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Design and development of semi-indirect non-electric pyrolytic reactor for biochar production from farm waste

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ABSTRACT

The paper describes the development of semi-indirect non-electric pyrolytic reactor of 1 kg capacity and for optimizing production process of biochar from diffferent farm wastes. Biochar was produced through pyrolysis of farm wastes, viz. maize cob, cotton stalk and coconut shell by using *Prosopis julifera* as a combustion fuel in the pyrolytic reactor. Biochar production from farm waste was optimized with different mass of combustion fuel such as 0.25, 0.50, 0.75 and 1.0 kg. Maximum residence time for obtaining maximum yield and characteristics of farm waste and biochar were also investigated. The maximum yield of biochar from maize cob, coconut shell and cotton stalks were found to be 34, 33 and 36% respectively. The optimum combustion and pyrolysis mass ratio was found as 0.5:1 for maize cob and cotton stalk and that of coconut shell was 0.75:1. The mass and energy closure efficiency of the developed pyrolysis unit were found to be 85% and 83% respectively. The organic carbon content of biochar ranged as 67-89% for the selected feed-stocks. The results indicated that the maximum amount of biochar was produced with minimum amount of combustion fuel enhancing low-cost by using the reactor. The developed pyrolytic reactor was found economically viable with payback period of 3.2 years. Through characterization of biomass and biochar, it was found that the reduction of bulk density of biochar output (215-278 kg/m^3) compared to raw farm waste (450-500 kg/m^3) was beneficial to improve soil health of cultivable land.

Key words: Farm waste, Combustion, Pyrolysis, Biochar, Pyrolytic reactor

Climate change is one of the most important challenges facing the modern world. Temperature increases have now been unequivocally proven and are occurring with an unprecedented rate. Mean global temperature has increased by 0.8°C since 1880 and may increase by an additional 3-7°C by 2100 under business as usual scenario (Allen *et al*. 2009). International efforts aimed to reduce the avoidable greenhouse gas (GHG) emissions or off-setting unavoidable emissions through sequestration of carbon in the environment (Lehmann *et al*. 2006). The growing concerns about climate change have brought biochar into limelight. Biochar is the carbon-rich product obtained by the heat treatment of biomass under limited or no oxygen (pyrolysis) in a closed container (Mukherjee *et al.* 2013) and it is basically identical to charcoal, but used for different purposes, which is used for non-energy purposes.

Pyrolysis biochar system offers one of the few available options for carbon-negative technology in the short-term (Ioannidou and Zabaniotou 2007). Pyrolysis converts organic matter into a carbon-rich solid (biochar) and volatile products by heating in the absence of oxygen. Through pyrolysis biochar systems carbon dioxide may be removed from the atmosphere, assimilated firstly by plant growth then stored as a stable form of carbon in the soil rather than returning to the atmosphere through decomposition. Biochar production under a controlled system may provide a higher yield and have fewer detrimental effects on the environment. These characteristics make biochar an exceptional soil amendment for use in sustainable agriculture. The addition of biochar to soil offers a potential environmental benefit by preventing the loss of nutrients and thereby protecting water resources. Also, it improves a host of soil physical properties. Furthermore, soils containing biochar have a strong affinity for organic contaminants (Yu *et al*. 2009). Application of biochar with inorganic fertilizers significantly increases the yields of a number of crops (Coumaravel *et al*. 2011).

MATERIALS AND METHODS

The farm waste selection for this study was made based on their availability at different locations. Three different biomaterials were selected for production of biochar and *Prosopis julifera* was selected as combustion fuel. The three selected pyrolysis biomaterials were maize-cob (*Zea mays*), cotton-stalk (*Gossypium* spp) and coconut-shell (*Cocos nucifera).*

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Based on the performance evaluation of existing pyrolysis unit and previous studies (Basso *et al.* 2013, Ellens and Brown 2012, Binhang *et al.* 2012, Subramanian *et al.* 2011, Niels *et al.* 2009, Yoshikage *et al.* 2008), a new pyrolysis unit was developed for production of biochar to increase the efficiency and reduce the consumption of combustion fuel. The various procedures involved in the design of the reactor are given below.

Pyrolysis chamber: Based on the mass and density of selected biomass, the pyrolysis chamber was designed and the energy required for pyrolysis was calculated.

Volume of pyrolysis chamber (considering diameter to height ratio as 1:1) = $\pi d^2 h/4$ …3.1

where, d and h are diameter and height of pyrolysis chamber respectively in m

Heat required for pyrolysis Q, kJ= $mCp\Delta T$ …3.2

where, m, mass of feed (kg); Cp, specific heat of feed (kJ/kg/k); and ΔT, optimum pyrolysis temperature (K).

Combustion Chamber: The volume of combustion chamber was designed based on the mass and density of combustion fuel. Also the combustion fuel required to produce sufficient energy for the pyrolysis process was calculated. For the required amount of fuel the dimensions of the combustion zone was calculated as follows,

$$V_c = (m_c/\rho) \quad \text{…3.3}$$

\Volume of pyrolysis chamber (considering diameter to height ratio as 1:2),

$$V_c = \pi d_c^2 h_c/4 \quad \text{…3.4}$$

where, V_c, volume of combustion chamber (m^3); m_c, mass of combustion fuel (kg); and ρ, density of combustion fuel, kg/m^3.

Air inlet: In order to design the air inlet, the stoichiometric air requirement for the complete combustion of fuel and the area required to supply air were calculated.

Theoretical air required for combustion = $(11.6C + 34.8(H_2–O_2/8))/100$ kg/kg of fuel

Actual volume of air supplied per kg of fuel = (1+ (EA/100)) × theoretical air

Area required for air supply is calculated as follows,

$$Q_a = AV \quad \text{…3.5}$$

where, Q_a, quantity of air (m^3/min); A, cross sectional area of the opening (m^2); and V, velocity of air (m/min).

Mass and energy balance is a good indicator of the system performance. One of the fundamental laws of physics states that mass can neither be produced nor destroyed, it is conserved. Equally fundamental is the law of conservation of energy. Although energy can change in form, it cannot be created or destroyed. These two laws of physics provide the basis for the mass and energy balance.

Mass balance: Mass balance study was conducted for one batch of pyrolysis of promising biomass with *Prosopis julifera* as combustion fuel. The various input and output considered and the corresponding calculation procedure was given below.

Total mass input (M_I), kg = $M_{IC} + M_{IA} + M_{IP}$ …3.6

Total mass output (M_O), kg = $M_{OB} + M_{OFG} + M_{OA}$ …3.7

Mass balance is given as,

$M_I – M_O – x = 0$ ... 3.8

$(M_{IC} + M_{IA} + M_{IP}) – (M_{OB} + M_{OFG} + M_{OA}) – x = 0$

where, x, unaccounted mass (g); M_{IC}, mass input for combustion (kg); M_{IA}, air supplied for complete combustion (kg); M_{IP}, mass input for pyrolysis (kg); M_{OB}, mass output through biochar (kg); M_{OFG}, mass output through flue gas (kg); M_{OA}, mass output through ash (kg).

Energy balance: The energy balance was carried out for one batch of pyrolysis process.

The various steps involved in calculation are explained below.

Total energy input (E_I), kJ = $E_1 + E_2$ ...3.9

Total energy output (E_O), kJ = $E_3 + E_4 + E_5$ ...3.10

Energy balance is given by,

$E_I – E_O – x = 0$ ...3.11

$(E_1 + E_2) – (E_3 + E_4 + E_5) – x = 0$

where, x, unaccounted mass (g); E_1, energy content in combustion fuel (kJ); E_2, energy content in biomass (kJ); E_3, energy content in biochar (kJ); E_4, energy content in flue gas (kJ); E_5, energy content in ash (kJ);

The study of pyrolysis of selected biomass for production of biochar was carried out in a developed pyrolysis unit. It follows semi-indirect heating method. A known quantity of selected biomass was filled in the pyrolysis chamber. The combustion chamber was filled with *Prosopis julifera* used as combustion fuel. The pyrolysis process was initialized by igniting the combustion fuel. The air supply for the combustion was provided from the bottom opening of the combustion chamber. After five minutes the fuel material was started to burn hotter and release smoke. The biomass was started to decompose due to the heat produced from combustion. After 30 minutes to 1 hr the biomass was completely converted to biochar emitting the volatile substances and enhancing the non-volatile carbon at the temperature of above 400 °C. At the time of closure of process, trace amount of gases with little smoke is releases indicating the completion. After that the chimney was removed and the pyrolysis chamber was covered with the lid. In order to prevent the conversion of biochar into ash, the bottom opening of the combustion chamber was covered with another lid. The reactor was cooled down after some hours and then biochar was taken out from the reactor.

Biochar yield (kg) = (weight of biochar/weight of biomass) × 100 …3.12

The bulk density of biomass and biochar was determined by using the standard of American Society for Testing of Materials (ASTM E-873-06). The biomass and biochar compositions were analyzed by proximate analysis based on standard methods (moisture content: ASTM D3173, ash: ASTM D3174, volatile matter: ASTM D3175 and fixed carbon: D3172) and the elemental composition such as carbon, hydrogen and oxygen was calculated using correlation analysis from proximate compositions of biomass samples suggested by Parikh and Channiwala (2007). The higher heating value (HHV) of biomass was measured based on ASTM D-2015 by using a bomb calorimeter (M/s Aditya, India). The total organic carbon content of the biochar was found out based on the procedure of ASTM D4373-02. The pH and EC of biochar were determined by using the procedure given by Rajkovich *et al*. (2011).

RESULTS AND DISCUSSION

Properties of biomass

Bulk density: The bulk density is the important physical property used for designing the logistic system for biomass handling, storage requirements and how the material behaves during subsequent thermo-chemical and biological processes (McKendry 2002). The bulk density of selected biomass varied from 395 to 500 kg/m^3 (Table 1). The high bulk density of 500 kg/m^3 was found for coconut shell followed by maize cob had 480 kg/m^3 and low bulk density of 395 kg/m^3 was found in *Prosopis julifera*. The results were on par with Woolf *et al*. (2010) and Subramaniam *et al.* (2011).

Proximate composition: The moisture content of biomass varied from 7.4 to 10.2%. The higher moisture content was found in coconut shell and lower moisture was found in *Prosopis julifera* (Table 1). Moisture content can have different effects on pyrolysis product yields depending on the conditions. However, increased moisture present when pyrolysis reactions are performed under pressure has been shown to systematically increase char yields (Antal and Gronli 2003). The volatile matter of biomass varied from 63.7 to 83.0%. The ash content varied as 1.4-17.1%. High volatile matter content with low ash is the main criterion for pyrolysis conversion. High volatile content and low ash content of the selected biomass feed stocks that favour the pyrolysis conversion technique. The fixed carbon content of biomass varied from 15.2 to 21.3%. The results of proximate composition were found to be on par with the results obtained by Jigisha *et al*. (2007), Verhejien *et al*. (2010) and Subramaniam *et al.* (2011). They denoted that volatiles, ash and fixed carbon of maize cob, cotton stalks and coconut shell varied as 62.90 to 83.01, 1.80 to 7.20 and 15.16 to 20.30 % respectively.

Elemental composition: The results of elemental composition of various biomass such as carbon, hydrogen and oxygen are presented in Table 1. High carbon content present in the biomass is most suitable for biochar production. Elemental carbon content varied from 41.24 to 48.6%. Coconut-shell had the high elemental carbon content and cotton-stalk had the low elemental carbon content. The elemental hydrogen and oxygen composition of selected biomass varied from 5.0 to 5.9% and 36.8 to 44.1% respectively. Among them, maize-cob had high elemental hydrogen and oxygen content and cotton-stalk had low elemental hydrogen and oxygen content. The results of elemental composition of coconut-shell and maize cob were on par with Shan-Wen Du *et al*. (2014).

Calorific value: The heat value, or amount of heat available in a fuel (kJ/kg), is one of the most important characteristics of a fuel because it indicates the total amount of energy that is available in the fuel. The heat value in a given fuel type is mostly a function of the fuel's chemical composition. The calorific values of biomass varied as 14.8-20.6 MJ/kg (Table 1). The higher calorific value was found in coconut-shell and lower in cotton stalk. The calorific value of biomass like cotton-stalk, rice husk and saw dust varied from 15 to 18 MJ/kg (Chen *et al*. 2003).

Description of developed pyrolytic reactor

The pyrolysis reactor with 1 kg capacity was designed and developed for biochar production and optimization from the farm waste. The reactor was made of galvanized iron.

The system consists of two chambers, one for combustion process to produce heat for biochar production and another one for pyrolysis process to convert the feedstock into carbon rich biochar. The combustion chamber has designed with the diameter of 18 cm and height of 24 cm. A grate is provided at the bottom of the combustion chamber to supply the stochiometric required air. The pyrolysis chamber has designed with the diameter of 18 cm and height of 18 cm. The bottom of the pyrolysis cylinder was provided with a grate of 32 holes (each hole of diameter 6 mm) to transfer the heat from combustion chamber to pyrolysis chamber through direct contact of flame heat to the feedstock. A chimney of 1 m height was provided on the top of the pyrolysis chamber for exhausting the flue gas. Glass wool of 5 cm thickness was used for insulating the reactor to avoid conductive heat loss during the process,

Table 1 Proximate composition of selected biomass

Biomass	Bulk density (kg/m^3)	Moisture content (%)	Calorific value (MJ/kg)	Elemental composition (%)			Proximate composition (dry basis) (%)		
				C	H	O	Volatile matter	Ash content	Fixed carbon
Prosopis julifera	395	7.4	20.1	48.0	5.9	44.0	81.5	1.4	17.1
Maize cob	480	9.6	17.8	47.4	5.9	44.1	83.0	1.8	15.2
Cotton stalk	450	10.2	14.8	41.2	5.0	36.2	63.7	17.1	19.2
Coconut shell	500	8.4	20.6	48.6	5.9	43.1	76.9	1.8	21.3

Fig 1 Pyrolytic reactor

based on the details given by Musale *et al*. (2013).

Optimization of biochar production

Pyrolysis study of selected biomass (1 kg) was carried out in the pyrolysis unit with different weights (0.25, 0.5, 0.75 and 1.0 kg) of 10 cm length *Prosopis julifera*. The different batch trails of optimization results are given in Table 2.

The biochar production under a controlled system may provide a higher yield and have fewer detrimental effects on the environment. These characteristics make biochar an exceptional soil amendment for use in sustainable agriculture (Verhejien *et al*. 2010).

From Fig 4, it is observed that the maximum yield of biochar from maize cob and cotton stalks were found as 34 and 33% with 0.5 kg *Prosopis julifera*. The optimum combustion and pyrolysis mass ratio was found to be 0.5:1. For coconut shell the maximum yield of biochar was calculated as 36% with 0.75 kg of *Prosopis julifera*. The mass ratio of combustion and pyrolysis fuel was 0.75:1.

Fig 5 shows that the optimization of residence time for biochar yield of selected biomass with different mass of combustion fuel. Cotton stalk had less residence time for getting maximum yield of biochar followed by maize cob and coconut shell.

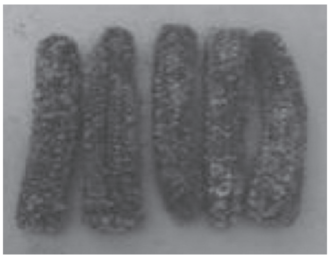

Fig 2 Char of maize-cob

Fig 3 Char of cotton-stalk

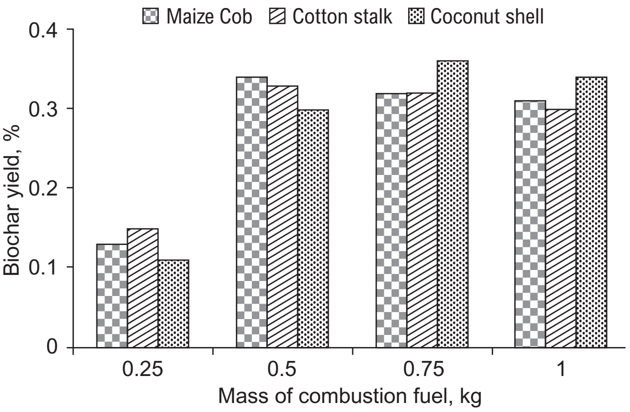

Fig 4 Optimization of biochar yield for selected biomass

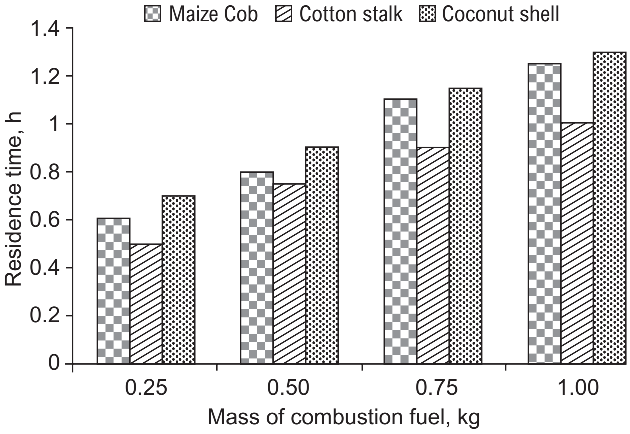

Fig 5 Optimization of residence time for biochar yield

Table 2 Optimization of biochar production in developed unit

Pyrolysis fuel	Biochar yield (kg) mass				Residence time (hr) mass				Efficiency of biochar yield (%) mass				Ash (kg) mass			
	0.25	0.50	0.75	1.00	0.25	0.50	0.75	1.00	0.25	0.50	0.75	1.00	0.25	0.50	0.75	1.00
Maize cob	0.13	0.34	0.32	0.31	0.60	0.80	1.10	1.25	13.0	34.0	32.0	31.0	0.08	0.10	0.13	0.15
Cotton stalks	0.15	0.33	0.32	0.30	0.50	0.75	0.90	1.00	15.0	35.0	31.0	30.0	0.09	0.11	0.13	0.14
Coconut shell	0.11	0.30	0.36	0.34	0.70	0.90	1.15	1.30	11.0	30.0	36.0	34.0	0.08	0.11	0.12	0.14

Table 3 Properties of biochar

Biomass	Bulk density (kg/m^3)	Moisture content	pH	EC (dS/m)	Total organic carbon (%)	Elemental composition, (%)			Proximate composition (dry basis, %)		
						C	H	O	Volatile matter	Ash content	Fixed carbon
Maize cob	224	5.26	8.2	0.95	75	59.2	5.3	32.9	18.10	1.95	79.95
Cotton stalk	215	4.85	8.3	0.70	67	57.7	5.1	31.9	16.80	4.56	78.64
Coconut shell	278	5.40	8.7	0.10	89	60.6	5.3	32.9	15.42	0.50	84.08

Mass and energy balance

The mass and energy closure efficiency of the developed pyrolysis unit were found to be 85% and 83% respectively. The measurements of tar content, producer gas is unable to measure, this accounts as unaccounted loss.

Properties of biochar

The nutrient content of biochars to range widely and be controlled by both biomass type and combustion conditions (Mukherjee *et al*. 2011). Biochar application significantly increased soil pH, readily available water content (defined as volumetric water available between 10 kPa and 100 kPa), soil organic carbon and decreased bulk density (Rogovska *et al*. 2014). Biochar may stabilise native soil organic carbon, through physical and chemical interactions between biochar, native soil organic carbon and soil minerals (Fang *et al*. 2014).

Bulk density: The incorporation of biochar into soil can alter soil physical properties such as structure, pore size distribution and density with logical implications in soil aeration, water holding capacity, plant growth and soil workability (Downie *et al*. 2009). Biochar has a bulk density much lower than that of mineral soils; therefore, the application of biochar can reduce the overall bulk density of the soil (Gundale and DeLuca 2006). The bulk density of biochar produced from pyrolysis of selected biomass varied from 215-278 kg/m^3 (Table 3). Coconut shell had high bulk density of 278 kg/m^3 and cotton stalk had low bulk density of 215 kg/m^3. These results were on par with the results of Downie *et al*. (2009) and Rogovska *et al*. (2014). He stated that depending upon the biomass and production temperatures, the density of biochar can range from 200-800 kg/m^3. Adding these low density biochar will improve the soil in two ways. First, it reduces the bulk density, allowing the root systems of plants to penetrate the soil and grow more easily. Second, lowering the density allows for greater moisture retention.

Proximate composition: The values of proximate composition such as moisture content, volatile content, ash content and fixed carbon are presented in Table 3. Biochar has a highly heterogeneous composition, which contains both stable and more labile components, and carbon, volatile compounds, mineral content (ash), and moisture are generally considered the most important constituents (Antal and Gronli 2003). The moisture, volatile and ash content of biochar decreased when compared to biomass. But the fixed carbon content in biochar found to be increased when compared with initial biomass. The moisture content of biochar ranged from 4.85-5.4%. High moisture content was found in coconut shell (5.4%) and low moisture content was found in cotton stalk (4.9%).The biochar produced from selected biomass had 15.4-18.1% volatile matter. Maize cob had high volatile matter (18.1%) followed by cotton stalk (16.8%). The low volatile matter was found in coconut shell (15.4%). On an average, the biochar produced from selected biomass had 0.5-4.6% ash. Maximum ash was found in cotton stalk and minimum was found in coconut shell. The fixed carbon of biochar varied from 78.6-84.1%. Higher fixed carbon content was found in coconut shell, which had 84.08% followed by maize cob had 79.95%. Lower fixed carbon was found in cotton stalk. These results were in good agreement with the results reported by Cora Bulmau *et al.* (2010) and Fang *et al*. (2014).

Elemental composition: The elemental composition of biochar produced from selected biomass are presented in Table 3. Elemental carbon content varied from 57.7 to 60.6%. Cotton stalk had low carbon content and coconut shell had high carbon content followed. Elemental hydrogen varied from 5.1 to 5.3% and oxygen content varied from 31.9 to 32.9%. These results were on par with Frederik Ronsse *et al.* (2013).The coconut-shell had high elemental carbon and low hydrogen and oxygen content. The carbon content of biochar increased while the oxygen and hydrogen contents decreased with increasing temperature. This indicates an increasing degree of carbonization. The degree of carbonization was described by the H/C ratio, because H was primarily associated with plant organic matter.

pH and EC: The application of biochar induced changes in soil chemical properties, viz. increasing the pH, total N and available P_2O_5, cation exchange capacity, amounts of exchangeable cations and base saturation, and decrease in the content of exchangeable Al^{3+} (Yamato *et al*., 2006). The pH of biochar varied as 8.2 to 8.7 (Table 3). The maximum pH was found in coconut shell and the minimum pH was found in maize cob. These results were on par with the results of Brown (2009), Chan and Xu (2009) and Verhoeven and Johan Six (2014). They denoted that the pH content of biochar varied from 6.2-9.6. The EC of biochar varied as 0.10-0.95 ds/m. Coconut shell had low EC and maize cob had high EC.

Total organic carbon: Biochar is first and foremost characterized by its high organic C content, which mainly comprises conjugated aromatic compounds of six C atoms linked together in rings (Table 3). The total organic content of biochar varied as 67 to 89%. Higher organic carbon content was found in coconut shell and lower amount was found in cotton stalk. These results are on par with Gaskin *et al*. (2010) and Basso *et al*. (2013). They reported that the total carbon content of biochar varies considerably depending on feedstock and may range from 400 to 900 g/ kg (40-90%). Chan *et al*. (2007) reported that nutrients were retained in soil and remain available to crops mainly by adsorption to minerals and soil organic matter. Usually, the addition of organic matter such as compost and manure into soil can help retain nutrients. Biochar was considered much more effective than other organic matter in retaining and making nutrients available to plants. Its surface area and complex pore structure are hospitable to bacteria and fungi that plants need to absorb nutrients from the soil. Moreover, biochar was a more stable nutrient source than compost and manure.

Biochar amendments to agricultural soils have been shown to reduce nutrient leaching and to have positive effects on soil physical, chemical and microbiological properties (Basso *et al*. 2013) that may act in synergy and result in improved crop performance. The combination of biomass pyrolysis and use of the resulting biochar as a soil amendment simultaneously provides bioenergy, carbon sequestration and soil conditioning (Woolf *et al*. 2010). The long-term carbon sequestration potential of such biochar practices relies on the recal-citrance of the biochar- carbon to microbial decomposition (Singh *et al.* 2012).

In addition to these purported benefits, biochar largely consists of a recalcitrant carbon fraction which has been demonstrated to be very stable, with a half-life of over 1000 years in the soil (Zimmerman 2010). Consequently, biochar production by pyrolysis of biomass effectively removes carbon from the atmospheric carbon cycle, transferring it to long term storage in soils. Biofuel production using modern biomass could produce a biochar by product through pyrolysis that results in 30.6 kg carbon being sequestered for every GJ of energy produced (Lehman *et al.* 2006).

Biochar therefore could help in the global challenge of carbon dioxide mitigation, as it results in a net removal of carbon from the atmosphere.

Cost economics

The total cost of the developed system for producing biochar from selected biomass worked as ₹ 4 000 including raw material, production, labor, repair and maintenance. The payback period was 3.2 years.

(i) The design of the semi-indirect non-electric pyrolytic reactor proved its performance for its designed capacity for production of biochar from farm wastes. The reactor also proved its superiority in producing maximum amount of biochar with minimum amount of combustion fuel enhancing low-cost.

(ii) The optimization of biochar production with different mass of combustion fuel such as 0.25, 0.50, 0.75 and 1 kg by using selected biomass was carried out to obtain the maximum yield of biochar.

(iii) The characterization of biomass and biochar pointed out the reduction of bulk density of biochar output (215-278 kg/m^3) compared to raw farm waste (450-500 kg/m^3) which is beneficial to improve soil health. The volatile matter present in the raw farm waste was reduced through pyrolysis process but the fixed carbon content was increased. The biochar with lower volatile content and higher fixed carbon content is beneficial for improving soil properties. In addition, the higher organic carbon content of 67-89% would be ideal for soil health of cropping land.

(iv) Among the selected biomass, coconut-shell had the maximum biochar efficiency of 36% and had the high total organic carbon content of 89%. The optimum combustion and pyrolysis mass ratio was found as 0.5:1 for maize cob and cotton stalk and that of coconut shell was 0.75:1. The mass and energy closure efficiency of the developed pyrolysis unit were found to be 85% and 83% respectively.

(v) The developed pyrolytic reactor was found economically viable with the total installation cost of ₹ 4 000 and payback period of 3.2 years.

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