Properties of Torrefied Biomass and Torrefied Pellet

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Abstract

This paper reviews the torrefaction biomass properties, which have to be measured both laboratory and pilot scales. In laboratory scale, the products from torrefaction process are called torrefaction biomass. The properties usually determined in laboratory scale are heating value, grindability, and energy yield. In pilot scale, the torrefied biomass is formed into pellet and called torrefied pellet. The important properties of torrefied pellet are durability, hydrophobicity, and bulk density. The standards procedure used for testing the torrefied biomass properties and torrefied pellet are described in this review. Finally, the effect of torrefaction temperature on the properties of torrefied biomass and torrefied pellet is explained.

Keywords: Biomass, Grindability, Properties, Proximate analysis, Torrefaction, and Ultimate analysis

Introduction

Raw biomass has many drawbacks, when considered as fuel, such as low heating value, high tenancy, high moisture content, low bulk density, poor grindability, high transport cost. Moreover, the raw biomass generates a lot of smoke when it is combusted due to its high oxygen content. The poor properties of raw biomass can be improved by torrefaction process. The properties of torrefied biomass are low moisture content, high energy density, and good grindability. In addition, torrefied biomass with pelletization, called torrefied pellet, has a higher bulk density, durability and hydrophobic than normal torrefied biomass and biomass pellet. This paper reviews the property of torrefied biomass and torrified pellet.

Torrefaction process

Torrefaction process is thermal decomposition of raw biomass, in inert atmosphere, at low temperature of 200 - 300°C. When the biomass is heated, the composition of biomass is decomposed. The decomposition mechanism can be described by two step reactions. First, hemicelluloses degraded; consequently, the light volatiles (mono- and polysaccharide fractions and dehydrosugars) and permanent gas (carbon dioxide and carbon monoxide) are revealed. Second, partial of cellulose and lignin decomposed. The level of cellulose and lignin decomposition depends on the torrefaction temperature.

The products of these decomposition are condensable gas including acetic acid, water, formic, methanol, lactic acid, furfural and hydroxyl acetone which are formed and condensed as liquid product.[1] Dehydration and decarboxylation reaction causes the increase of energy density, brittle property (good grindability) and low moisture content. These properties are attraction properties for fuel in combustion system.

Analysis of torrefied products

The products of torrefied process can be divided into 3 groups: solid, liquid, and gas product. The important properties of solid product, torrefied biomass, are heating value, chemical composition, and grindability. Heating value is determined by the direct combustion or estimation by mathematical model. Chemical composition is analyzed by proximate and ultimate analysis. After pelletization of solid product; bulk density, durability and hydrophobicity are also tested. The liquid products are diluted by 2-butanol because all liquid products do not dissolve in water.[1]

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Later, diluted liquid products are analyzed by HPLC to identify liquid product components. The gas product composition is identified by Micro GC.[1,2,3]

Properties of torrefied biomass

In this section, we will discuss three important properties of torrefied biomass such as heating value, energy yield, and grinability. The details of discussion are as follows.

Heating value

Heating value is the most important properties, when the biomass fuel is applied for direct combustion and co- combustion.

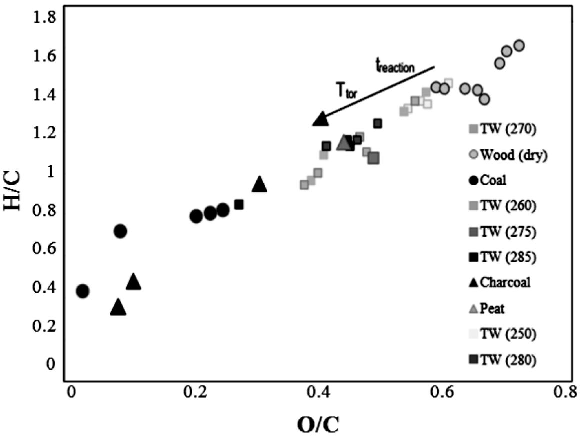

Figure 1 data plotting of wood, torrefied wood (TW), charcoal, coal, and peat on Van Krevelen diagram[8]

Normally, the heating value may be reported on two bases, higher heating value and gross calorific value as well as low heating value, net calorific value.[4] The heating value is determined by direct combustion in adiabatic bomb calorimeter, which is measurement conversion of enthopy between reactant and product, according to the ASTM – E 711,[5] NBR 8633/84.[6] Estimation of heating value can also be determined based on data of proximate analysis or ultimate analysis. Proximate analysis is conducted to determine fraction of ash , fixed carbon, moisture and volatile matter by TGA/DSC System (Metler Toledo),[2] according to ABNT NBR 8112/86,[6] ASTM D 5142-04 CEN/TS 14775:2004 (moisture), CEN/TS 14774-1-3:2004 (volatiles) and CEN/TS 15148:2005 (ash).[7] Ultimate analysis is conducted to determine element composition: C, H, O, N, S, and Cl by elemental analyzer, according to ASTM D 5373-08. For biomass from plants, the quantity of Cl is small compared with C, H, O, N, and S, thus Cl can be neglected.[2,4] Sheng et al.[4] The correlations for prediction of heating value using data from proximate and ultimate analysis are shown in Table 1. Erol et al.[5] The element composition of some biomass is shown in Table 2.

In addition, the data from ultimate analysis can also be used to identify the raw and torrified biomass with classification of coal. It can be done by Van Krevelen diagram. Before this diagram was used to classify biomass,Van Krevelen diagram was plotted in order to identify kerogen with type of petroleum.[9] Van Krevelen diagram was established with O/C ratio as horizontal axis and H/C ratio as vertical axis. As can be seen in Figure 1, dry wood has the highest O/C and H/C ratio, while coal and charcoal has the lowest. Moreover, torrefied wood with temperature of 275, 280, and 285°C has O/C and H/C ratio similar to peat. Thus, the co-firing torrefied wood with peat instead of peat firing may be conducted.

Chen et al.[10]studied the effect of temperature on higher heating value of torrefied biomass: bamboo, banyan, and willow. Figure 2 shows the relationship of the higher heating value versus the temperature. It can be seen from the figure that when temperature increases, the higher heating value increases.

Energy yield

Energy yield is defined as shown in Eq. (1).[2,11,12,13,14] It represents the energy which is still contained in biomass after it has undergone torrefaction process.

$$y_{energy} = \frac{m_{product} HHV_{product}}{m_o HHV_o} \times 100 \qquad (1)$$

It was found that the energy decreased with the increase of torrefaction temperature as can be seen in Figure 3.

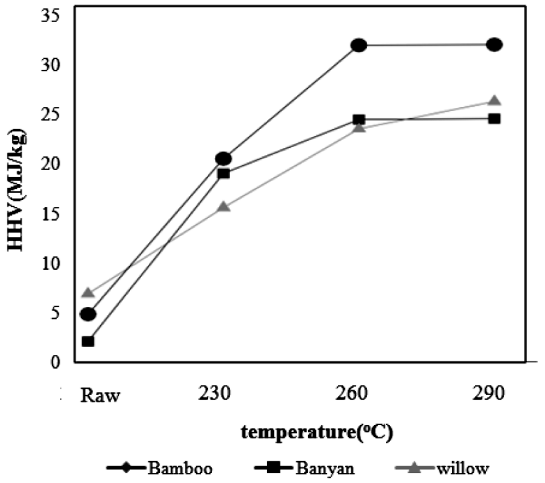

Figure 2 relationships between higher heating value and torrefaction temperature of bamboo banyan and willow [10]

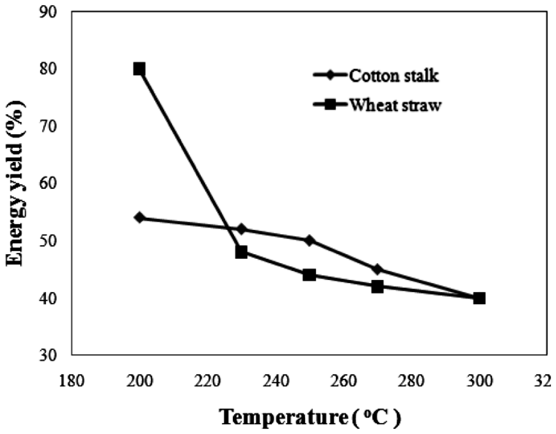

Figure 3 relationships between energy yield and torrefaction temperature[11]

Grindability

The reduction of particle size results in the increase of the efficiency and stability of combustion, and the decrease of the unburnt carbon amount in ash[7] Grindability reflects the amount of energy used in biomass size reduction. In co-combustion biomass with coal and pulverized coal in boiler, the grindability property plays an important role. Improvement of grindability was conducted to decrease tenancy of raw biomass in grinding process, resulting in the decrease of power consumption. The grindability for coals was tested by following the Hardgrove Grindability Index (HGI) [7,15] The higher value of HGI means the lower energy consumption in grinding or pulverizing process. It is the most significant property in commercially aspect because HGI index is used to identify torrefied biomass with classification of coal. The grindability test followed British Standard BS 1016–112:1995,[7] ASTM D409-51(1961).[11,15] The Hargrove Grindability Machine is shown in Figure 4. According to ASTM D409-51 (1961), [44] torrefied sample of 50 g was placed into grindability machine. The compressive force of 290 N was applied at the top of the machine and the grinding time was 3 minute. Once the grinding completed, the sample was sieved through 75 micron sieve and the weight of sample passing through sieve was recorded. In order to calculate the HGI value, the calibration chart had to be established. Standard reference sample with known HGI was ground. The weight of the original sample (50 g) minus the weight of the material retained on the 75 micron sieve was noted. Plotting on linear scale coordinated with the calculate weight of material passing 75 micron versus the Hardgrave Grindability Index of the standard reference sample. A straight line was fitted to these four points by method of least squares. The typical calibration chart was shown in Figure 5.

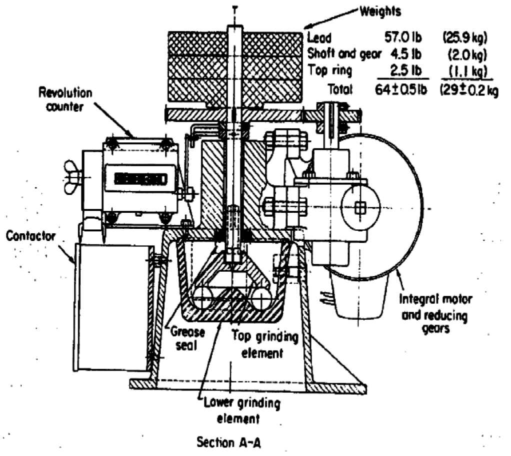

Figure 4 Hardgrove Grindability Machine[44]

The form of relationship between the weight of material passing sieve and HGI value can be written as follows:

$$M_H = m(HGI) + b \tag{2}$$

Where, M_H represents the weight (g) of ground product passing the 75 micron sieve, m represents slope of calibration chart, and b represents intersection point on vertical axis. The estimation of HGI for torrefied biomass, which is defined as HGI equivalent (HGI_{equiv}), can be calculated by Eq.(3).

$$HGI_{equiv} = \frac{M_H - b}{m} \quad (3)$$

Table 3 shows the correlation of HGI_{equiv}, grinding equipment, and standard used in previous work. It is noted the constant value in these correlation is specific to each grinding machine.

On the other hand, establishment of calibration chart for a new grinding machine is needed.

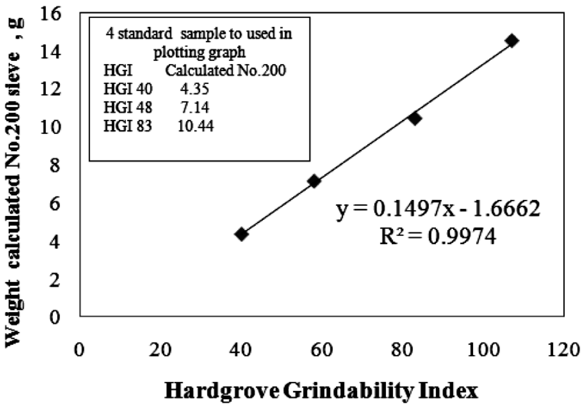

Figure 5 the typical calibration chart [7]

In order to confirm that the HGI equivalent can be used to compare with HGI of standard reference coal, Bridgeman et al.[7] compared the particle size distribution of torrefied biomass with standard reference coal, and the results are shown in Figure 6. From the figure, the size distribution of miscanthus D is similar to coal with HGI value of 92 and 66. Thus, it can be predicted that the HGI equivalent of miscanthus is in range of 66-92.

Table 4 HGI value of willow and miscanthus at various torrefaction temperature and residence time[7]

t (min)	d (mm)	Willow		Miscanthus	
		m (%)	**HGIequiv**	**m (%)**	**HGIequiv**
-	-	0.5	0	0.1	0
10	Small	4.7	24	5.1	26
60	Small	1	0	1.2	1
10	Large	2.6	10	2.8	11
60	Large	9.1[a]	51[a]	13.4[a]	79[a]

Note: [a]Single result, not duplicated

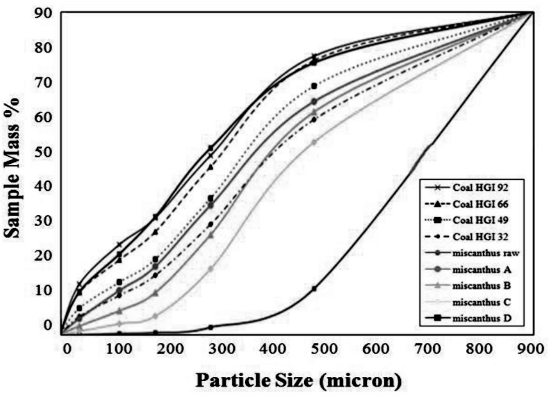

Figure 6 particle size distribution of miscanthus and coal[7]

Table 4 shows that the HGI equivalent of miscanthus D is 79. It is evident that HGI equivalent, determined by above correlation, can be compared with HGI of coal. In addition, it can be seen from Table 4 that the increase of torrefaction temperature results in the increase of HGI value.

Properties of torrefied pellet

The torrefaction and pelletization processes are combined in commercial scale. The final product is called torrefied pellet[8]. The important properties of torrefied pellet are heating value, bulk density, durability and hydrophobicity. As determination procedure of heating value of torrefied pellet is similar to torrefied biomass discussed above, this section explains bulk density, durability and hydrophobicity.

Durability

There are two methods to determine of durability: hardness and tumbling methods. The details of each method are as follows:

Hardness method

This method measures durability of torrefied pellet by hardness testing called Meyer hardness (H_M). The torrefied biomass pellet was placed on a flat plate and pressed by 6.35 mm cylinder as shown in Figure 7. Then, the force destroying a pellet was recorded.[26,29] Equation for calculation of the Meyer hardness is as follow.

$$H_M = \frac{F}{\pi\left(Dh - h^2\right)} \qquad (6)$$

Where, D represents the diameter of probe (m), h represents indentation depth (m), F is the force that destroys a pellet (N).

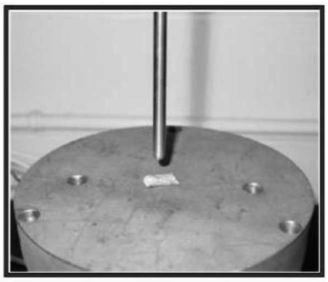

Figure 7 the test set up of Meyer hardness[29]

Tumbling method

Torrefied pellet durability was determined by tumbling method according to the EN15210-1. The test set up of tumbling method is shown in Figure 8. Torrefied pellet without dust of 500 g was filled into chamber and exposed to 500 rotations in time interval of 10 minutes. The equation of durability value can be written as follows.[30]

$$DI = \frac{m_f}{m_b} \qquad (7)$$

Where, m_b represents the mass of torrefied pellet before testing (kg), and m_f represents the mass of dust free torrefied pellet after testing (kg).

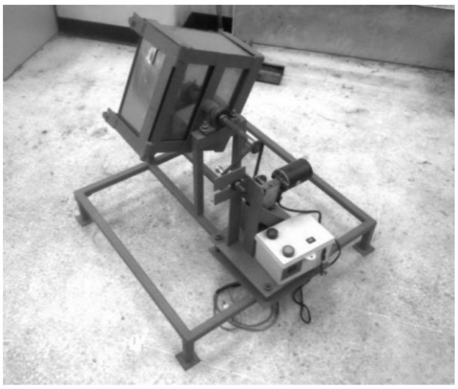

Figure 8 the test set up of tumbling method[46]

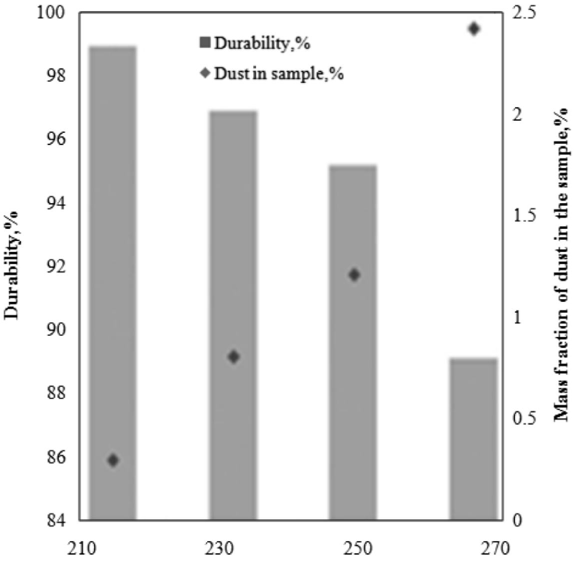

Figure 9 the effect of torrefaction temperature on durability[30]

Figure 9 shows the effect of torrefaction temperature on durability. It can be seen from the figure that the raw biomass as reference parameter has the highest durability, while the durability of torrefied biomass decreases with the increase of torrefaction temperature.

Bulk density

The bulk density was defined as quotient of torrefied pellet bulk mass and its volume. The bulk density could be determined by filling torrefied pellet into the standard box of 305 mm in length, 305 mm in width, and 305 mm in height as shown in Figure 10 (ASTM E-873).[45,46] The torrefied pellet was released from the height of 610 mm, then the box was jolted with 150 mm in height for 5 times to ensure that the box was full of torrefied pellet Finally, it was weighed and calculated for bulk density value. Table 5 showed the bulk density of torrefied pellet of previous researches.

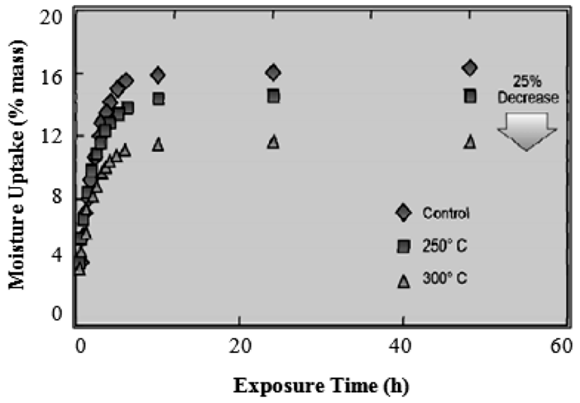

Figure 11 the relationship between moisture uptakes and exposure time[31]

Hydrophobic

Torrefaction process resulted in hydrophobic characteristic of product. The hydrophobicity occured when OH groups were destroyed causing the biomass to lose the capacity to form hydrogen bond. Non-polar unsaturated structures were formed resulting from above chemical rearrangement reaction. Lignin was decomposed and become plastic coating on biomass.[26] These mechanisms made low uptake moisture of the torrefied biomass. The hydrophobicity of torrefied pellets could be evaluated by immersing torrefied pellet in water for a specific time, e.g., 15 hours.[8] The hydrophobicity was evaluated by means of the amount of moisture uptake after testing. Sokhansanj et al.[26], Li et al.[32] compared amount of moisture uptake between torrefied pellets with raw biomass. They found that the amount of moisture uptake decreased with the increase of torrefaction temperature as can be seen in figure 11.

Conclusion

This paper reviews the properties of torrefied biomass and torrefied pellet such as heating value, energy yield, grinability, durability, bulk density, and hydrophobicity. The test method and effect of torrefaction temperature on these properties are also reviewed.

Figure 10 the test set up for bulk density testing[46]

Table 1 Correlation for prediction of heating value

Number	Name of author	Correlation (HHV,MJ/kg)	R^2
1	Based on proximate analysis	HHV =-10.81408+0.3133(VM+FC)	0.533
2	Jimennezand Gonzalez[33]	HHV =19.914-0.2324Ash	0.625
3	Changdong Sheng et al.[4]	HHV=0.196*FC + 14.119	-0.647
4	Demirbas[34]	HHV=0.312*FC + 0.15332*VM	-0.306
5	Demirbas[34]	HHV=0.3543*FC + 0.1708*VM	0.247
6	Cordero et al.[35]	HHV=-3.0368+0.2218VM+0.2601FC	0.617
7	Changdong Sheng et al.[4]	$\text{NHV}= -116 – 1.33\text{Ash}-0.005\text{VM}+1.92(\text{VM}+\text{Ash}) -0.0227(\text{VM}+\text{Ash}) -0.0122 (\text{VM})^2 + 0.0299 (\text{Ash})^2$	0.898
	M.Erol et al.[5]	$+6133 (\text{OM})^{-1}- 0.82(\text{Ash})^{-1}$	
8		HHV=0.1905VM + 0.2521FC	0.9953
	Chun-Yang Yin[16]		
9	Based on Ultimate analysis	HHV=0.4373C-1.6701	0.666
10	Tillman[36]	HHV=0.3259C+3.4597	0.758
11	Changdong Sheng et al. [36]	HHV=0.3516C+1.16225H-0.1109O+0.0628N+0.10456S	0.720
12	Boie[37]	HHV=0.328C+1.4306H-0.0237N+0.0929S-(1- Ash/100)(40.11H/C) + 0.3466	0.647
13	Graboski, Bain[38]	HHV=0.3491C+1.1783H+0.1005S-0.1034O-0.0151N-0.0211Ash	0.733
14	Channiwala, Parikh[43]	$\text{HHV}=3.55\text{C}^2 – 232\text{C}-2230\text{H}+51.2\text{C} \times \text{H} + 131\text{N}+20600$	0.943
15	Friedl et al. [17]	HHV=0.335C+1.423H-0.0154O-0.145N	0.081
16	Demirbas[34]	HHV=-0.763+0.301C+0.525H+0.064O	0.792
17	Jenkins[39]	HHV= - 1.3675 +0.3137C+0.7009H+0.0318O	0.834
18	Changdong Sheng et al.[4]	HHV=0.2949C + 0.8250H	0.9976
	Chun-Yang Yin[16]		
19	Based on chemical composition	HHV=0.1739Ce + 0.2663L+0.3219E	-0.503
20		HHV=[1-Ash/(100-Ash)](0.1739Ce + 0.2663L+0.3219)	-0.451
21	Shafizadeh and Degroot[a,40]	HHV= 0.1739Ce+0.2663(1-Ce’)	-1.068
22	Jimennez and Gonzalez[a,33]	HHV=0.0889L+16.8218	-0.875
	Tillman[a,36]		
	Demirbas[a,34]		

[a] Ce represent weight percent of cellulose and hemicelluloses , L represent lignin and extractives on dry basis biomass, and Ce’ represent cellulose (cellulose and hemicelluloses) on dry extractable-free basis

Table 2 Element composition of some biomass

Biomass	Ultimate analysis				Proximate analysis			HHV (MJ/kg)
	C	H	O	N	VM	FC	A	
Bagasse (sugar cane)[18]	44.80	5.80	49.10	0.25	67.31	-	1.53	15.50
Bamboo[6,10]	43.84	6.05	46.53	0.07	73.56	19.94	3.51	18.70
Cotton stalk[12]	46.43	6.18	42.62	0.80	76.92	19.19	2.70	-
Empty fruit bunches(oil palm)[19]	45.53	5.46	43.40	0.45	-	-	-	17.02
Kernel shell (oil palm)[19]	46.68	5.86	42.01	1.01	-	-	-	19.78
Lucerne[14,41]	50.10	7.40	41.80	0.70	87.30	12.2	0.5	20.40
Mesocarp (oil palm)[19]	46.92	5.89	42.66	1.12	-	-	-	19.61
Rape stalk[20]	46.96	6.13	41.95	0.37	76.35	19.30	3.16	18.75
Reed canary grass[18]	48.60	6.80	37.30	0.30	82.50	12.10	5.50	19.50
Rice straw[19]	39.00	5.08	40.96	1.03	68.83	17.46	8.59	17.12
Rubber seed kernel Straw[21]	43.21	5.97	50.25	0.55	-	-	-	-
Straw pellet[8,42]	47.50	5.80	42.40	0.40	79.00	-	7.10	17.40
Wheat straw[18,41]	47.30	0.63	45.50	6.40	80.80	19.20	4.60	17.80
Straw[18]	44.30	6.80	42.40	0.80	76.40	17.30	6.30	18.90
Corn stover[42]	44.30	5.80	48.20	0.40	79.00	-	7.10	17.40
Rice husk[2]	50.45	4.65	43.94	5.35	-	-	-	20.00
sugar cane residue[13]	44.04	6.55	40.45	0.24	80.45	8.60	10.95	17.40
Banyan[13]	49.19	6.94	46.53	0.43	93.60	3.65	2.5	17.80
Beech[10,12]	46.20	6.08	45.20	0.08	77.57	18.03	1.11	20.29
Birch[8,22,42]	47.20	6.00	48.20	0.40	84.20	15.50	0.30	18.30
Eucalyptus[22]	45.50	6.20	44.60	0.10	-	-	-	16.44
Larch[11]	49.00	6.10	44.90	0.20	-	-	-	19.40
Lauan wood[8,42]	48.80	6.10	44.36	0.10	82.80	-	0.10	19.50
Leucaena[23]	48.77	6.77	41.80	0.10	75.08	17.22	-	20.41
Loblolly pine[14]	50.10	7.40	43.34	0.70	86.10	13.10	0.80	20.30
Logging residue chip[24]	50.25	5.97	45.19	-	-	-	-	19.55
Pine wood chip[25]	47.29	6.20	45.76	0.42	82.17	16.07	1.77	18.79
Sawdust[25]	47.21	6.64	43.95	0.17	85.98	13.7	0.27	18.46
Willow[23,26]	48.54	6.21	44.80	1.50	80.49	619.	0.24	-
Wood briquette[8,10,18,42]	47.20	6.10	40.24	0.34	87.60	42	1.70	19.00
Wood pellet[27]	49.37	6.59	44.90	-	-		2.80	20.02
Mallee[41]	48.50	0.05	34.14	6.60	83.05	10.70	0.30	18.58
Three pine pellet[28]	60.3	5.3	42.64	0.18	59.50	19.20	0.70	22.00
Jeffrey Pine[29] and White Fir[3]	51.21	6.02	41.26	0.12	-	16.95	-	18.60
	49.02	5.93	-	0.11	-	35.30	-	20.32

Table 3 The correlation for HGI equivalent of torrefied biomass.

Biomass	Grinding equipment	The standard reference coal	HGI equivalent
Miscanthus[7] and willow[7]	Retsch PM 100 ball mall	HGI 32, HGI 49, HGI 66,HGI 92	$HGI_{equiv} = \frac{M_H - 0.9856}{0.1575} \quad (4)$
Wheat straw[15]	Hardgrove grinder (3200LB,AUBEMA,Germany) follow by ASTM D409-51(1961)[44]	HGI 33 , HGI 53 , HGI 68	$HGI_{equiv} = \frac{M_H + 5.2521}{0.3577} \quad (5)$

Table 5 Summarized properties of various solid fuels

Properties	Initial Particle size (mm)	Particle Density (kg/m^3)	Bulk Density (kg/m^3)	Moisture Content (%)
Wood pellets[28]	-	1103-1901	498-649	8-10
Wood chips[28]	-	N/A	209-273	41-51
Torrefied pellets[28]	-	1280-1361	610-668	3.9-4.1
Torrefied pellets[29]	0.23	1419	157	1.96-3.06
of Three Pine	0.67	1431	197	2.71-3.58
	0.81	1381	165	3.92-4.27

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