Analysis of biochar from carbonisation of wheat straw using continuous auger reactor

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Abstract: The agricultural residue is considered as one of the promising organic biomass materials for getting energy-rich products (such as biochar, bio-oil, and syngas, etc.) via thermochemical conversion route. In the current study, the biochar was produced from wheat straw using continuous auger reactor and analysis of produced biochar in terms of product yield, energy yield, and its physicochemical composition. Carbonisation of wheat straw was carried out in a continuous auger reactor at four different temperatures i.e., 350°C, 400°C, 450°C, 500°C by keeping 5 min of residence time respectively. The maximum mass and energy yield of wheat straw biochar was recorded at 400°C. The wheat straw to biochar conversion efficiency in a continuous auger reactor was about 30%. The higher heating value (HHV) of produced biochar was varied from 20 MJ/kg–23 MJ/kg, so it indicates that biochar can be efficiently used in thermal applications. The physicochemical characterisation of biochar produced at 400°C was also carried out at bioenergy laboratory. The obtained biochar showed higher carbon content of 70%, H/C and O/C ratio were found to be 0.022 and 0.29, respectively.

Keywords: wheat straw; energy; biochar; carbonisation; auger reactor; agro waste.

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1 Introduction

India is agricultural dominant country which produces excess amount of crop residues about 500 million tons (Mt) annually, from which 84–141 Mt/yr considered as surplus crop residues (DPR). Some peasants from countryside's are burning this surplus residue in open field, which is mainly available after the harvesting of previous crops. Biomass has some advantages being a low sulphur content, CO_2 neutral, and being easy to use as s fuel for the replacement of commercial fossil fuels. There are various thermochemical conversion routes such as pyrolysis, gasification, torrefaction, and liquefaction etc. although pyrolysis or carbonisation is considered as one of the efficient process for the production of biochar, bio-oil, and pyrolytic gases mainly known as syngases. Biochar is organic carbon-rich material, is produced via the carbonisation process at a moderate temperature range (400–500°C), under an inert atmospheric condition (Panwar et al., 2019). However, due to unique physiochemical properties, biochar is well recognised for multiplications as a soil amendment, energy fuel, act as adsorbent for heavy metal removal from water bodies, supercapacitors, etc. (Lehmann et al., 2011).

According to the European Biochar Foundation (EBC), biochar produced from pyrolysis using selected biomass feedstock is recognised as a heterogeneous product which is rich in minerals and aromatic carbon (EBC, 2012). In addition, because of unique properties like physiochemical composition, mineral content, high surface area, higher heating value (HHV), microporosity, sorption capacity, etc. biochar showed good potential as a soil amendment, waste treatment, and for composting of various waste materials (Czekała et al., 2016). The physical and chemical property of pyrolysis products mainly depends on pyrolytic conditions (temperature, time and heating rate, etc.) and type of feedstock. Crop residue is mainly made up of lignin, hemicelluloses, and cellulose; therefore, resulting solid end product i.e., biochar showed high content of organic carbon, nitrogen, phosphorous, potassium, hydrogen, etc. while lower in the O/C and H/C molar ratio, respectively. Due to these significant properties, biochar possesses extensive applications in waste management, climate change mitigation, soil improvement, and energy production. Mostly biochar produced via the moderate carbonisation temperature is being utilised in soil application for improving the soil fertility and to enhance the nutrient availability. While biochar produced at higher carbonisation temperature shows extensive applications for remediation of organic and inorganic pollutants from soil, water, and gaseous phase (Pawar and Panwar, 2020;

Pawar et al., 2020). There are various traditional technologies for biochar production that may be batch type kilns such as earthen, brick-concrete, metal kilns and retorts which showed minimum biomass to biochar conversion efficiency. However, continuous production of organic biochar from biomass was found to be one of the promising methods for achieving maximum biochar yield (25–35%), along with the quality of biochar and greater flexibility towards the biomass feedstock (Gwenzi et al., 2015).

There are very few studies on the characterisation of wheat straw derived biochar. The effect of temperature on biochar yield and its physiochemical composition has been extensively studied in the current article. Recently, biochar production by using batch type kilns was investigated by various literatures. However, limited information on continuous auger reactor based biochar production system is available for the carbonisation of wheat straw. In present study, the auger reactor was used for the production of biochar from carbonisation process using wheat straw as a feedstock. In addition, the thermal performance of auger reactor was carried out at three dissimilar carbonisation temperature's for evaluating the physicochemical properties of biochar.

2 Material and methods

2.1 Feedstock

Wheat straw is one of the important crop residues in the southern part of the Indian state of Rajasthan. Therefore, the wheat straw sample was collected from the instructional farm of Maharana Pratap University of Agriculture and Technology, (MPUAT), Udaipur. Wheat straw was cleaned, ground and separated in uniform particle size.

2.2 Analysis of wheat straw and biochar

The proximate analyses of wheat straw in terms of volatile matter content, moisture content, carbon content, and ash content were carried out as per the methodology suggested by American Society for Testing and Material (ASTM). The HHV of wheat straw and resulting wheat straw biochar (shown in Figure 1) was calculated with the help bomb calorimeter. The ultimate analysis of wheat straw biochar performed using the CHNS analyser. The bulk density of the wheat straw sample was carried out using a measuring cylindrical container.

Figure 1 Raw wheat straw and produced bio-char (see online version for colours)

2.3 Thermal performance

The mass and energy yield (MY and EY) of wheat straw produced biochar was carried out in a developed system to analyse the further applicability of the system. The mass and energy yield play a significant role in determining the feasibility of the carbonisation process in a developed continuous auger operated biochar production system. The MY and EY indicates the total mass of wheat straw and energy ratios of a produced wheat straw biochar to the precursor wheat straw sample respectively and estimated by following the equations (1) and (2)

$$\text{MY}(\%) = \frac{\text{Total mass of produced (kg)}}{\text{Mass of biomass as received}} \times 100 \tag{1}$$

$$\text{EY}(\%) = \frac{\text{Mass of biochar (kg)} \times \text{Heating value of biochar (MJ/kg)}}{\text{Mass of biomass (kg)} \times \text{Heating value of biomass (MJ/kg)}} \times 100 \tag{2}$$

In the initial inception, energy is required to start the carbonisation process. Therefore, the energy required for the carbonisation of wheat straw became an important aspect because of its suitability in carbon-negative industry. Although according to Panwar et al. (2019), increasing demand for energy for biochar production through the carbonisation process has been made a significant issue in the carbon industry. The total energy requirement for biochar production through the carbonisation process depends on several factors such as type of feedstock, operating conditions in terms of temperature and residence time, etc.

3 Results and discussion

3.1 Characteristics of wheat straw

The proximate analysis of wheat straw is shown in Table 1. The percentage of volatile matter in wheat straw was about 76 wt. %, while the ash percentage in wheat straw was found to be approximately 3 wt. %. Therefore, for this, it was observed that nearly 87 wt. % matter is considered as combustible in raw wheat straw. The HHV of the wheat straw sample was about 14.79 MJ kg^{-1}, which found nearly equal or slightly higher as compared to other crop residues including rice husks (Mansaray et al., 1998), sesamum stalks (Zabaniotou et al., 2008), rice straw, and linseed stalks (Hiloidhari et al., 2014), etc. The bulk density of wheat straw was recorded around 90 kg m^{-3}.

Table 1 Characteristics of wheat straw

S. no.	*Biomass sample*	*MC, %*	*VM, %*	*Ash content, %*	*FC, %*	*Bulk density, kg/m³*	*Calorific value, MJ/kg*
1	Wheat straw	10	76	3	11	90	14.79

3.2 Heating analysis

The thermal performance of auger reactor for wheat straw biochar production was carried out at four carbonisation temperatures (350, 400, 450, 500°C) and at three dissimilar heating rates (10°C/min, 15°C/min and 20°C/min) respectively. In addition to these operating conditions, the wheat straw biochar was produced at 5 min of process time by keeping 22 auger revolutions. Here, diesel burner was used to attain the carbonisation temperature inside the reactor for biochar production. As the fuel feeding rate enhanced, the carbonisation temperature, as well as heating rate, also increased at higher level and it was observed that the relations between the two were significant. Further, it was observed that during the carbonisation process diesel consumption rate was increased from 0.28 to 0.49 l, the heating rate was also subsequently enhanced. As the fuel feeding rate was 0.29 l, the carbonisation temperature attained up to 350°C, which could lead to a maximum biochar yield. Similarly, as the oil consumption rate increased more about 0.49 l, the carbonisation temperature reached nearly 500°C, which significantly drops the biochar yield. Table 2 shows obtained higher yield and lower yield of biochar at lower and higher carbonisation temperatures.

Table 2 Performance analysis of wheat straw in auger reactor for bio-char production

Carbonisation temperatures, °C	350	400	450	500
System capacity, kg/h	25–30	25–30	25–30	25–30
Process time, min	5	5	5	5
Screw revolutions, RPM	18	18	18	18
Bio-char yield, kg	8.20	9.00	7.30	5.00
HHV of wheat straw sample, MJ/kg	15.69	15.69	15.69	15.69
HHV of wheat straw bio-char, MJ/kg	24.00	24.84	23.02	21.90
Mass yield, percent	27	30	24	16
Energy yield, percent	41.80	47.00	35.70	22.70
Required fuel quantity, l	0.28	0.35	0.40	0.49
Calorific value of diesel fuel, MJ/kg	45.00	45.00	45.00	45.00

3.3 Characterisation of wheat straw biochar

The wheat straw biochar produced at 400°C temperature showed maximum mass as well as energy yield shown in Tables 3 and 4.

The experiment findings revealed that auger reactor was capable to produce high yield biochar from wheat straw. The developed continuous auger reactor-based biochar production system gives more biochar yield with significant physicochemical characteristics of biochar. From the study, it was observed that during the carbonisation process wheat straw biochar produced at moderate temperature contain higher organic carbon while total oxygen and hydrogen content significantly dropped. As studied by Imam et al. (2012), biochar contains some weaker bonds that cracks after achieving the moderate carbonisation temperature which causes reduction in oxygen and hydrogen percentage in resulting biochar. Here, wheat straw produced biochar contains a maximum percentage of organic carbon nearly 70 % along with increased C:N ratio approximately 81, respectively. According to Srinivasarao et al. (2013) organic carbon-rich biochar play important role in the sustainability of agricultural productions mainly increases water holding capacity of the soil, essential nutrients, and soil health and reduces atmospheric carbon concentration.

Availability of nitrogen (N) in soil significantly effect on the growth of plant and its productivity, generally, any plants uptakes the nitrogen very rightly from the soil through the roots (Atkinson et al., 2013), owing to this here it was observed that produced wheat straw biochar contain 0.87 % Nitrogen.

However, biochar stability in the soil is significantly influenced by the production condition and type of precursor material. Furthermore, according to the findings reported by Spokas (2010) the obtained biochar which contains a lower O/C molar ratio led to more stability in soil. The authors also found that biochar which contain a molar oxygen to carbon (O:C) ratio is greater than 0.6, can stable for a half-life of 100 years in that soil. In addition, if it was ranged between 0.2–0.6, then the half-life will range between 100 and 1,000 years. Here, the obtained wheat straw biochar at 400°C contain very lower O/C molar ratio of 0.29, which justifies the finding reported by spokes (2010) and therefore the obtained biochar will remain stable for more than 100 years in agricultural soil Also, the hydrogen to carbon molar ratio (H/C) determines the biochar carbon structure as well as stability in soil. Here, wheat straw derived biochar contains the lowest H/C ratio 0.022, which represents the aromaticity of derived biochar. The quantity of biochar as a soil amendment depends on the available macronutrient such as magnesium (Mg), calcium (Ca), nitrogen (N), potassium (K), etc. concentration in produced biochar. Although, sometimes increased concentration of micronutrient like ferrous (Fe), zinc (Zn), copper (Cu), etc. may create adverse effects on soil.

Table 3 Molar ratio and chemical composition wheat straw biochar produced at 400°C

C, %	*H, %*	*N, %*	*O, %*	*C/N molar ratio*	*H/C molar ratio*	*O/C molar ratio*	*MC, %*
70.00	1.57	0.87	20.76	80.45	0.022	0.29	6.80

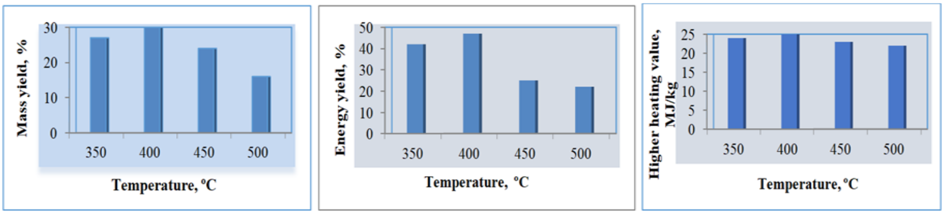
Table 4 Mineral analysis of produced wheat straw bio-char

Ca, %	*Fe, %*	*Zn, %*	*Na, %*	*K, %*	*S, %*	*N, %*
0.04	0.0055	0.038	0.10	0.10	0.021	0.0013

3.4 Mass and energy yield

Table 2 presents the biochar and energy yield, the calorific value of both wheat straw and its biochar. The yield of biochar was recorded at four different carbonisation temperatures by keeping the same process time and revolutions of the screw auger. As Figure 2 revealed that, the mass yield of wheat straw biochar at 350, 400, 450, and 500°C were 27, 30, 24, and 16%, respectively, noticed that, as carbonisation temperature was raised, the mass yield slightly reduced. A comparable finding also studied by Sirijanusorn et al. (2013) and recorded 22 wt % biochar yield at a maximum temperature of 500°C. Also, the energy yield of wheat straw biochar was estimated by investigating the increase in the calorific value of prepared biochar for selected feedstock after carbonisation. Figure 2 revealed the energy yields of the wheat straw biochar were found to be to 41.80, 47.00, 35.70, and 22.70% at 350, 400, 450, and 500°C respectively, which also indicated that as carbonisation temperature was increased, energy yield slightly decreased. According to Kung et al. (2015) carbonisation of organic biomass at 400 ^{0}C is considered as the most suitable condition for organic carbon-rich biochar production.

Figure 2 Influence of carbonisation temperature on mass yield, energy yield, and HHV (see online version for colours)



4 Conclusions

The auger reactor technology is considered as more suitable for continuous auger reactor based biochar production from different crop residues. The auger reactor was able to produce a good quality and quantity wheat straw biochar with a 5 min of process duration. Therefore, more quantity of biomass could be handled with a minimum period. Here, the wheat straw derived biochar showed higher mass as well as energy yield at 400°C temperature as compared to other carbonisation temperature as at 350, 450, and 500°C temperatures. Therefore, high yield biochar was characterised and found that produced wheat straw biochar contains 70.00 % organic carbon (C) and 1.57 % hydrogen (H2). Finally, it was concluded that continuous auger reactor-based biochar production from different agro-waste opens a new window to farmers as well as rural management which helps indirectly to increase the crop residue management.

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Abbreviations

HHV	Higher heating value
EBC	European Biochar Foundation
MPUAT	Maharana Pratap University of Agriculture and Technology
ASTM	American Society for Testing and Material
MY	mass yield
EY	energy yield
Mt	million tons
BC	Biochar.