Torrefaction as Solution to Stubble Burning

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Abstract: Agriculture has been the dominant sector of India's Gross Domestic Product. Contribution by agriculture and other allied sectors is pegged at more than Rs 18 lakh crore in FY19. Crop Residue Management is a challenge for the farmers all across the nation. From the total residue produced in the country, nearly 99.2 MT is burnt at the farm, of which more than 60% is by rice and wheat. Lack of traditional use of residue, clearing the field in short time to sow the next crop in time leads to stubble burning. Stubble burning has become a major pollutant lately. Burning crop residue is a crime under the Air Pollution Control Act of 1981. Although, government's execution lacks firmness, thus encouraging finding the alternatives. One such process is Torrefaction. This agricultural waste can be efficiently utilized for the purposes which currently are being served by coal based power plants, with additional advantage of residue management. In this work, effect of torrefaction on rice stubble, and the physiochemical properties are discussed. Results so obtained are conducive in designing feasible logistic studies, and more applications of farm based agricultural residue. The torrefaction behaviors of the agricultural residues from plains of North India of rice straw were investigated, and the torrefaction process carried on them resulted in a proof that the torrefied biomass of plant origin has energy potential and calorific value equivalent to that of conventional fossil fuels. This paves way for deploying the process of torrefaction in sustainable energy generation.

1. Introduction

The world today is in the grip of a looming crisis. With the threat of climate change on one hand, and that of food security coupled with the rising population on the other, more and more emphasis is being given on leveraging the most out of agriculture. Non conventional resources have found a place into the government's budgets, but with little to meager implementation. One such non conventional source of energy is that of Biomass. Biomass is anything which is derived out of a product made from the process of photosynthesis by plants. Vegetable oils, timber, wood, leaves, manure, plants, and sewage are some of the examples of bio mass. From among the list of non conventional sources of energy, biomass holds a dominant position. For decades, mankind has been deriving energy out of the conventional fossil fuels, thereby emitting a large number of pollutants into the atmosphere. On the other hand, biomass, perhaps, is the only non conventional source of energy having carbon as one of its constituent.

As per IEA, biomass accounts for almost 10% of world's energy demand in 2005 [1]. Given the high potential it has towards energy production as well as sustainable development, it is predicted that the use of bio fuels as source of energy will see a boom after the third decade of the 21st century [2]. There are generally two methods of energy production from biomass; one is the thermo-chemical processes including combustion, gasification, pyrolysis, and the other being that of biological processes like that of anaerobic digestion and fermentation. The first method has a comparative better efficiency over the second one. Even after there are ample of evidences showing the advantages of biomass energy production over usual conventional sources of energy, what withholds the energy producers from switching to biomass are the factors like that of high storage cost of biomass, its hygroscopic nature, its heterogeneity, high risk of microbial degradation, and its thermal instability releasing high amounts of tar, which in turn is hurdle in using biomass for energy conversion purposes [3-5]. Apart from these, the other withholding parameters are its high moisture content, low energy potential and bulk density. It is for these reasons that the biomass is required to be dried before proceeding for the process of energy production.

In India, rice and wheat account for the major crops, and consequently for large scale generation of agricultural residue. Agricultural residue refers to the left over after the crops have been harvested. More than 80% of farmers in North India prefer burning the agricultural left over in order to save time and save labor [6]. Rice husk, is hence most readily available, and has been on the forefront in causing smog pollution chambers in the capital city of New Delhi in the fall of the year, every year. While considering its properties, rice straw is particularly more tenacious than coal due to its lingo-cellulose structure thus, it is difficult to grind. These disadvantages can be removed by pre-treatment by Torrefaction process before co-firing with coal in pulverised coal power plants.

2. Torrefaction

Torrefaction is a mild pyrolysis process that takes place within the temperature range of 225-300 $^{\circ}$C in the absence of oxygen which decomposes the lingo cellulose structure and the highly reactive hemi-cellulose fraction to increase energy density of bio-fuel. Torrefaction is a thermal treatment that occurs in an inert atmosphere [7]. Taking these challenges into cognizance, bio-energy production involving thermal conversion of biomass can incorporate torrefaction as a preprocessing method in the production chain to overcome the aforementioned issues. Because gasification process efficiency, among other factors, depends on feedstock properties, biomass properties are improved upon torrefaction for better thermal conversion of the material [8].

A mass loss of about 40% is achieved during torrefaction with an energy loss in the range of 5 and 10%. The energy and bulk densities of the biomass are also increased; moisture is expelled after torrefaction leading to ease of feedstock ignition during thermal conversion [9] [10]. The products formed during the process are solid char, gases and aqueous compounds [11]. Solid fuel is a better feedstock for entrained flow gasification and can also be co-fired with coal for power generation. For woody biomass, energy density increase as approximately 70% while biomass remains with 90% of its original energy content [12]. Gases from the torrefaction process can be used to operate the process auto-thermally to minimize energy consumption by the process. One of the most prominent differences between torrefied biomass and coal is the lower heat value (LHV). While the LHV of coal is typically in the range of 25 to 30 MJ/kg (dry basis), it is within the range of 18 to 23 MJ/kg (dry basis) for biomass depending on the torrefaction conditions.

The properties of the torrefied agricultural residues were closer to that of coal; therefore, torrefaction was a promising method for biomass to combine with coal co-gasification. Despite these facts, the process of torrefaction has received little to no response from the industries. There is hardly any company working in this field commercially in India. Majority of the research work is limited to proximate analysis and calorific value determinations. One reason could be attributed to the lack of enough research on the process, the conventions, its merits and demerits, and the way forward.

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2.1 Need of Torrefaction

As mentioned, torrefaction process has the advantages of reducing the moisture, compacting on the bulk of the density, improvising on the hygroscopic and heterogeneity of the rice straw.

India is the fourth largest agricultural production nation and leads the countries with highest export growth in the decade with year-round crop cultivation, generates a large amount of agricultural waste, including crop residues [13]. Approximately 92 metric tons of crop waste is burned every year in India, causing excessive particulate matter emissions and air pollution. Crop residue burning has become a major environmental problem causing health issues as well as contributing to global warming. . However, the alarming rise of air pollution levels caused by crop residue burning in the city of Delhi and other northern areas in India observed in recent years, especially in and after the year of 2015, suggest that the issues is not yet under control [14]. In general, torrefaction consumes hemi-cellulose markedly, whereas the degradation extents of cellulose and lignin depend strongly on the adopted torrefaction temperature [15-16].

During the process, the input biomass typically loses 20-30 % of its mass (bone dry basis) and 10% of its heating value, which is used as a heating fuel for the torrefaction process. Since the torrefied product already loses a certain quantity of volatiles in the course of thermo-chemical treatment, smaller quantity remains after the combustion process. There is little chance to observe fungal growth and microbial activity, given the very dry torrefied biomass [17].

Table 1, clearly gives the torrefied pellets an edge over the conventional sources of energy, including that of coal.

Table 1: BTU Values of various materials

Material	BTU Values Per Pound
Coal	10,000 to 12,000
Wood Pellets	8,500
Green Wood	4,200 to 4,4000
Torrefied Wood	10,000 to 11,000

BTU = British Thermal Units

3. Materials and Methodology

The three states which account for the highest percentage of stubble burning are Uttar Pradesh, Punjab, and Haryana in that order [18]. Further categorization of the report found that, among various Kharif and Rabi crops, the share of Rice Straw to stubble burning was the highest, followed by Wheat. Hence, the samples of the study were collected from the states of Uttar Pradesh, and Haryana, India. Both the samples taken are of Rice Straw.

3.1 Sample Acquisition and Preparation

The agricultural residues of rice straw were taken from the locations of Kanpur Dehat (Uttar Pradesh), and Ganaur (Haryana), respectively. Table 2, gives the latitudes and longitudes of the sample collection sites.

Table 2: Co-ordinates of sample collection sites

Sample Location	Latitudes	Longitudes
Kanpur Dehat, Uttar Pradesh, India	26.4123 °N	80.2857 °E
Ganaur, Haryana, India	29.1042 °N	77.106

°N = Degrees North of Equator,   °S = Degrees South of Equator

3.2 Pre Treatment

The samples were pre-treated to remove sand particles and foreign materials and as well sun dried to reduce moisture content. Removal of sand particles is necessary in order to avoid interference with the chemical processes of ash content determination and volatile matter determination.

3.3 Torrefaction Procedure

A muffle furnace was used to perform torrefaction experiments at laboratory scale while volatile torrefaction products were flared. Rice straw was resized to 100 mm from their original sizes and 12 g of resized straw was weighed out into crucibles of known weights. Samples were charged into the furnace at subsequent temperatures and residence times. As soon as the reaction temperature reached the set temperatures for each of the three experimental runs, the experiment was stopped. This was counted from the time the experiment began at room temperature to the time the torrefaction reaction temperature reached 200, 250, and 300 °C, respectively. A residence time of 5 min was maintained in the furnace for each reaction temperature to allow the reaction run to completion. The residence time was made relatively short to avoid severe sample decomposition while still in the furnace. During the experiment, condensable and non-condensable as well as solid, liquid, and gaseous products were produced and were all collected and preserved for analysis.

3.4 Moisture Content Determination

Moisture content analyzer was used to determine the moisture content of the sample inserted into the analyzer. The procedure was repeated three times for every sample of rice straw and the average value of the three readings so obtained was taken. Table 3 shows the moisture content as determined from the experiment.

Table 3: Moisture content values of the samples

Samples	Original Weight (in g)	Moisture Content Reading (in %)
Sample 1 (Kanpur Dehaat)	11.45	8.47
Sample 2 (Ganaur)	11.45	4.18

g = grams,   % = percentage

3.5 Volatile Matter Determination

Empty crucible was weighed to the nearest 0.001 g with the aid of a sensitive weigh balance. Sample was added into the crucible before it was placed in a furnace set to the temperature of (900 ± 10) °C. After seven minutes, the crucible was removed and placed in a desiccator to cool at room temperature before it was weighed. Table 4, shows the observations.

Table 4: Volatile matter values of the samples

Samples	Initial Weight (in g)	Final Weight (in g)	Volatile Matter (in %)
Sample 1 (Kanpur Dehaat)	69.21	60.37	77.233
Sample 2 (Ganaur)	70.42	60.5	86.641

g = grams,   % = percentage

3.6 Ash Content Determination

Empty crucible was weighed to the nearest 0.001 g. Sample was added into empty crucible before it was reweighed and heated into a muffle furnace set to the temperature of (650 ± 10) °C. After a residence time of one hour thirty minutes, the crucible and its content were removed and allowed to cool in a desiccator and then weighed.

Table 5: Ash content values of the samples

Samples	Weight associated with ash (g)	Ash Content (%)
Sample1 (Kanpur Dehaat)	1.637	15.62
Sample 2 (Ganaur)	1.051	9.58

g = grams,   % = percentage

3.7 Fixed Content Determination

The fixed carbon content was determined by computing the difference between 100 and the sum of the moisture, volatile matter and Ash contents of the samples.

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Table 6: Fixed carbon content values of the samples

Samples	Ash Content (in %)	Volatile Matter (in %)	Fixed Carbon = 100 – [Ash Content + Volatile Matter] (in %)
Sample 1 (Kanpur Dehaat)	60.37	77.233	7.147
Sample 2 (Ganaur)	60.5	86.641	3.780

% = percentage

3.8 Calorific Value Determination

The method used for calorific value determination was the Bento's model, as per the following equation.

CV (kcal/kg) = 44.75 X (Volatile Matter) – 5.85 X (Moisture Content) +21.2

Table 7:Calorific values of the samples

Samples	Calorific Value (in kcal/kg)
Sample 1 (Kanpur Dehaat)	3427.83
Sample 2 (Ganaur)	3873.93

Kcal/kg = Kilo Calories per Kilogram

The values of Calorific Values, so obtained by calculating, were then compared with the Calorific Values as determined by using Bomb Calorimeter. A bomb calorimeter is a type of constant-volume calorimeter used in measuring the heat of combustion of a particular reaction. The following table compares the values of the Calorific Values, as per Bomb Calorimeter and by calculation, and the percentage error between the two calorific values.

Table 8: Calorific values of the samples by bomb calorimeter and percentage error

Samples	CV by calculation (in kcal/kg)	CV by bomb calorimeter (in kcal/kg)	% Error
Sample 1 (Kanpur Dehaat)	3427.83	3434.5262	0.195
Sample 2 (Ganaur)	3873.93	4071.97	4.863

% = Percentage,   Kcal/kg = Kilo Calories per Kilogram

The mass yield, energy yield, and degree of carbonization were determined by the following equations.

$$\text{Mass Yield (in \%)} = \left(\frac{\text{Mass torrefied}}{\text{Mass untorrefied}}\right) \times 100$$

$$\text{Energy Yield (in \%)} = \left(\frac{\text{CV torrefied}}{\text{CV untorrefied}}\right) \times \text{Mass Yield}$$

$$\text{Degree of Carbonization} = \left(\frac{\text{CV torrefied}}{\text{CV raw biomass}}\right) \qquad [19]$$

4. Result and Outcomes

Fig 1. shows that upon increasing the torrefaction temperature from 200 °C to 350 °C gradually, the mass yield of the agricultural residue of rice straw decreases. Highest moisture content was determined from the Kanpur Dehat sample of Uttar Pradesh, followed by that of Punjab and Haryana. Kanpur Dehat's sample also recorded the highest ash content and fixed carbon content. Ganaur's sample recorded the highest calorific value when calculated using Bento's model. Upon confirmation by calculating the calorific values of the sample with the help of a Bomb Calorimeter, having an Energy Equivalent of 2399.89 kcal/kg, Kanpur Dehat sample recorded the most accuracy with a percentage error of less than 1%. Sample 2 of Ganaur in Haryana recorded the highest error in calorific value determination between Bento's model, and that by using Bomb Calorimeter, amounting to approximately 4.8%.

With an untorrefied calorific value, calculated using bomb calorimeter, equal to 3434.5262 kcal/kg, Sample 1 from Kanpur Dehat (Uttar Pradesh), was torrefied initially at 250 °C for 20 mins, the mass yield recorded was 73.28%, Energy Yield of

79.75%, and HHV or Calorific Value equivalent to 4431.57 kcal/kg.When the same sample was further torrefied at 300 °C and 350 °C , the mass yield was observed to be 54.55%, and 55.60% respectively. The energy yield, however showed good results, with values of 83.72% and 90.14% respectively.

The calorific value peaked from 6249 kcal/kg at 300 °C to 6601.1 kcal/kg at 350 °C, implying that on increasing the torrefaction temperature, better quality of bio-coal with significantly improved properties can be obtained.

(a)

(b)
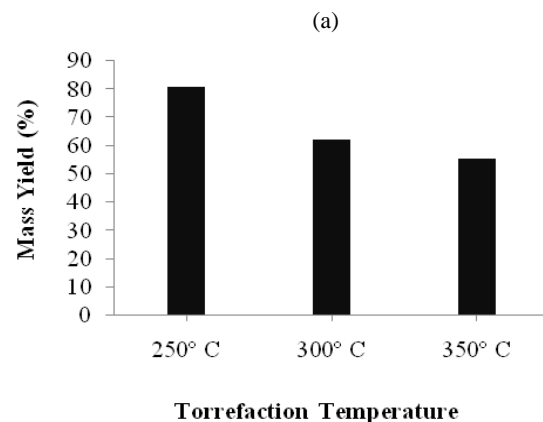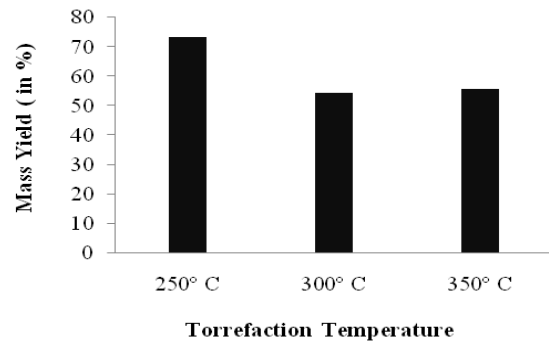
Fig. 1: Comparison of Mass Yield of (a) Sample 1 from Kanpur Dehat, Uttar Pradesh, India, and (b) Sample 2 from Ganaur, Haryana, India

Similarly for Sample 2 from Ganaur in Haryana, the untorrefied calorific value as obtained from bomb calorimeter was 4071.97 kcal/kg compared to 3873.92 kcal/kg from Bento's model. This sample was also torrefied initially at 200 °C.

At this temperature, the sample recorded mass yield and energy yield of 80.76% and 90.37% respectively.
The HHV or Calorific Value at this temperature came out to be 4556.17 kcal/kg. Upon further torrefaction at 250 °C, mass yield decreased to 62.30% and energy yield increased to 94.78%.

When the torrefaction temperature was raised to 350 °C, mass yield further fell to 55.61%, while energy yield registered an increase of more than 2%.

The HHV or Calorific Value came out to be 6194.88 kcal/kg and 7110.75 kcal/kg at 300 °C and 350 °C respectively.

The following table shows the residence time at the torrefaction temperatures carried out.

Table 9: Residence time against torrefaction temperature

| Temperature	Residence Time
250 °C	20 minutes
300 °C	25 minutes
350 °C	25 minutes

°C = Degrees Celcius

Fig 2, clearly shows that as the torrefaction temperature was increased gradually from 250 to 350 °C, the energy yield of the rice straw agricultural residue registered an increase in the value.

(a)

(b)
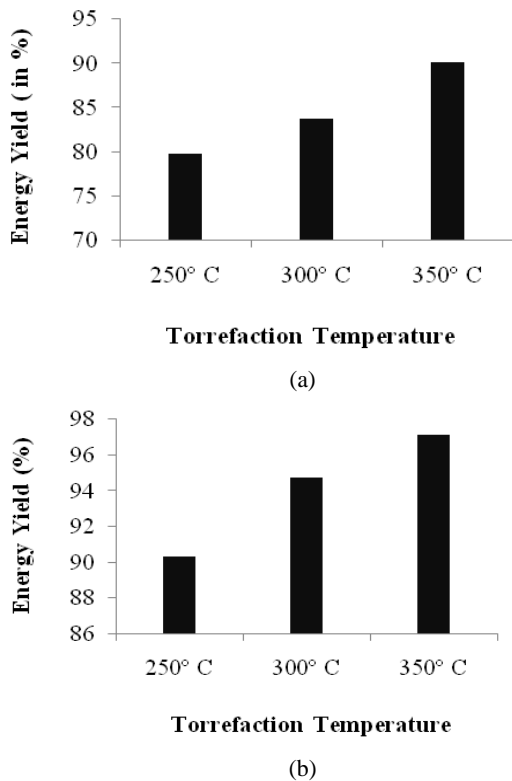
Fig. 2: Comparison of Energy Yield of (a) Sample 1 from Kanpur Dehat, Uttar Pradesh, India, and (b) Sample 2 from Ganaur, Haryana, India

The ratio of the calorific value of torrefied biomass to raw biomass is referred to as the degree of carbonization, which is a very important parameter in defining the extent of efficiency received in the torrefied sample over the raw biomass which is yet to be torrefied. Figure 3, shows a comparison of the Calorific Values of the two samples.

(a)

(b)
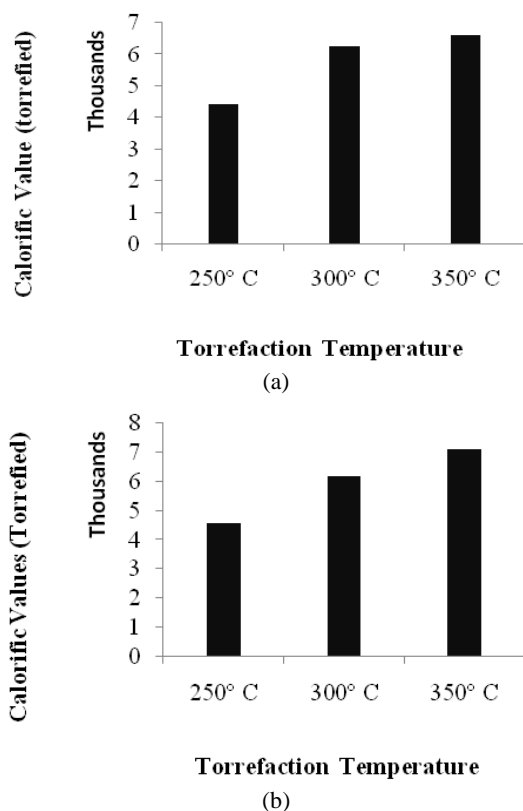
Fig. 3: Comparison of Calorific Values of-
(a) Sample 1 from Kanpur Dehat, Uttar Pradesh, India
(b) Sample 2 from Ganaur, Haryana, India

It is clearly visible that for Sample 1 of Kanpur Dehat in Uttar Pradesh, the degree of carbonization (DC) rises from 1 at 0 °C to 1.92 at 350 °C, while for Sample 2 from Ganaur, Haryana, DC varies from 1 at 0 °C to 1.75 at 350 °C. Since for the raw biomass, on which there is no torrefaction performed as of now, the ratio of Calorific Value of torrefied biomass tot that of untorrefied biomass remains equal to 1 at 0 °C. From 0 °C as the temperature rises gradually to the temperature range of torrefaction process of 250 °C – 350 °C, the degree of carbonization is seen to increase.

(a)

(b)
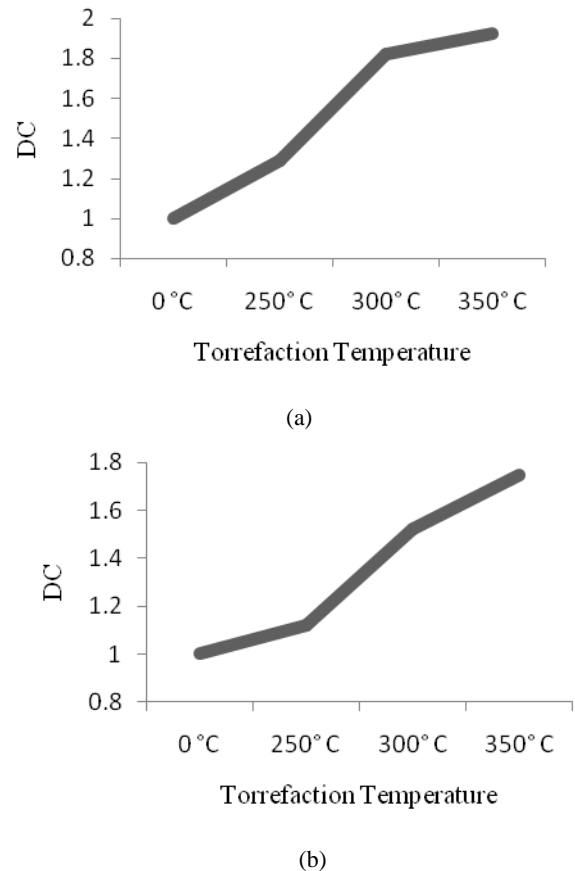
Fig. 4: Comparison of Degree of Carbonization of -
(a) Sample 1 from Kanpur Dehat, Uttar Pradesh, India.
(b) Sample 2 from Ganaur, Haryana, India

5. Conclusions

From the research carried out, the following conclusions are drawn: (i) Increase in torrefaction temperature above 250 °C effectively decreased the mass yield, bulk density, moisture content and hygroscopity which may be attributed to decomposition of hemi-cellulose and cellulose to release volatiles. (ii) Increase in torrefaction temperature above 250 °C decreased the oxygen and hydrogen content while carbon content increased simultaneously, which can be attributed to higher proportions of hydrogen and oxygen in liberated compounds than carbon. (iii) The degree of carbonization and calorific value increased with increase in torrefaction temperature, which might be attributed to effective removal of moisture. (iv) Increase in torrefaction temperature above 250 °C drastically reduced process product yield without significant increase in calorific value which implies reduced conversion efficiency of the process. Therefore, the light torrefaction is a proper operation to pretreat biomass for producing fuels in the form of pellets. Further research is required to be carried on the overall economic feasibility torrefied bio fuels in the form of pellets hold for the energy sector in the economy. Factors like storage cost, distribution cost and incidentials, and opportunity costs are some of them.

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