.69	19.48
Ash	%w (db)	38.14	35.76	36.05	37.18
Volatile matter (VM)	%w (db)	61.27	63.90	62.21	61.62
Fixed Carbon (FC)	%w (db)	0.59	0.34	1.74	1.2
Higher Heating value (HHV)	MJ/kg	17.34	16.81	16.68	16.40

Note: (ar) as received; (db) dry basis

To assess the quality of bio-pellets, the Indonesian National Standard (SNI 8021:2014) for wood pellets is used as a comparison. In that standard, several parameters required include a minimum density of 0.8 g/cm^3, a maximum water content of 12%, a maximum ash content of 1.5%, a maximum volatile matter content of 80%, a minimum fixed carbon content of 14%, and a minimum calorific value of 4,000 cal/g (16,736 MJ /kg). The pellets produced in this research met the requirements for pellet density and volatile matter content. However, the water content, ash content, and fixed carbon content do not meet the requirements. Further drying of the pellets is necessary to reduce the water content which can also increase the calorific value of the pellets. On the other hand, the nature of cow dung with a high ash content may require chemical pre-treatment before being used. The combustion operating procedures in the furnace may also be adapted to handle solid fuels with high ash content

3.2 Thermal Weight Loss Characteristics of Bio-pellets

The TG and DTG curves resulting from the thermogravimetric analysis are presented in Fig. 2. The blue solid line represents the TG curve, and the orange solid line represents the DTG curve. It is found that the pattern of these curves is similar to the combustion of BLP and BDP-15. The thermal decomposition includes three stages separated by the orange dashed lines: (1) water evaporation and some volatiles release stage, (2) volatile component combustion stage, and (3) fixed carbon oxidation stage. The start and finish temperature of each stage along with the mass loss percentage during the BLP and BDP-15 combustion process are presented in Table 2. Furthermore, the black dashed lines in Fig. 2 are guidelines for determining the combustion characteristics.

For the thermal decomposition of BLP, the first stage starts at 95 °C and finishes at 368 °C corresponding to water evaporation followed by the release of some volatiles [9], and the weight loss at this stage is about 17.8%. The lower temperature range of this stage is found for the decomposition of BDP-15, which starts at 90 °C and finishes at 341 °C, with a weight loss is about 14.7%. The second stage is the volatilization and combustion of the volatiles, it starts from the finish temperature of the first stage to 413 °C for BLP and 415 °C for BDP-15. The main weight loss is found in this stage, it reaches 30.6% and 38.1% for BLP and BDP-15, respectively [5]. The content of hemicellulose, cellulose, and a part of lignin as the main biomass components are decomposed at this stage to generate volatiles which are then burned. The third stage is after 415 °C corresponding to the lignin slow oxidation and decomposition of the carbon [5,18]. The weight loss at this stage is about 18.2% and 17.3% for BLP and BDP-15, respectively. At the end temperature of the combustion process of 700 °C, the remaining solid weight accounted for 33.5% and 29.9% for BLP and BDP-15, respectively. The remaining solid residue may consist of undecomposed carbon, ash, and other non-decomposable substances. This solid residue may further decompose at higher temperatures above 700 °C [9].

The combustion characteristics of biomass can be evaluated by the comprehensive combustion characteristic index (S), the formula shown in Eq. (1). The higher value of the index S indicates the good performance of biomass combustion [18].

$$S = ((dX/dt)_{max}.(dX/dt)_{mean})/(T_i^2.T_f) \qquad (1)$$

The $(dX/dt)_{max}$, $(dX/dt)_{mean}$, T_i, and T_f are the maximum combustion rate (%/min), the average combustion rate (%/min), ignition temperature (°C), and burn-out temperature (°C), respectively. The average combustion rate is calculated by the following formula:

$$(dX/dt)_{mean} = \beta(\alpha_i - \alpha_f)/(T_f - T_i) \qquad (2)$$

where β is the heating rate (10 °C/min), α_i is the conversion of reaction (%) corresponding to the ignition temperature point, α_f is the conversion of reaction (%) corresponding to the burn-out temperature point.

The ignition temperature (T_i), burn-out temperature (T_f), maximum combustion rate, and maximum combustion rate temperature (T_{max}) are obtained from TG and DTG curve in Fig. 2 by the following method [16]. Draw the vertical line that passes the peak point P of the DTG curve, this will intersect the TG curve at point A. The tangent line L_2 of the TG curve passes through point A, which intersects the horizontal line L_1 when the sample begins to lose weight. The value of abscissa corresponding to this intersection is the ignition temperature (T_i). On the other hand, the abscissa of the intersection of L_2 and the horizontal line L_3 at the end of the TG curve corresponds to the burn-out temperature (T_f). The ordinate value of the P point on the DTG curve corresponds to the maximum combustion rate ($(dX/dt)_{max}$), while its abscissa corresponds to the maximum combustion rate temperature (T_{max}). The results of combustion characteristics of bio-pellet are shown in Table 2.

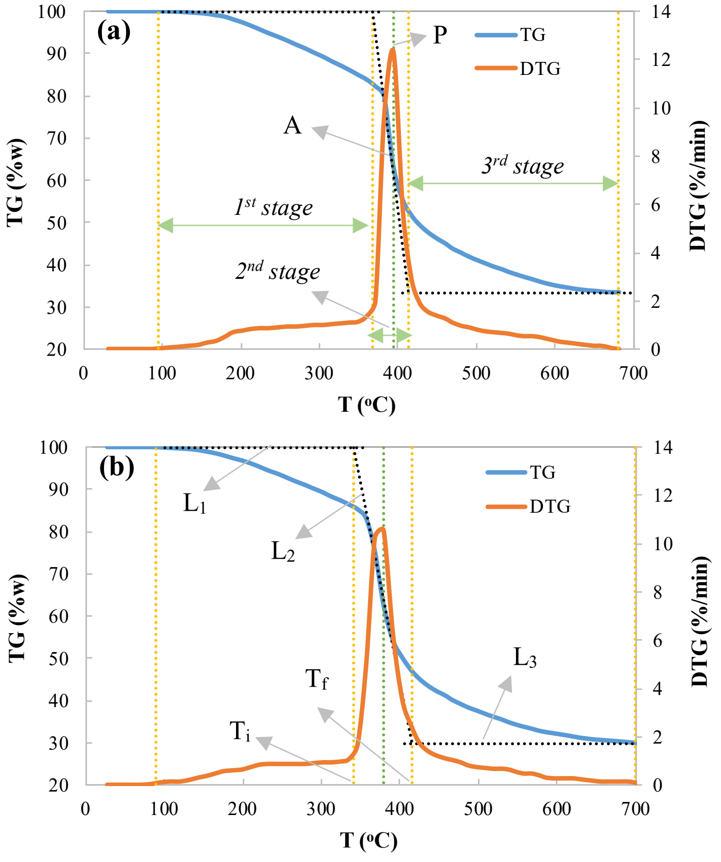

Figure 2. Thermogram curve of bio-pellet combustion: (a) BLP; (b) BDP-15

Table 2. Thermal characteristics of bio-pellet in an oxidative air atmosphere

Thermal Characteristics		Unit	BLP	BDP-15
Stage 1	Start	°C	95	90
	Finish	°C	368	341
	Mass loss	%	17.8	14.7
Stage 2	Start	°C	368	341
	Finish	°C	413	415
	Mass loss	%	30.6	38.1
Stage 3	Start	°C	413	415
	Finish	°C	681	700
	Mass loss	%	18.2	17.3
T ignition (Ti)		°C	368	341
T burn-out (Tf)		°C	413	415
T max		°C	394	379
Maximum combustion rate (DTG max)		%/min	12.29	10.55
Average combustion rate (DTG avg)		%/min	6.79	5.15
Comprehensive combustion index (S)		$1/(\text{min}^2.\text{K}^3)$	$1.49\text{x}10^{-06}$	$1.13\text{x}10^{-06}$

As shown in Fig. 2 and Table 2, the P point that represents the maximum peak with the corresponding Tmax is found at 394 °C and 379 °C for BLP and BDP-15 bio-pellet, respectively. The peak in the temperature range of 300-400 °C was also found from the thermal decomposition of cattle manure [5,9]. Moreover, the ignition temperature of BDP-15 is lower than BLP due to the higher simple sugar content in molasses. This content decomposes at low temperatures, resulting in the maximum combustion rate temperature being lower than BLP and the burn-out temperature which is not much different from BLP. These characteristics are advantageous in terms of thermal decomposition. Meanwhile, the maximum and average combustion rates of BDP-15 are lower than BLP. According to the comprehensive combustion characteristic index (S) [18], the BLP and BDP-15 have index S that are not much different. This indicates that the combustion performance of both bio-pellets is similar.

3.3 Kinetic parameters of bio-pellet combustion

The combustion of solid biomass belongs to the weight loss of the sample during decomposition. The thermogravimetric experiments as described in the method provide sample mass data at various times during combustion. The global combustion reaction of solid biomass accords with [18]:

$$B\ (solid) +\ G\ (gas) \rightarrow P(products)$$

In the above reaction, the solid (B) is oxidized by the oxidizing gas (G) to produce products (P) that are comprised of solid (ash), tars, and gases. The kinetic or mass loss rate of solid B decomposition is described as follows:

$$d\alpha/dt = k.f(\alpha) \tag{3}$$

The conversion of reaction (α) is determined by $\alpha = (m_0 - m_t)/(m_0 - m_f)$, where m_0 is the initial mass of sample, m_t is the mass of sample at certain time ($_t$), and m_f is the final mass of sample at the end of pyrolysis. The rate constant (k) is calculated by the Arrhenius equation:

$$k = A\exp\left[-E/(RT)\right] \tag{4}$$

where A is the pre-exponential factor (1/min), E is the activation energy of the reaction (kJ/mol), R is the universal gas constant (8.314 J/mol.K), and T is the reaction temperature (K).

In this study, the non-isothermal condition of thermogravimetric analysis is related to the use of a constant heating rate *β*, and the equation (t) can be obtained by substituting $\beta = dT/dt$ into Eq. (3):

$$d\alpha/f(\alpha) = (k/\beta)dT \tag{5}$$

$$d\alpha/f(\alpha) = (A \exp{[-E/(RT)]}/\beta)dT \tag{6}$$

Integration of both sides of Eg. (6), and let the $F(\alpha) = \int_0^\alpha d\alpha/f(\alpha)$, we found:

$$F(\alpha) = (A/\beta) \int_{T0}^{T} \exp{[-E/(RT)]}\, dT \tag{7}$$

According to the Coats-Redfern method [9, 17, 19] for the reaction order n = 1, the equation is simplified to:

$$\ln{[-\ln{(1-\alpha)}/T^2]} = \ln{[AR(1-2RT/E)/\beta E]} - E/RT \tag{8}$$

In the above equation, the term $(1-2RT/E) \approx 1$, and the $\ln{[AR(1-2RT/E)/\beta E]}$ is a constant. The straight line will be constructed by plotting $\ln{[-\ln{(1-\alpha)}/T^2]}$ versus $1/T$, and then the kinetic parameters E and A are obtained by the slope and intercept of the straight curve.

Figure 3 shows each stage's plotting and straight line curve for the combustion of BLP and BDP-15. In each stage, the fitting equation and correlation coefficient (R^2) are obtained. The equation coefficients are then used to calculate the kinetic parameters A and E. Furthermore, the resulting kinetic parameters (A and E) of bio-pellet combustion according to the first-order Coast-Redfern method are shown in Table 3. The values of correlation coefficients are higher than 0.91, this indicates that the selected kinetic model is appropriate. The better curve fitting may be obtained by selecting other types of solid-state reaction mechanisms other than first-order reaction [19]. A detailed discussion of this topic may be necessary and better presented in a separate publication.

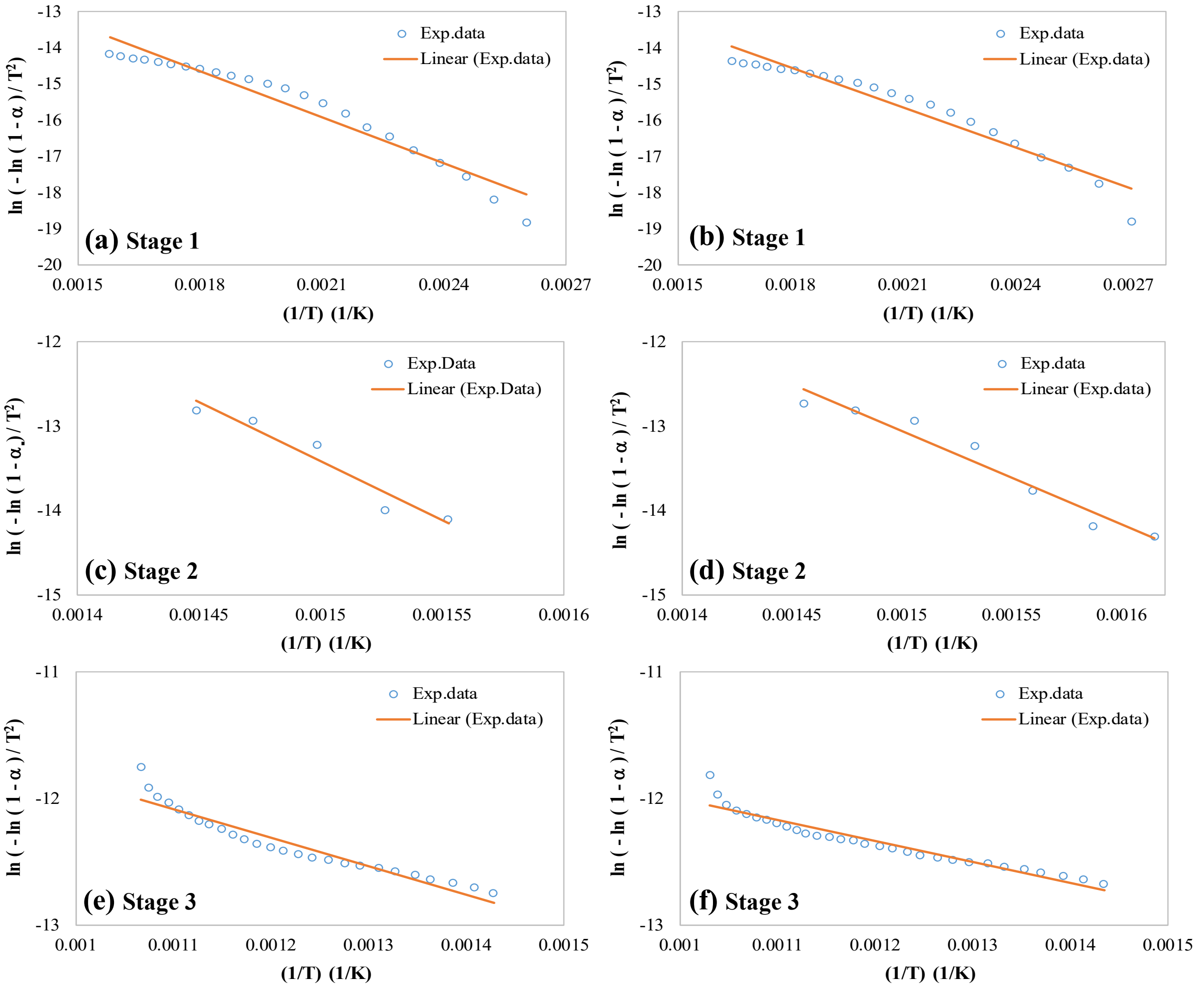

Figure 3. Fitting straight line of each stage for the combustion of (a,c,e) BLP; (b,d,f) BDP-15

Table 3. Kinetic parameters of bio-pellets combustion by using the first-order Coast-Redfern method

Sample	T range (^{o}C)	Fitting equation	Activation energy E (kJ/mol)	Pre-exponential factor A (1/min)	Correlation coeff. (R^2)
BLP	95-368	y = -4,239.8x - 7.0107	35.25	3.83×10^{1}	0.9401
	368-413	y = -14,028x + 7.6287	116.63	2.88×10^{8}	0.9307
	413-681	y = -2,253.5x - 9.5992	18.74	1.53×10^{0}	0.9143
BDP-15	90-341	y = -3,697.3x - 7.8604	30.74	1.43×10^{1}	0.9381
	341-415	y = -11,058x + 3.5375	91.94	3.80×10^{6}	0.9508
	415-700	y = -1,652.5x - 10.349	13.74	5.29×10^{-1}	0.9198

For the first stage of BLP combustion, which ranged from 95 ^{o}C to 368 ^{o}C (Fig. 3(a)), the activation energy and pre-exponential factor are 35.25 kJ/mol and 3.83 x 10^{1} (1/min), respectively. The lower activation energy and pre-exponential factor are found for the first stage combustion of BDP-15, which are 30.74 kJ/mol and 1.43 x 10^{1} (1/min), respectively. This is consistent with a lower starting temperature of the first stage of BDP-15 decomposition (at 90 ^{o}C) compared to BLP decomposition (at 95 ^{o}C).

As shown in Table 3, a lower activation energy and pre-exponential factor are also found for the second stage of BDP-15 combustion (91.94 kJ/mol and 3.80 x 10^{6} (1/min), respectively) compared to BLP combustion (116.63 kJ/mol and 2.88 x 10^{8} (1/min), respectively), corresponding to a lower starting temperature of the second stage decomposition. The previous researcher reported a lower activation energy (68.8 kJ/mol) and pre-exponential factor (8.89 x 10^{4} (1/min)) in the devolatilization stage of raw cow dung combustions [9]. Nevertheless, the higher values of these kinetic parameters in the devolatilization stage were reported by another study [19].

The same tendency is also found in the third stage of decomposition but with a relatively similar starting decomposition temperature. At this stage, the activation energy and pre-exponential factor of BDP-15 combustion are 13.74 kJ/mol and 5.29 x 10^{-1} (1/min), respectively, compared to BLP combustion which is 18.74 kJ/mol and 1.53 x 10^{0} (1/min), respectively. A lower activation energy and pre-exponential factor have been reported by previous studies for the char combustion stage which are 2.55 kJ/mol and 1.10 x 10^{-2} (1/min), respectively [9]. On the other hand, the higher activation energy in the second stage of decomposition compared to other stages is due to the increasing complexity of the reactions that occur.

4. CONCLUSION

The effect of the molasses addition as a binding agent in the production of cow dung bio-pellet has been studied on the bio-pellet characteristics and combustion kinetics. The lower average density was obtained for bindered bio-pellets and tends to decrease gradually with the increasing molasses weight percentage. The calorific value of bindered bio-pelles was also lower than the biderless one. The higher amounts of water in the raw mixtures of bindered bio-pellets were responsible for these results. This also caused the expansion of the pellets after ejection from the mold due to higher residual stress. It decreased the axial compressive strength of bindered bio-pellets which was associated with increased fracture properties. On the other hand, the ash content of bio-pellets tended to decrease, while the volatile matter and fixed carbon tended to increase with the addition of molasses.

The thermogravimetric analysis provided information that the combustion of cow dung bio-pellets took place in three stages of decompositions: (1) water evaporation and some volatiles release, (2) volatilization and combustion of the volatiles with the most weight loss percentage, and (3) slow oxidation and decomposition of the carbon. The bindered bio-pellet began to decompose at lower temperatures than the binderless bio-pellet with a higher weight loss percentage. Nevertheless, the average combustion rate of the binderless bio-pellet was higher than the bindered one. According to the comprehensive combustion index S, the combustion performance of binderless and bindered bio-pellets was similar. The addition of molasses as a binder tended to reduce the ignition temperature and activation energy at each stage of bio-pellet combustion.

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