An Index for Quantifying the Degree of Torrefaction

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Torrefaction, a thermochemical pre-treatment process, is used to enhance the properties of biomass to make it more compatible with solid fossil fuels. A quantitative index (TI) is proposed here to define the degree or quality of torrefaction especially for its use in the energy industries. Torrefaction index is defined as the ratio of energy density enhancement factor of the product at the specified condition to that at a reference condition, which is torrefaction at 300 °C for 60 min. The index, calculated for a wide range of data shows a linear dependence on torrefaction temperature. Numerical values of this index were in range of 0.93 to 0.95, 0.95 to 0.97, and 0.97 to 1.0 for light, medium, and severe torrefaction conditions, respectively. Based on a wide range of experimental data of woody biomass, two empirical correlations for mass and energy yields were developed. These correlations permitted prediction of TI without performing torrefaction of the biomass.

Keywords: Biomass; Degree of torrefaction; Index; Mass yield; Energy yield

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INTRODUCTION

Rising energy demands associated with rise in living standards and overall economic growth, especially in non-OECD countries, have greatly increased the consumption of fossil fuels, which has resulted in higher emissions of carbon dioxide. It has elevated the atmospheric CO_2 concentration by as much as 85 ppm in the last 55 years, reaching a current level of 406 ppm (Perovich *et al*. 2012). This value is not too far from the 450 ppm limit, the world body recognizes as the maximum CO_2 concentration the earth's habitation can tolerate without major upsets (O'Neill and Oppenheimer 2002). This underscores the importance of the immediate use of alternative, carbon free, and renewable energy sources (Chen *et al.* 2015).

While much progress is being made with renewable options such as solar and wind, the extent of their implementation is not sufficient to arrest the rapid rise in CO_2 levels, especially from increasing carbon emissions from coal-fired plants around the world. Co-firing coal with biomass in existing coal-fired plants could, however, immediately reduce greenhouse gas (GHG) emissions worldwide at affordable costs. This option is already being practiced commercially in many plants, but due to its high bulk volume, low C/H ratio, hydrophobic nature, fibrous behavior, and low energy density, only a limited amount of biomass (5 to 10% of total energy) is being co-fired with coal (Basu *et al*. 2011). Further increase in the share of the carbon neutral energy source biomass is not feasible without significant modifications to the existing coal-fired power plants. However, the pretreatment of biomass through torrefaction could increase its share to as much as 60 to 80%.

Torrefaction, a thermochemical pretreatment process results in important positive changes to the chemical compositions and physical properties of biomass, making it very similar to coal without major losses in its energy content. Torrefied biomass is thus considered a potential substituent for coal in pulverized coal-power plants. This process is performed within a narrow temperature range of 200 to 300 °C at a low heating rate and in a non-oxidizing environment (Tumuluru *et al.* 2010; Nhuchhen *et al.* 2014). Conventional pyrolysis that is carried out at a higher temperature range primarily produces liquid fuels, whereas the torrefaction process mainly produces a solid product (Tumuluru *et al.* 2010; Nhuchhen *et al.* 2014). Carbonization, though similar to torrefaction, is carried out at much higher temperatures and results in the loss of much of the energy and mass of the raw biomass.

Much work has been done to understand the process of torrefaction and to study the effects of different operating parameters (temperature, residence time, size, presence of oxygen) on the yield and qualities of torrefied products from various biomasses (Nhuchhen *et al.* 2014; Chen *et al.* 2015). However, little attention has been directed towards defining a numerical representation of the quality of the torrefied product. In contrast, coffee roasting, which is also a torrefaction process, has well defined grading scale such as Dark Roast, Mild Roast, French Roast, *etc*. These grades are based on the roasting temperature of coffee (Basu 2015).

Torrefaction being a relatively new process has some important knowledge gaps. Lack of a quantitative assessment of the extent or degree of torrefaction is one of these gaps. Additionally, there is no large database on a wide range of torrefied biomass. For preliminary assessment of a commercial torrefaction project, it is not always practical or cost effective to experimentally determine the torrefaction characteristics of all candidate biomasses. Existing data or correlations could help in the selection of a biomass for a specific application, especially in terms of its cost effectiveness.

An index that quantifies the degree of torrefaction and shows the effect of biomass type and operating parameters on the quality of torrefaction is also currently lacking. Though some researchers have used terms such as light, mild, and severe in an attempt to grade the degree of torrefaction, there is no quantitative measure of this grade.

While developing a correlation, Almeida *et al.* (2010) noted a linear relationship between mass loss (*ML*), Energy yield (*EY*), and fixed carbon (*FC*) content for a wide range of temperatures and residence times varying from 1 to 5 h, as shown in Eq. 1,

$$\begin{aligned} FC &= 16.3\,(1 - 0.046\,ML\%) && \text{For wood} \\ EY &= 1 - 0.006\,(ML\%) && \text{For wood} \qquad (1) \end{aligned}$$

For this, Almeida *et al.* (2010) suggested mass loss as the severity index of torrefaction. Such a definition could be useful for metallurgical industries, especially for pig iron production, where fixed carbon content alone is important. It may not be very useful for energy industries.

Presently, torrefied wood and other biomasses are being seriously considered for use in large co-fired coal-fired power plants to reduce net carbon emissions to the atmosphere. For the use of torrefied biomass one would naturally require a ‘wellness index’ to compare one product with another for their use for energy conversion. Chen *et al.* (2014a) defined a torrefaction severity index based on the mass loss during the torrefaction process. Such a definition is much more focused on the mass yield rather than energy yield and density change, which are of greater importance for energy conversion. Li *et al.* (2012)

observed a linear relationship between energy yield and mass yield. Although the authors claimed that the severity of torrefaction increases with an increase in energy yield, no explicit suggestion on severity was proposed. Peng *et al.* (2013) used mass loss as an indicator of torrefaction severity and developed a linear relationship between energy density or higher heating value (*HHV*) and mass loss expressed as,

$$HHV = 19.85 + 9.34\ (ML\%) \tag{2}$$

Chen *et al.* (2014a) proposed a non-dimensional parameter based on the rate of mass loss during torrefaction. It is difficult to use this parameter because very little experimental data provide information on the rate of mass loss. One needs to perform new experiments to determine this parameter (a practice not feasible in many situations). Therefore, the goal of the present study was to develop a quantitative parameter for measuring the degree of torrefaction, specifically keeping in mind its use in the energy industries.

RESULTS AND DISCUSSION

A large set of data on torrefied biomass from a wide range of work of different investigators, 140 in number, was collected, and out of that 106 sets of data were analyzed (Table A1, A2). The tabulated information was used to develop torrefaction index and correlations for estimation of torrefaction attributes.

Torrefaction Attributes

To characterize a torrefied biomass, the most frequently used parameters are solid mass yield (*MY*), energy yield (*EY*), and energy density enhancement factor (*EDEF*). These parameters are defined below.

$$MY_{daf} = \frac{Mass\ of\ torrefied\ biomass\ on\ dry\ ash\ free\ basis}{Mass\ of\ raw\ biomass\ on\ dry\ ash\ free\ basis} \tag{3}$$

$$EY_{daf} = \frac{Energy\ in\ torrefied\ product\ on\ dry\ ash\ free\ basis}{Energy\ in\ raw\ biomass\ on\ dry\ ash\ free\ basis} \tag{4}$$

$$EDEF = \frac{Energy\ density\ of\ torrefied\ biomass}{Energy\ density\ of\ raw\ biomass} = \frac{HHV_{tor}}{HHV_{raw}} \tag{5}$$

As the definitions of mass yield and energy yield are based on dry ash free (*daf*) basis for all data, the cellulose, lignin, and hemicellulose contents of the biomass were converted into dry ash and extractive free basis and tabulated in Tables A1 and A2.

Development of Torrefaction Index

The largest use of torrefied biomass is likely to be for its cofiring with coal in power plants (Tumuluru *et al.* 2011). Many power plants procure biomass across great distances and, at times, from overseas. The share of biomass in cofired plants is generally defined by the amount of useful heat that comes from the biomass. The higher the share of energy from the biomass, the greater the reduction in GHG emission per unit MWh generated from the power plant. Carbon credit attributed to the plant is generally proportional to this amount. As such, the energy content of the torrefied biomass fired is of primary concern in such plants (Basu *et al.* 2011). For this reason, the energy content of the pretreated biomass, rather than the mass of feed, is a major concern for its use in energy industries. This was taken into consideration to develop this index.

Energy densification alone does not appear sufficient to define the quality of a torrefied biomass. If that were the case, charcoal produced from a biomass would have the highest quality because of its high energy density, and all power plants would be buying charcoal for cofiring. However, charcoal is more expensive per unit of energy delivered, and it also lacks other qualities like the presence of volatiles for facilitating combustion. While it does obtain the highest energy density, charcoal has the lowest mass and energy yields, which consequently increases the purchase cost of fuel on an energy content basis. Thus, one receives the lowest amount of energy from a given mass of raw biomass. An index used to define the quality or degree of torrefaction should reflect this aspect for energy use.

This study defined the index in terms of energy density enhancement in a dimensionless form by dividing its value at a given state by that of a reference state.

The Index

As mentioned earlier, the extent to which the heating value (energy density) of the biomass increases due to torrefaction is a primary concern of defining its quality. The power industry, potentially the largest user of torrefied biomass, likes to pack as much energy as possible into a given volume of biomass in order to minimize shipping and handling costs, and simultaneously not pay much for buying the fuel at its source. Use of energy yield alone as an index of torrefaction, therefore, could be misleading, as the highest energy yield means the poorest, or least severe, torrefaction. It is simpler to picture that the more severe the torrefaction, the higher is the torrefaction index.

In this study, energy density enhancement was used as an index for torrefaction, which presented the enhancement of the energy density of biomasses (dry ash free (daf)) through torrefaction rather than energy yields. As such, the torrefaction index was defined in terms of EDEF, and expressed in a non-dimensional form by comparing its value to that of a reference state,

$$Torrefaction\ Index = \frac{Energy\ density\ enhancement\ for\ design\ condition\ (tp)}{Energy\ density\ enhancement\ for\ reference\ condition\ (ref)} \qquad (6)$$

where *tp* refers to design condition of torrefaction and *ref* refers to the reference state.

The energy density enhancement factor is different from the energy yield (*EY*), which is the ratio of energy content of the raw and torrefied biomass, but they are related as below:

$$EY = \frac{HHV_{tor} \times Mass_{tor}}{HHV_{raw} \times Mass_{raw}} = EDEF \times MY \qquad (7)$$

Mass yield, used by some to define the quality of torrefaction, has a bearing on the energy yield and/or energy density, but the relationship is not as direct as it is for EDEF.

Reference State

A higher extent of torrefaction results in a higher EDEF value. This generally increases with temperature. Torrefaction at temperatures higher than 300 °C yield biomass products with higher energy densities, but at the expense of other attributes. For example, torrefaction above 300 °C lowers the lignin content of the product, compromising its pelletization capability.

Additionally, torrefaction above 300 °C leads to a reduction in total energy and volatile matter contents. This increases the ignition temperature of the torrefied biomass (Du *et al.* 2014) and leads to increased tar formation due to large scale depolymerization of the cellulose. As a result, torrefaction above 300 °C is not desirable. Therefore, 300 °C was considered to be a reference temperature and 60 min a reference residence time. Very few torrefaction technologies use longer than 60 min as the reaction time (Felfli *et al.* 1999; Bates and Ghoniem 2012). This prompted the inclusion of 60 min as a reference time.

Torrefaction index (*TI*) compares the energy density enhancement at a given state at a value of 300 °C and 60 min, where *EDEF* would have the maximum value.

$$TI = \frac{EDEF_{tp}}{EDEF_{300,60}} \tag{8}$$

Thus, for all biomasses, the maximum value of the torrefaction index is 1.0 at the reference state, and in the course of torrefaction it increases from its lowest value in the raw biomass.

The energy density enhancement factor (*EDEF*) can also be expressed as ratio of energy yield (*EY*) to solid mass yield (*MY*).

$$TI = \frac{EDEF_{tp}}{EDEF_{ref}} = \left(\frac{EY}{MY}\right)_{tp} \times \left(\frac{MY}{EY}\right)_{ref} \tag{9}$$

Solid mass yield and energy yield can be calculated using correlation Eqs. 12 and 13, respectively.

Previous researchers (Almeida *et al.* 2010) found a linear correlation between energy yield and mass yield. By expressing this as $EY = a + b\ MY$, one can write the torrefaction index presented in Eq. 9 in terms of mass yield,

$$TI = \frac{\left[b + \frac{a}{MY}\right]_{tp}}{\left[b + \frac{a}{MY}\right]_{300,60}} \tag{10}$$

where the subscript in the denominator defines the reference condition of 300 °C and 60 minutes.

This could potentially allow for predictions of the degree of torrefaction of a biomass of known polymeric composition at a specified torrefaction condition (*tp*) making the index (*TI*) a powerful tool for preliminary design or selection of biomass that could be used before investing in actual torrefaction tests on feedstock.

Effect of Temperature on Torrefaction Index

Torrefaction index (presented in Table A4) was calculated using experimental data from Table A1 and A2. At a particular torrefaction temperature, the variation of the torrefaction index with changes in torrefaction time was negligible. Therefore, the torrefaction index was plotted only against temperature (Fig. 1) as $TI = F(T)$. The trend line obtained was linear and had a R^2 value of about 90%, showing the index depended more on the torrefaction temperature.

$$TI = f(T) = 0.0006\ T + 0.7987 \tag{11}$$

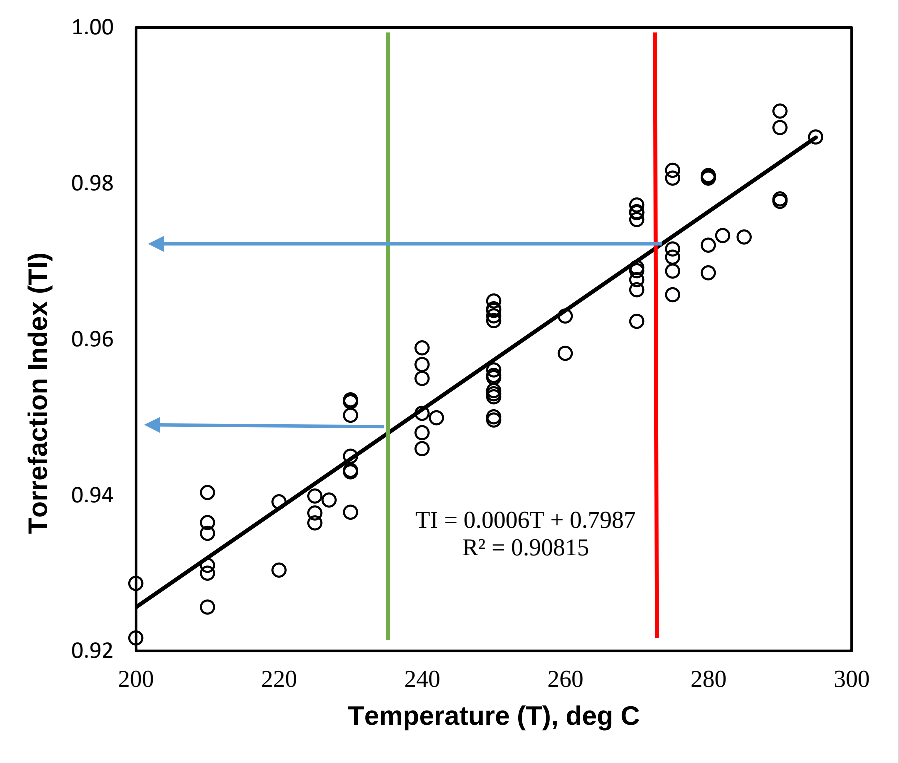

Fig. 1. Variation of calculated torrefaction index and torrefaction temperature

Torrefaction Regimes

The torrefaction index can also give a numerical range of the three regimes of torrefaction (light, mild, and severe), suggested by previous researchers. Numerical values for the broadly defined torrefaction regimes were determined (Basu 2013). Following the suggestion of Chen *et al.* (2015), 235 °C and 275 °C were chosen as the boundary temperatures between light-to-mild and mild-to-severe torrefactions, respectively. Considering this, three regimes of the torrefaction index were defined corresponding to three regimes of torrefaction, as shown in Table 1.

Table 1. Torrefaction Index in Different Regimes

Torrefaction Regimes	Temperature (°C)	Torrefaction Index (TI)
Light	200 to 235	0.93 to 0.95
Medium	235 to 275	0.95 to 0.97
Severe	275 to 300	0.97 to 1.00

Empirical Correlation

The characteristics of torrefied biomasses are very important to investors when preparing a prefeasibility report and making investment decisions. They not only confirm economic feasibility, but also ensure the technical viability of using upgraded biomasses in a specific biomass energy conversion technology. At the prefeasibility stage, torrefaction data of all biomasses being considered for the project is not always available. However, if the magnitude of the torrefaction index of a candidate biomass at given operating conditions can be estimated, the prefeasibility study can be conducted with a much higher level of accuracy. Furthermore, it could help select the best biomass for a given project.

The following is an attempt to develop empirical correlations for the assessment of the torrefaction index of biomasses based on their known compositions. It is important to note that these values are meant only for preliminary assessment and are not a substitute for their experimental measurements.

Using Eq. 6 one can calculate the degree of torrefaction of a biomass of known energy yield at a specified torrefaction condition (*tp*). This makes the index (*TI*) a powerful tool for preliminary design, or biomass selection, before investing in torrefaction tests on feedstock provided *EY* is known for a biomass of given polymeric composition.

To develop one such correlation experimental data on solid mass yields (*MY*) was collected for different biomass types at various operating conditions. The collected data was grouped in two different sets. Set I data from Table A1 were used to develop the correlations and Set II data from Table A2 were used to verify the correlations. For these two sets, the composition of cellulose, lignin, and hemicellulose was converted into dry ash and extractive free basis, and remaining data values were tabulated as dry ash free basis.

Analyses were carried out to develop correlations for the mass yield and the energy yield as a function of operating conditions including torrefaction temperature and time, and the properties of biomass as per ultimate analyses, proximate analyses, and polymeric compositions. This analysis found that the use of polymeric composition, which can appropriately incorporate types of biomass, had more predictive ability than its proximate analyses and the ultimate analyses. This observation was expected because torrefaction is essentially the degradation of hemicellulose, cellulose, and lignin. As such, the polymeric composition of the biomass would have a higher influence on mass or energy yield than the constituents of elemental or proximate analyses.

Data from Table A1 were used to develop a correlation between energy yield (*EY*) and *daf* basis. The relation can be expressed as follows,

$$EY\,(\%) = 35952 - 358.34\,Cel - 358.35\,Hem - 358.43\,Lig - 0.09\,T - 0.02\,\tau \quad (12)$$

where *Cel*, *Hem*, and *Lig* are percentages (%) of cellulose, hemicellulose, and lignin, respectively, in raw biomass. Torrefaction temperature is *T* in °C, and torrefaction time is τ in s.

Energy yield from the developed correlation above was compared that measured. The comparison between the two is shown in Fig. 2. The R^2 value was reasonably good, but not very high. This is because biomass samples were from a wide range of types. If the biomasses were restricted to specific groups, a higher degree of accuracy could have been achieved for the correlation.

Similarly, a correlation for mass yield is defined as follows:

$$MY\,(\%) = 31208 - 310.78\,Cel - 310.89\,Hem - 311.07\,Lig - 0.14\,T - 0.05\,\tau \quad (13)$$

These values could be substituted into expression (Eq. 9) of the torrefaction index to get a preliminary assessment of the degree of torrefaction for a specific biomass when torrefied at a specific condition.

This expression could also help determine a choice of biomass, and/or its torrefaction conditions, at the planning stage of an energy project.

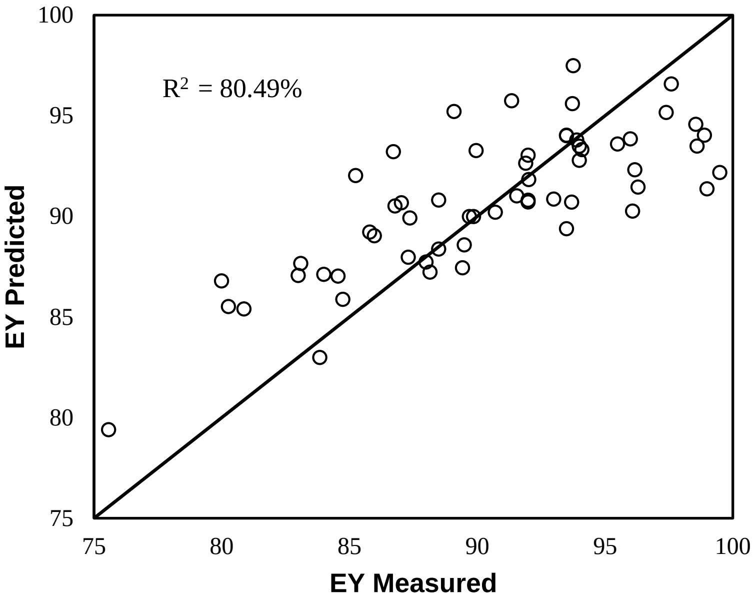

Fig. 2. Comparison of predicted and measured mass yield

CONCLUSIONS

1. For quantitative assessment of the quality of torrefied biomass, especially in the context of its use in the energy industry, a numeric index termed the Torrefaction Index (*TI*) was introduced. It is defined as the ratio between energy density enhancement factor at a given condition, and that at a reference condition (300 °C and 60 min) of the torrefied product. The index showed a linear dependence on the torrefaction temperature for a wide range of biomasses.
2. A torrefaction index may be calculated for known values of *EY* and *MY*, which can be estimated from polymeric composition of the biomass or from experimentally determined values for more precise values for preliminary assessments. The severity of torrefaction was determined from the numerical values of the torrefaction index. These values were 0.93 to 0.95 for mild, 0.95 to 0.97 for medium, and 0.97 to 1.0 for severe torrefaction. Thus, a powerful pre-assessment tool was established wherein a planner can get a reasonable quantitative idea of the quality of the torrefied product, even before conducting torrefaction tests in a laboratory or pilot plant.
3. Analyses of a large set of data from a wide range of biomasses obtained from different researchers show that parameters mass yield (*MY*) and energy yield (*EY*), correlate well with the polymeric compositions of the biomasses and their torrefaction conditions. Two empirical correlations were developed for predictions of *MY* and *EY* of a biomass of known hemicellulose, cellulose, and lignin content after it was torrefied at a specified temperature and time. A reasonable agreement was found when these correlations were used to predict *MY* and *EY* for an independent set of experimental data from a wide range of biomasses. Better agreement would be expected if the correlation was developed for a specific group of biomass, instead of a wide range.

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APPENDIX

Table A1. List of Mass Yield (*MY*), Energy Density Enhancement Factors (*EDEF*), and Energy Yield (*EY*) of Various Biomasses at Different Torrefaction Conditions and Raw Biomass Compositions (Set I: Used for Development of the Correlations)

Material	Ref.	Raw Biomass			Torrefied Biomass			Torrefaction Condition	
		Dry ash & extractive free basis (%)			Dry ash free basis				
		Cellulose	Hemi cellulose	Lignin	*MY* (%)	*EDEF*	*EY* (%)	Temp (C)	Time (min)
Reed Canary Grass	[i]	53.32	37.17	9.51	92.60	1.01	93.50	230	50
Wheat Straw		51.75	38.60	9.65	91.00	1.03	93.50	230	50
Willow		59.11	16.91	23.98	79.80	1.08	85.80	270	50
Spruce	[ii]	43.49	20.51	36.00	76.00	1.11	84.00	280	52
Fir		38.21	25.75	36.05	72.93	1.14	83.00	280	52
Pine bark		30.71	21.06	48.24	69.21	1.16	80.00	280	23
Pine wood chips	[iii]	54.01	16.89	29.09	89.01	1.06	94.00	225	30
Logging Residue		48.75	17.24	34.01	88.46	1.04	92.00	225	30
		48.75	17.24	34.01	81.32	1.13	92.00	250	30
Leucaena, Woody BM	[iv]	35.98	34.57	29.46	91.09	1.03	93.73	200	30
		35.98	34.57	29.46	86.50	1.04	89.96	225	30
Lauan	[v]	40.49	15.74	43.77	82.00	1.12	91.90	220	30
		40.49	15.74	43.77	82.00	1.12	92.02	220	60
		40.49	15.74	43.77	80.00	1.14	91.56	220	90
		40.49	15.74	43.77	79.00	1.15	90.72	220	120
Oil Palm Fiber	[vi]	34.90	44.20	20.90	75.50	1.17	88.50	250	60
Eucalyptus		56.90	18.10	25.00	83.60	1.12	93.70	250	60
		56.90	18.10	25.00	75.80	1.17	88.50	275	60
Loblolly Pine	[vii]	59.41	13.09	27.50	83.80	1.07	89.70	250	80
		59.41	13.09	27.50	74.20	1.12	83.10	275	80
Rice Straw	[viii]	49.04	30.01	20.96	86.17	1.06	91.35	210	20
		49.04	30.01	20.96	80.23	1.11	89.10	210	40
		49.04	30.01	20.96	78.38	1.09	85.25	250	20
Cotton stalk		48.03	16.48	35.49	86.54	1.14	98.56	210	20
		48.03	16.48	35.49	82.74	1.20	98.90	210	40
		48.03	16.48	35.49	83.68	1.18	98.61	210	60
		48.03	16.48	35.49	72.15	1.29	93.00	250	20
Spruce wood	[ix]	42.29	26.37	31.34	80.00	1.09	87.30	285	17
		42.29	26.37	31.34	77.00	1.10	84.75	310	8
Rice husk	[x]	54.08	26.50	19.42	97.63	1.00	97.60	200	30
		54.08	26.50	19.42	91.32	1.03	93.90	230	30
Miscanthus x *Giganteus*	[xi]	50.72	24.30	24.97	92.30	1.04	96.00	230	10
		50.72	24.30	24.97	88.80	1.06	94.10	230	30
		50.72	24.30	24.97	81.10	1.19	96.30	250	30
Spruce Pine	[xii]	54.71	17.39	27.91	79.34	1.11	88.16	280	76
		54.71	17.39	27.91	68.43	1.18	80.88	295	92

		54.71	17.39	27.91	69.08	1.16	80.27	310	36
Reeds		50.63	34.95	14.43	78.63	1.11	87.04	250	90
		50.63	34.95	14.43	78.72	1.10	86.79	270	27
		50.63	34.95	14.43	78.11	1.10	85.98	290	13
wheat	[xiii]	54.11	29.86	16.04	79.66	1.12	89.43	307	10
		54.11	29.86	16.04	64.29	1.18	75.58	392	15
		54.11	29.86	16.04	86.89	1.08	93.77	199	10
		54.11	29.86	16.04	72.28	1.17	84.56	310	15
		54.11	29.86	16.04	71.04	1.18	83.85	352	20
		54.11	29.86	16.04	97.48	1.01	98.78	133	10
		54.11	29.86	16.04	93.95	1.03	96.41	156	15
		54.11	29.86	16.04	80.21	1.08	86.72	242	20
Barley		51.78	36.03	12.19	95.92	1.02	97.40	227	10
		51.78	36.03	12.19	78.96	1.11	87.37	282	15
Corn cob	[xiv]	40.09	43.64	16.26	89.66	1.07	96.18	250	20
		40.09	43.64	16.26	76.90	1.17	89.86	275	20
		40.09	43.64	16.26	84.59	1.14	96.08	275	10
Coffee Residue	[xv]	37.26	54.57	8.17	89	1.07	95.5	240	30
		37.26	54.57	8.17	84	1.12	94.00	240	60
		37.26	54.57	8.17	74	1.24	92.00	270	30
Sawdust		47.52	14.73	37.75	77	1.14	88.00	270	60
Rice Husk		45.90	27.16	26.93	93	1.07	99.50	240	30
		45.90	27.16	26.93	91	1.09	99.00	240	60
		45.90	27.16	26.93	82.5	1.13	93.50	270	30
		45.90	27.16	26.93	77.5	1.15	89.50	270	60

[i] Bridgeman *et al.* (2008)	[ii] Peng *et al.* (2013)
[iii] Phanphanich & Mani (2011)	[iv] Wannapeera *et al.* (2011)
[v] Chen *et al.* (2011a)	[vi] Lu *et al.* (2012)
[vii] Yan *et al.* (2009)	[viii] Nam & Capareda *et al.* (2015)
[ix] Strandberg *et al.* (2015)	[x] Chen *et al*. (2014b)
[xi] Xue *et al.* (2014)	[xii] Grigiante & Antolini (2015)
[xiii] Satpathy *et al.* (2014)	[xiv] Zheng *et al.* (2013)
[xv] Chen *et al.* (2012)	

Table A2. Mass Yield (*MY*), Energy Density Enhancement Factor (*EDEF*), and Energy Yield (*EY*) of Various Biomasses at Different Torrefaction Conditions and Raw Biomass Compositions (Set II: For Verification of the Correlation)

Material	Ref.	Raw Biomass			Torrefied Biomass			Torrefaction Condition	
		Dry ash & extractive free basis (%)			Dry ash free basis				
		Cellulose	Hemi cellulose	Lignin	*MY* (%)	*EDEF*	*EY* (%)	Temp (C)	Time (min)
Reed Canary Grass	[i]	53.32	37.17	9.51	84.00	1.03	86.60	250	50
		53.32	37.17	9.51	72.00	1.07	77.10	270	50
Wheat Straw		51.75	38.60	9.65	82.60	1.04	86.20	250	50
		51.75	38.60	9.65	71.50	1.09	78.20	270	50
Willow		59.11	16.91	23.98	95.10	1.01	96.50	230	50
		59.11	16.91	23.98	89.60	1.03	92.70	250	50
		59.11	16.91	23.98	72.00	1.10	79.20	290	50
Pine	[ii]	37.99	27.23	34.78	70.86	1.09	77.00	280	52
Pine wood chips	[iii]	54.01	16.89	29.09	82.02	1.10	90.00	250	30
		54.01	16.89	29.09	72.95	1.19	87.00	275	30
Logging Residue		48.75	17.24	34.01	69.99	1.17	82.00	275	30
Leucaena, Woody BM	[iv]	35.98	34.57	29.46	46.67	1.21	56.40	250	900
Banyan	[v]	57.07	12.19	30.74	72.00	1.24	89.21	230	30
Oil Palm Fiber	[vi]	34.90	44.20	20.90	63.80	1.25	79.70	275	60
Loblolly Pine	[vii]	59.41	13.09	27.50	60.50	1.21	73.20	300	80
Rice Straw	[vii]	49.04	30.01	20.96	78.89	1.10	86.58	210	60
Cotton stalk		48.03	16.48	35.49	69.27	1.27	87.84	250	40
		48.03	16.48	35.49	62.79	1.37	85.80	290	20
Spruce wood	[ix]	42.29	26.37	31.34	89.00	1.06	93.98	260	25
Rice husk	[x]	54.08	26.50	19.42	80.36	1.03	83.00	260	30
Miscanthus x *Giganteus*	[xi]	50.72	24.30	24.97	87.00	1.06	91.80	250	10
		50.72	24.30	24.97	76.90	1.11	85.60	270	10
Spruce Pine	[xii]	54.71	17.39	27.91	89.88	1.07	96.21	280	20
		54.71	17.39	27.91	80.45	1.12	90.18	295	30
		54.71	17.39	27.91	79.72	1.11	88.56	310	17
Reeds		50.63	34.95	14.43	67.34	1.16	78.25	270	120
		50.63	34.95	14.43	68.74	1.15	79.18	290	43
		50.63	34.95	14.43	68.68	1.17	80.10	310	14

Barley	[xiii]	51.78	36.03	12.19	81.71	1.07	87.26	388	10
		51.78	36.03	12.19	91.28	1.02	93.01	314	10
		51.78	36.03	12.19	60.92	1.16	70.62	427	15
		51.78	36.03	12.19	76.40	1.11	85.17	405	20
Sawdust	[xiv]	47.52	14.73	37.75	92	1.07	98.50	240	30
		47.52	14.73	37.75	88	1.10	97.00	240	60
		47.52	14.73	37.75	83	1.13	93.50	270	30

[i] Bridgeman *et al.* (2008)

[ii] Peng *et al.* (2013)

[iii] Phanphanich & Mani (2011)

[iv] Wannapeera *et al.* (2011)

[v] Chen *et al.* (2011b)

[vi] Lu *et al.* (2012)

[vii] Yan *et al.* (2009)

[viii] Nam & Capareda (2015)

[ix] Strandberg *et al.* (2015)

[x] Chen *et al.* (2014b)

[xi] Xue *et al.* (2014)

[xii] Grigiante & Antolini (2015)

[xiii] Satpathy *et al.* (2014)

[xiv] Chen *et al.* (2012)

Table A3. Validation of Mass Yield and Energy Yield Correlations

Ref.	Measured		Predicted			
	MY	*EY*	*MY* predicted %	*MY* error	*EY* predicted %	*EY* error
[i]	84.00	86.60	85.65	1.65	92.17	5.57
	72.00	77.10	82.85	10.85	90.31	13.21
	82.60	86.20	85.46	2.86	92.15	5.95
	71.50	78.20	82.66	11.16	90.29	12.09
	95.10	96.50	86.49	-8.61	92.93	-3.57
	89.60	92.70	83.69	-5.91	91.07	-1.63
	72.00	79.20	78.09	6.09	87.35	8.15
[ii]	70.86	77.00	75.12	4.26	87.15	10.15
[iii]	82.02	90.00	83.20	1.18	91.15	1.15
	72.95	87.00	79.70	6.76	88.83	1.83
	69.99	82.00	78.24	8.25	88.38	6.38
[iv]	46.67	56.40	37.66	-9.01	67.45	11.05
[v]	72.00	89.21	86.04	14.04	92.91	3.70
[vi]	63.80	79.70	77.58	13.78	88.48	8.78
[vii]	60.50	73.20	74.58	14.08	85.33	12.13
[viii]	78.89	86.58	88.22	9.34	94.66	8.08
	69.27	87.84	80.89	11.63	90.31	2.47
	62.79	85.80	76.29	13.50	87.13	1.33
[ix]	89.00	93.98	80.36	-8.64	90.06	-3.92
[x]	80.36	83.00	83.55	3.20	91.00	8.00

[xi]	87.00	91.80	84.58	-2.42	91.99	0.19
	76.90	85.60	81.78	4.88	90.13	4.53
[xii]	89.88	96.21	79.79	-10.09	88.73	-7.48
	80.45	90.18	77.19	-3.26	87.07	-3.11
	79.72	88.56	75.74	-3.98	86.03	-2.53
	67.34	78.25	78.17	10.84	88.00	9.75
	68.74	79.18	79.22	10.48	88.22	9.04
	68.68	80.10	77.90	9.22	87.16	7.06
[xiii]	81.71	87.26	67.68	-14.03	80.19	-7.07
	91.28	93.01	78.04	-13.24	87.07	-5.94
	60.92	70.62	61.97	1.05	76.43	5.81
	76.40	85.17	64.80	-11.59	78.34	-6.83
[xiv]	92	98.50	82.33	-9.67	91.33	-7.17
	88	97.00	80.83	-7.17	90.52	-6.48
	83	93.50	78.13	-4.87	88.54	-4.96

[i] Bridgeman *et al.* (2008)	[ii] Peng *et al.* (2013)
[iii] Phanphanich & Mani (2011)	[iv] Wannapeera *et al.* (2011)
[v] Chen *et al.* (2011b)	[vi] Lu *et al.* (2012)
[vii] Yan *et al.* (2009)	[viii] Nam & Capareda (2015)
[ix] Strandberg *et al.* (2015)	[x] Chen *et al.* (2014b)
[xi] Xue *et al.* (2014)	[xii] Grigiante & Antolini (2015)
[xiii] Satpathy *et al.* (2014)	[xiv] Chen *et al.* (2012)

Table A4. Values of Torrefaction Index (*TI*) Calculated from Eq. (8) and (9)

Material	Ref.	Dry ash & extractive free basis (%)			Torrefaction Condition		Predicted		
		Cellulose	Hemicellulose	Lignin	Temp (°C)	time (min)	*EDEF* (tp)	*EDE*F (ref)	*TI*
Reed Canary Grass	[i]	53.32	37.17	9.51	230	50	1.06	1.12	0.95
		53.32	37.17	9.51	250	50	1.08	1.12	0.96
		53.32	37.17	9.51	270	50	1.09	1.12	0.98
Wheat Straw		51.75	38.60	9.65	230	50	1.07	1.12	0.95
		51.75	38.60	9.65	250	50	1.08	1.12	0.96
		51.75	38.60	9.65	270	50	1.09	1.12	0.98
Willow		59.11	16.91	23.98	230	50	1.07	1.13	0.95
		59.11	16.91	23.98	250	50	1.09	1.13	0.96
		59.11	16.91	23.98	270	50	1.10	1.13	0.98
		59.11	16.91	23.98	290	50	1.12	1.13	0.99
Spruce	[ii]	43.49	20.51	36.00	280	52	1.15	1.18	0.98

Pine		37.99	27.23	34.78	280	52	1.16	1.18	0.98
Fir		38.21	25.75	36.05	280	52	1.16	1.18	0.98
Pine bark		30.71	21.06	48.24	280	23	1.18	1.22	0.97
Pine wood chips	[iii]	54.01	16.89	29.09	225	30	1.08	1.15	0.94
		54.01	16.89	29.09	250	30	1.10	1.15	0.96
		54.01	16.89	29.09	275	30	1.11	1.15	0.97
Logging Residue		48.75	17.24	34.01	225	30	1.09	1.16	0.94
		48.75	17.24	34.01	250	30	1.11	1.16	0.95
		48.75	17.24	34.01	275	30	1.13	1.16	0.97
Leucaena, Woody BM	[iv]	35.98	34.57	29.46	200	30	1.08	1.18	0.92
		35.98	34.57	29.46	225	30	1.10	1.18	0.94
Banyan	[v]	57.07	12.19	30.74	230	30	1.08	1.15	0.94
Lauan	[vi]	40.49	15.74	43.77	220	30	1.11	1.20	0.93
		40.49	15.74	43.77	220	60	1.12	1.20	0.94
Oil Palm Fiber	[vii]	34.90	44.20	20.90	250	60	1.12	1.16	0.96
		34.90	44.20	20.90	275	60	1.14	1.16	0.98
Eucalyptus		56.90	18.10	25.00	250	60	1.10	1.14	0.96
		56.90	18.10	25.00	275	60	1.12	1.14	0.98
Rice Straw	[viii]	49.04	30.01	20.96	210	20	1.06	1.14	0.93
		49.04	30.01	20.96	210	40	1.07	1.14	0.94
		49.04	30.01	20.96	210	60	1.07	1.14	0.94
		49.04	30.01	20.96	250	20	1.09	1.14	0.95
Cotton stalk		48.03	16.48	35.49	210	20	1.08	1.17	0.93
		48.03	16.48	35.49	210	40	1.09	1.17	0.93
		48.03	16.48	35.49	210	60	1.09	1.17	0.94
		48.03	16.48	35.49	250	20	1.11	1.17	0.95
		48.03	16.48	35.49	250	40	1.12	1.17	0.96
		48.03	16.48	35.49	290	20	1.14	1.17	0.98
Spruce wood	[ix]	42.29	26.37	31.34	260	25	1.12	1.17	0.96
		42.29	26.37	31.34	285	17	1.14	1.17	0.97
Rice husk	[x]	54.08	26.50	19.42	200	30	1.05	1.13	0.93
		54.08	26.50	19.42	230	30	1.07	1.13	0.94
		54.08	26.50	19.42	260	30	1.09	1.13	0.96
Miscanthus x *Giganteus*	[xi]	50.72	24.30	24.97	230	10	1.07	1.15	0.94
		50.72	24.30	24.97	250	10	1.09	1.15	0.95
		50.72	24.30	24.97	270	10	1.10	1.15	0.96
		50.72	24.30	24.97	230	30	1.08	1.15	0.94
		50.72	24.30	24.97	250	30	1.09	1.15	0.96
Spruce Pine	[xii]	54.71	17.39	27.91	280	20	1.11	1.14	0.97
		54.71	17.39	27.91	295	30	1.13	1.14	0.99

Reeds		50.63	34.95	14.43	270	27	1.09	1.13	0.97
		50.63	34.95	14.43	290	13	1.10	1.13	0.98
		50.63	34.95	14.43	290	43	1.11	1.13	0.99
wheat	[xiii]	54.11	29.86	16.04	242	20	1.07	1.13	0.95
Barley		51.78	36.03	12.19	227	10	1.05	1.12	0.94
		51.78	36.03	12.19	282	15	1.09	1.12	0.97
Corn cob	[xiv]	40.09	43.64	16.26	250	20	1.09	1.15	0.95
		40.09	43.64	16.26	275	20	1.11	1.15	0.97
		40.09	43.64	16.26	275	10	1.11	1.15	0.97
Coffee Residue	[xv]	37.26	54.57	8.17	240	30	1.08	1.14	0.95
		37.26	54.57	8.17	240	60	1.09	1.14	0.96
		37.26	54.57	8.17	270	30	1.10	1.14	0.97
Sawdust		47.52	14.73	37.75	240	30	1.11	1.17	0.95
		47.52	14.73	37.75	240	60	1.12	1.17	0.95
		47.52	14.73	37.75	270	30	1.13	1.17	0.97
		47.52	14.73	37.75	270	60	1.14	1.17	0.98
Rice Husk		45.90	27.16	26.93	240	30	1.10	1.16	0.95
		45.90	27.16	26.93	240	60	1.11	1.16	0.96
		45.90	27.16	26.93	270	30	1.12	1.16	0.97
		45.90	27.16	26.93	270	60	1.13	1.16	0.98

[i] Bridgeman *et al.* (2008)
[ii] Peng *et al.* (2013)
[iii] Phanphanich *et al.* (2011)
[iv] Wannapeera *et al.* (2011)
[v] Chen *et al.* (2011b)
[vi] Chen *et al*. (2011a)
[vii] Lu *et al.* (2012)
[viii] Nam & Capareda (2015)
[ix] Strandberg *et al.* (2015)
[x] Chen *et al*. (2014b)
[xi] Xue *et al.* (2014)
[xii] Grigiante & Antolini (2015)
[xiii] Satpathy *et al.* (2014)
[xiv] Zheng *et al.* (2013)
[xv] Chen *et al.* (2012)