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Sustainable Utilization of Paddy Straw in Punjab for Biochar Production: Estimating the Energy and Emission Potential**

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ARTICLE INFO

Article history:
Received 31 May 2020
Received in revised form
29 September 2020
Accepted 29 October 2020

Keywords:
Biochar
Energy
Paddy straw
Pollutant emission
Pyrolysis

ABSTRACT

The burning of tonnes of paddy straw in the open field by the farmers in Punjab has resulted in air pollutant emissions causing serious environmental and health consequences. The paper presents a study on the utilization of the surplus paddy straw in Punjab for biochar production by pyrolysis. From the study, 7.60 MT of paddy straw are available in Punjab as surplus. The pyrolysis study was set at four different operating temperature conditions 300, 400, 500 and 600ºC with biochar conversion efficiency of 57.87, 42.90, 37.19 and 35.63 % respectively. The corresponding energy yield potential obtained from converted biochar were 77.51, 60.46, 56.25 and 55.59 PJ respectively. The analysis of air pollutant emission from burning of paddy straw was further quantified in terms of CO_2, CH_4, N_2O, TPM, NMHC CO, NO_x, SO_2 and PM 2.5 emissions and the net GHG CO_2 emission was recorded as 8264.64 Gg/year.

1. INTRODUCTION

1.1 General

Double cropping of rice-wheat in the Indo-Gangetic basin of India covers a total area of 10 mha (million hectare) out of which, 2.6 mha area lies in Punjab state[1]. Intensive farming is widely practised in the state which is followed by widespread open field burning of the rice and wheat. The remains from the burning of straw are left over the soil surface as a soil preparation step before the next cropping season [2][3]. The annual production of paddy straw in Punjab is 23 million tonnes out of which more than 18.4 million tonnes (80%) of the total paddy straw are left to burn in the open fields[4]. In India, the latest data obtained has reported 49.14 million tonnes of crop residues are left to burn in the open field annually. Rice straw holds the major share in the open field burning among all crops nearly 48%. As the demand for food in the country is significantly increasing, so is the crop residue burning. The rice straw residue burning in India is estimated to be increasing at a rate of 0.91 million tonnes per annum and contributes 26.89% of the world's total rice straw production[5].

There are several factors leading to open burning of crop residues on the farm, two major factors are: firstly, the limited usefulness value it has to the farmers and the huge bulk area it requires to store and transport them making their removal a labour intensive and expensive task. Secondly, the intensive farming practise which involves the crop rotation of rice and wheat simultaneously in the same field makes it difficult for the farmers to handle the bulk crop residue and most farmers are ultimately opt for the faster and convenient option of burning in the open fields[2], [6]. The burning of paddy straw in open fields occur annually for more than three weeks which is followed by the formation of thick smoke blanket over the entire west to the east of Indo-Gangetic plain as a result of the burning. The consequence of such practise in the region has resulted in adverse respiratory ailments, they are potential carcinogens both for human and animals and are also responsible for polluting the air leading to increased carbon emissions leading to global warming which pose one of the biggest threat to mankind today [2], [7], [8]. Such actions has led to a number of initiatives by the state and central government to find sustainable crop residue management practises like use of paddy straw in industries like bio-thermal plants, paper industries, mushroom cultivation, bio-gas production and as a soil amendment [4]

1.2 Energy Potential from Paddy Straw

The conversion of paddy straw into useful form of energy takes place by two conversion routes namely, biological and thermo-chemical process. As the demand for energy in the rural areas has been increasing rapidly in the recent times, power generation from biomass holds a very promising scope[9][10]. Punjab has the highest percentage of surplus paddy straw in the country which are left or burnt in the open field resulting in heavy GHG emissions, possessing toxicological properties which is a huge threat to the environment [11], [12]. It has been reported experimentally that 1

**This paper was presented at the *ICUE 2020 International Conference on Energy, Environment, and Climate Change* held at the Asian Institute of Technology, Pathumthani, Thailand from 20-22 October 2020.

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tonne of paddy straw releases 1460 kg of CO_2, 60 kg of CO, 2 kg of SO_2, 3 kg of particulate matter and 199 kg of ash [13]. A typical composition of paddy straw contains about 20% ash as a result of which the average content of energy in paddy straw is 15.03 MJ/kg and 14 MJ/kg at 10% moisture content [11], [14],[15].

The harmful consequence of environmental pollution by burning of paddy straw has led to a greater challenge of how to manage the crop residues in a better way and what are the possible alternatives that could be adopted for value addition. All possible ways of energy generation from paddy straw by making pellets and using as a cooking fuel in rural areas, as a fuel in biomass power plants, anaerobic digestion for methane production, bio-ethanol production and solid biochar, bio-oil and gas yield from pyrolysis can be seen in the recent times [11] [12], [17].

This paper presents a study of estimating the availability of surplus paddy straw available in Punjab and its potential of conversion by thermochemical route treatment called pyrolysis to obtain biochar. The energy yield potential of biochar, obtained from the pyrolysis process of paddy straw was calculated and the best condition for biochar conversion was determined based on the different operating condition. The potential of emission from open burning of paddy straw with the net GHG CO_2 emission was quantified and presented in this study.

2. METHODOLOGY

2.1 Characterization of Paddy Straw and Biochar

The paddy straw used for the study were collected from study area Punjab. Characterization of the biomass material were subjected to proximate and ultimate analysis. The proximate analysis was performed based on the standards set by ASTM which was used to determine the moisture content (ASTM E871-82), volatile matter (ASTM E872-82), ash content (ASTM D1102-84) and fixed carbon content [18]. The ultimate analysis study was for the determination of contents carbon hydrogen and nitrogen by use of an elemental analyser [16]. For a detail analysis of the characteristic weight loss during pyrolysis of paddy straw, thermogravimetric analysis (TGA) was performed on the samples. Using TGA analyzer DSC-TGA-Q600 (TA-Instruments) at the Indian Institute of Technology, Delhi. Nitrogen gas was purged, at a volumetric rate of 100 ml min^{-1}, inside the reactor to remove air present inside the reactor and the sample was heated from room temperature (25ºC) to 900ºC at a heating rate of 10ºC/min.

2.2 Potential of Biomass Available from Paddy Straw

Out of the total area 53600 km covered by Punjab 82.6% falls under cultivable agricultural land, 4.45% is under forest area, 10.43 % area under land unavailable for cultivation and uncultivable land 1.55% under barren land [14]. The gross potential of a biomass from paddy straw can be determined if we know the biomass residue to product ratio [19]. The estimation of Gross paddy straw residue potential was calculated by [20].

$$CR_g = PrC \text{ x } RPR \quad (1)$$

Where, CR_g is the potential of the paddy straw in MT, PrC the amount of the crop production in Punjab is 10.552 MT [21] and RPR is the residue production ratio of the paddy straw which is 1.5 from reference [22]

Crop residues are utilized by the farmers for a number of applications and therefore, not all paddy straw can be available for use in conversion of energy. The potential of the surplus biomass residue is calculated by[20] :

$$CR_s = CR_g \text{ x } SF \quad (2)$$

Where, CR_s is the surplus biomass paddy straw in MT, CR_g is the potential of the paddy straw in MT and SF is the fraction of surplus residue available which is taken 48% for Punjab [20]

2.3 Energy Potential of Biomass Derived from Paddy Straw

The determination of energy generation potential from paddy straw can be found out by multiplication of net paddy straw quantity potential by the lower heating value. The energy estimation potential model given by Bhattacharya is [19]

$$Q = (CR_s \; x \, LHV) \quad (3)$$

Where Q is the energy potential in GJ/yr, CR_s is the amount of surplus biomass from paddy straw in MT/yr, LHV is the lower heating value of paddy straw in GJ/ton

2.4 Pyrolysis of Paddy Straw

Paddy straw can be converted into valuable energy form with the help of pyrolysis technology. Pyrolysis is the process of thermochemical conversion of organic biomass material by releasing the volatile matter from them leaving behind a carbon rich product known as biochar [23]. The volatile matter comprise of condensable gases also known as bio-oil and non-condensable gases. The characteristics of pyrolysis process are influenced by several parameters such as type of biomass, temperature of the process, heating rate, size of particles, reaction atmosphere, residence time and the reaction involved in the process[24], [25].

2.5 Parameters for Pyrolysis of Paddy Straw

The pyrolysis of rice straw was conducted in a batch-type pyrolysis reactor under an inert atmosphere at three different temperatures 300, 400, 500 and 600ºC with a heating rate of 10ºC/min and 1 h residence time. The process temperature, residence time, and heating rate were set in the Programmable Logic Controlled reactor to achieve the desired output. To remove the pyrolysis vapours, Nitrogen gas was supplied continuously inside the reactor so as to create an inert atmosphere.

2.6 Energy Analysis of Paddy Straw

Analysis of energy was performed for each component based on the energy available in the paddy straw, energy input for operating the reactor and the energy of biochar obtained from pyrolysis process (bio-oil and syngas were not considered in the current study)

The heat energy required to carry out pyrolysis can be calculated by the following Equation (4) [26][25]

$$En_{heat} = m_{biomass_{wet}} * \Delta H_{water,T} + m_{biomass_{dry}} * C_{p_{biomass}} * (T_{pyrolysis} - T_{Ref.}) \quad (4)$$

Where En_{heat} is the heat energy required in PJ, $m_{wet\ biomass}$= ($m_{biomass}$ x M)/100 is mass of wet biomass in kg, M is the moisture content in kg, $\Delta H_{water,T}$ is change in specific enthalpy of water at reference temperature to the pyrolysis target temperature in kJ/kg, $m_{dry\ biomass}$ =(100-M) x $m_{biomass}$/100 is Mass of dry biomass in kg, $C_{p,ave_{biomass}}$ is the average specific heat of biomass (ranges from 1.3-1.5 kJ/kgK, hence selected average specific heat 1.4 kJ/kgK) [27]. For biochar the energy value was calculated by the following Equation (5):

$$En_{char} = m_{char} * LHV_{char} \quad (5)$$

Where En_{char} was biochar energy value in PJ, mc_{har} was the mass of biochar in kg and LHV_{char} was latent heat value of biochar MJ/kg

2.7 Estimation of Air Pollutants from Open Paddy Straw Burning

Quantification of the emissions due to the open burning of rice straw was based on the guidelines given by Intergovernmental Panel on Climate Change (IPCC) 2006. For the determination of air pollution amount due to burning of paddy straw, a term called emission factor (EF) is used which is expressed in terms of mass of emitted pollutants per unit mass of the dry fuel consumed. In this calculation, the EF value specific to open field burning of biomass residue has been considered. Thus, the equation to express the air pollutant emission [2]

$$E = CR\,x\,EF\,x\,f_C \quad (6)$$

Where E is the emission in Mg/yr, EF is the Emission factor, F_c is the Combustion factor (0.8 value for mass fraction combusted during fire as given by IPCC 2006 guidelines) and CR is the quantity of rice straw which were subjected to burning.

The amount of GHG emissions in CO_2 equivalent estimated from burning of rice straw was done with the Equation (6) [12]:

$$E_{GHG} = E_{CO_2} + E_{CH_4} xGWP_{CH_4} + E_{N_2O} xGWP_{N_2O} \quad (6)$$

Where, E_{GHG} denotes total greenhouse gas emission in CO_2 equivalent terms in Gg/year, E_{CH4} and E_{N20} denotes emission from CH_4 and N_2O in g/kg, GWP_{CH4} and GWP_{N2O} denote global warming potential of CH_4 and N_20 which are taken as values 25 and 298 respectively for GHG emission calculation [12].

3. RESULTS AND DISCUSSION

3.1 Characterization of Paddy Straw and Biochar

3.3.1 For paddy straw

The moisture content of paddy straw was 9.8 ± 0.2 % and lower heating value was 15.76 MJ/kg. The values obtained from the characterization of the paddy straw are shown in Table 2.

Table 1. Air pollutant factors [2].

Pollutant Name (Unit)	Emission Factor (g/kg)	Combustion factor
CO_2 (g/kg)	1,460	0.80
CH_4 (g/kg dry fuel)	1.20	0.80
N_2O (g/kg dry fuel)	0.07	0.80
CO (g/kg)	34.70	0.80
Non-methane hydrocarbons NMHC (g/kg)	4.00	0.80
NO_x (g/kg)	3.10	0.80
SO_2 (g/kg)	2.00	0.80
Total particulate matter TPM (g/kg)	13.00	0.80
Fine particulate matter PM 2.5 (g/kg)	12.95	0.80

Table 2. Air pollutant factors [2].

Proximate analysis (wt %)	
Volatile matter	76.32 ± 0.1
Fixed carbon	9.08 ± 0.95
Ash	13.91 ± 0.7
Ultimate Analysis (%)	
C	37.18
H	5.81
N	0.62
O^*	56.39

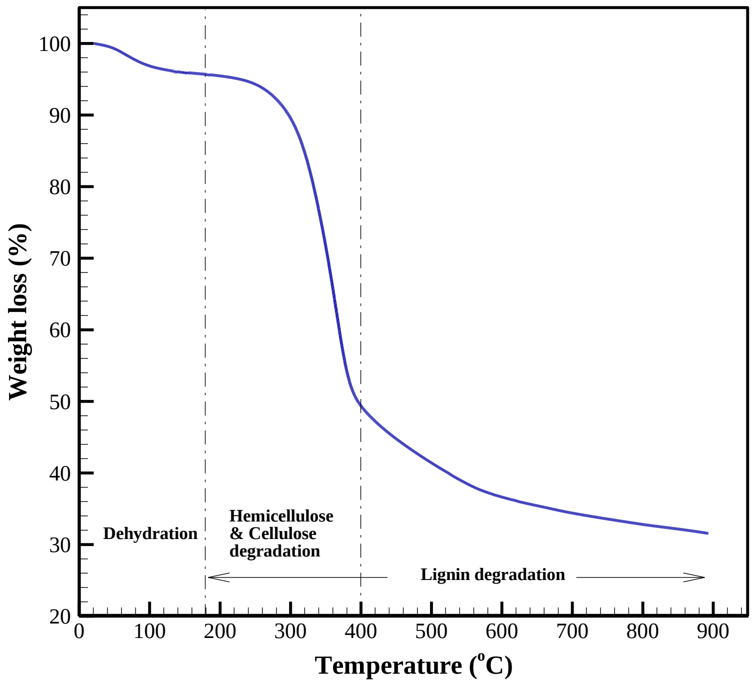

Fig. 1. TGA curve of rice straw at 10 ºC min^{-1}.

Table 3. Characterization of biochar.

Pyrolysis temperature (ºC)		300	400	500	600
Yield (wt. %)		57.87	42.90	37.19	35.63
HHV(MJ/kg)		17.63	18.55	19.91	20.13
Conversion (%)		42.13	57.10	62.81	65.37
Proximate analysis (%dry)	VM	38.65	21.14	14.54	9.05
	FC*	43.91	53.15	55.64	57.63
	Ash	17.44	25.71	29.82	33.32
	VM /FC	0.88	0.39	0.26	0.15
Ultimate analysis (dry%)	C	65.92	72.38	80.09	85.13
	H	5.14	4.58	2.46	2.19
	N	3.78	3.16	1.29	1.63
	O*	25.16	19.88	16.16	11.05
	O/C	0.38	0.27	0.20	0.13
	H/C	0.08	0.06	0.03	0.02

From the TGA Analysis, pyrolysis process is taking place in the range of 190-900ºC. In this region (active pyrolysis), hemicellulose and cellulose decomposition take place (190-400ºC), 40-45% weight loss observed in this region. Among the three constitutes, lignin degradation is most difficult, which covers a broad temperature range (passive pyrolysis) 190-900ºC. The result of TGA clearly indicated that the yield of biochar would vary at different temperature operating conditions.

3.3.2 For biochar

The results of biochar characterization were obtained from pyrolysis of paddy straw at different operating temperature conditions are in Table 3.

As the operating temperature increased, the carbon content in biochar also increased linearly. The value of H/C reduced with the increasing temperature which was due to the increasing aromatic structure during the biochar formation [28]. The value of O/C also decreased with increasing temperature which indicated higher carbonization degree because of the elimination of hydrophilic functional groups from the surface of the material caused by charring effect [29] [30].

3.2 Amount of Surplus Paddy Straw Available

From the study, the value of the amount of gross paddy straw residue potential in Punjab was 15.828 MT and the amount of surplus paddy straw residue potential 7.6 MT

3.3 Potential of Biochar Yield from Paddy Straw

The pyrolysis of rice straw was conducted in a batch-type pyrolysis reactor under an inert atmosphere at three different temperatures 300, 400, 500 and 600ºC. The yield of the surplus biochar obtained from pyrolysis of paddy straw was calculated and shown in Table 4.

Table 4. Biochar yield at different operating parameters.

Parameters	Biochar (MT)
300ºC	4.39
400ºC	3.26
500ºC	2.83
600ºC	2.63

3.4 Energy Potential of Biomass Derived from Paddy Straw

The determination of energy generation potential from paddy straw was calculated as per the method mentioned in Section 2.3 (Equation 3). From the value of surplus biomass amount and heating value of the paddy straw, the estimated energy potential for Punjab was calculated as 119.7356 PJ

3.5 Energy Input for Pyrolysis

Energy input that would be required during pre-treatment (size reduction) of paddy straw 7.6 MT of paddy straw is 569.808 GJ.

The surplus biomass available in the study area, having a moisture content of 9.8±0.2 % when subjected to pyrolysis at operating temperature conditions 300, 400, 500 and 600ºC, the amount of energy required to carry out the reaction was calculated according to Equation 4. The amount of energy for heat required to attain temperatures 300, 400, 500 and 600ºC are shown in Table 5.

Table 5. Energy input required for pyrolysis.

Temperature	Energy input for pyrolysis (PJ)
300	4.32
400	5.28
500	6.24
600	7.19

3.6 Energy Potential from Biochar

The value of energy yield from biochar, was calculated for the yields obtained at four different operating temperature conditions. The resultant values of the energy yield at experiment condition from the analysis is shown in Table 6.

Table 6. Energy potential from biochar.

Parameters	Total biochar energy potential (PJ)
300ºC	77.51
400ºC	60.46
500ºC	56.26
600ºC	55.59

From energy yield we concluded that condition parameter set at 300ºC gave the maximum yield of biochar. The study showed that increase in the operating temperatures resulted in decreased biochar yield while the value of HHV in biochar was observed to increase with the increaseing operating temperature.

From the above analysis of energy potential, the energy potential obtained from biochar was observed as higher than the energy required to carry out the reaction. This implies that the pyrolysis process for biochar production is energy efficient.

3.7 Estimation of Air Pollutants from Open Paddy Straw Burning

The quantification of the emissions from burning of rice straw in the open field was based on the guidelines given by Intergovernmental Panel on Climate Change (IPCC) 2006. The estimation of the emissions contributing to the air pollution from the surplus paddy straw in Punjab were calculated using Equation 6 and shown in Table 7.

Table 7. Estimation of air pollutants from open paddy straw burning.

Pollutant name	Emission Factor (EF) (g/kg$_{dry\ fuel}$)	Emission (Gg)
CO_2	1,460	7986.43
CH_4	1.20	6.56
N_2O	0.07	0.38
CO	34.70	189.81
NMHC	4.00	218.88
NO_x	3.10	16.96
SO_2	2.00	10.94
TPM	13.00	71.11
PM 2.5	12.95	70.84

The amount of pollutants observed from the results obtained in Table 7 shows the surplus paddy straw available in Punjab which are mostly subjected to burning in the open field. Based on the study of emission factors from rice straw given by Zhang et. al and Irfan et. al the emission factor value considered in the current study for the calculation of pollutant emissions observed a variation in the values of CO_2, CH_4, CO, NO_x and SO_2 [31]–[33]. This variation in the emission values indicated that such variation occurred due to the difference in the location of the study area. Thus emission factor is an important parameter for delivering results which represent the actual situation if the study area. From burning of surplus paddy straw, the net GHG CO_2 emission was recorded as 8264.64 Gg/year.

4. CONCLUSION

- The availability of surplus paddy straw in Punjab and its extensive open field burning resulting in harmful emissions to the environment has been a major concern in India.
- This paper presented the study of surplus paddy straw available in Punjab, the energy potential by

pyrolysis treatment at different operating temperatures 300ºC, 400ºC, 500ºC and 600ºC to obtain biochar and the potential of emission from open burning of paddy straw with the net GHG CO_2 emission was quantified and presented in this study.

- The amount of surplus paddy straw residue potential obtained from the Gross paddy straw residue potential in Punjab was 7.6 MT.
- From pyrolysis treatment of paddy straw, the yield of biochar from the surplus paddy straw at different operating temperatures 300ºC, 400ºC, 500ºC and 600ºC were 4.39MT, 3.26MT, 2.83MT and 2.63MT, respectively
- The resultant energy potential of the biochar available were 77.51PJ, 60.46PJ, 56.26PJ and 55.59PJ, respectively.
- It was evident from the results that the energy potential of biochar decreased with the increasing temperature which was due to a major effect of decreasing yield in biochar as operating temperature increased. From the analysis of energy potential of the biochar obtained and the energy required to carry out the pyrolysis, the energy potential from biochar was higher than the energy required to carry out the reaction and thus the pyrolysis process was justified as energy efficient.
- The quantification of air pollutants from open field burning of paddy straw for CO_2 was 7986.43Gg, CH_4 was 6.56Gg, N_2O was 0.38Gg, CO was 189.81Gg, non-methane hydrocarbon was 218.88Gg, NO_x was 16.96Gg, SO_2 was 10.94Gg, Total Particulate Matter was 71.11Gg and PM 2.5 was 70.84Gg.
- The net GHG CO_2 emission for open field burning of paddy straw was recorded as 8264.64 Gg/year.

ACKNOWLEDGEMENT

The authors would like to gratefully acknowledge the Centre for Rural Development and Technology for supporting in the experimental work. The authors would also like to sincerely acknowledge Mr Ujjiban Kakati for his assistance during the experiment.

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