Experimental Investigation on Energy Recovery System for Continuous Biochar Production System

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Authors' contributions

This work was carried out in collaboration among all authors. Author LJ work on slow pyrolysis under the guidance of authors NLP, BLS, SJ, DS and NKJ and wrote the first draft of the manuscript. Author NLP managed the analyses of the study. All authors read and approved the final manuscript.

Original Research Article

ABSTRACT

Fossilfuel requirement is the necessity for fulfilling the global energy needs, which is increasing day by day due to this it will drain in future. Bio-energy became as one of the vital alternatives to replace fossil fuel. Thermochemical conversion of biomass for obtaining the bioenergy is getting more popular in the recent time. In the present study, slow pyrolysis is used for bio-energy production from the waste biomass available in the form of crop residues of Groundnut Shell (GS), Chana Straw (CS) and Wheat Straw (WS) using the developed continuous biochar production system (Pratap Kiln) to produce biochar. An energy recovery system consisting of cooling chamber was developed to recover the bio-oil from the waste flue gas (syngas). The pyrolysis of selected biomass was carried out at 450°C and residence time of about 4 min. The yield of biochar and bio-oil and syngas properties were determined. The maximum biochar yield was found in CS feedstock

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as 35% followed by WS and GS, i.e. 33% and 29%, respectively. The bio-oil recovery in GS, CS and WS was 31%, 26% and 30% respectively, whereas the syngas production was 40%, 39% and 37% respectively.

1. INTRODUCTION

Energy is one of the most major essential demands of present societies for their sustainable development. To fulfill this demand significantly the consumption of and depletes the fossil fuels' sources [1]. The renewable energy produced from the renewable sources, which are not limited in nature and can be reproduced in the limited time period [2]. The sources of renewable energy are of the solar energy, wind energy, biomass, hydro energy. In the renewable-energy generation, the biomass sector is contributed 12% energy generation from total production of the energy. The maximum Biomass energy production is higher in the state of Maharashtra of 2516.10 MW followed by the Uttar Pradesh 2115.51 MW and Karnataka 1881.80 MW out of total production of India is about 9861.31MW energy production [3]. Biomass is renewable, widely available, uniformly distributed, carbon neutral and more economical than other renewable sources due to which it becomes a high-potential energy source. The classifications of biomass resources are illustrated in Fig. 1. [4].
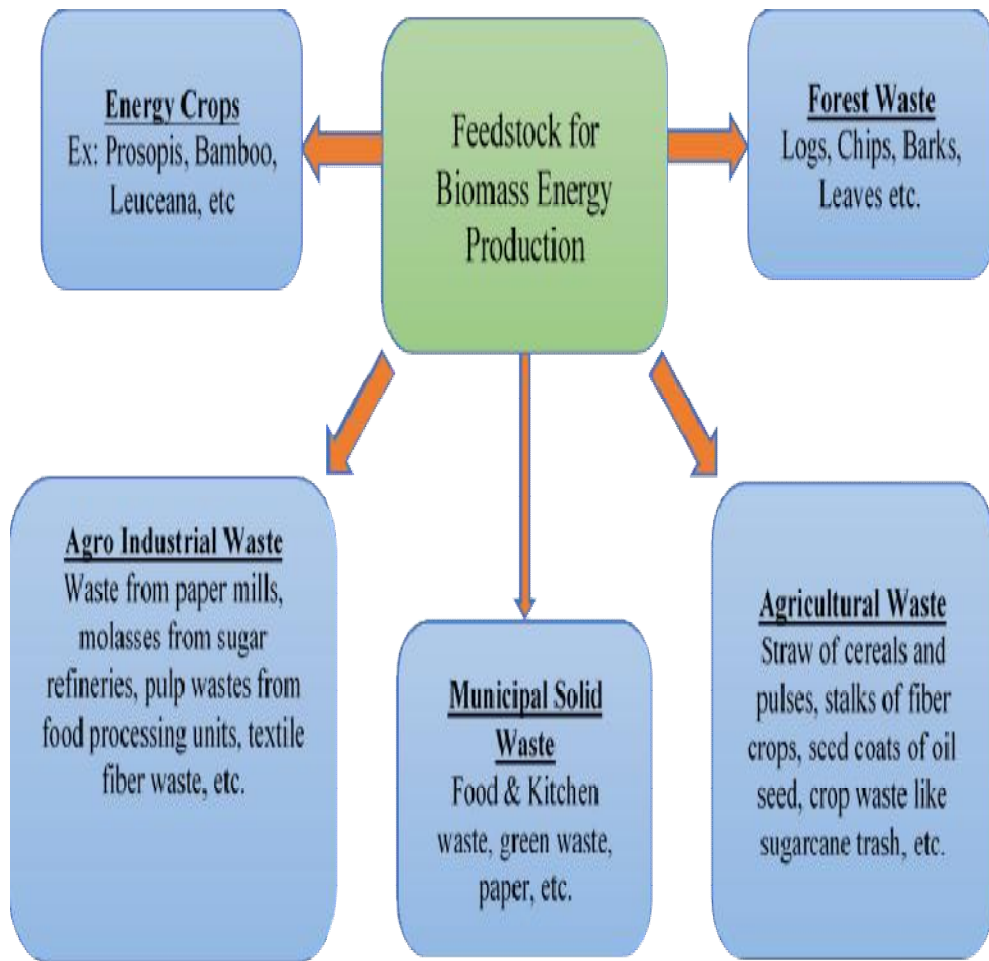
Fig. 1. Classifications of biomass resources

The major crop residues available in India are straws of paddy, wheat, millet, sorghum, pulses (pigeon pea), oilseed crops (castor, mustard) etc [5]. Similarly, the agro-industrial residues are rice husk, groundnut shell, cotton waste, mustard husk, coffee husk, cassava peels coir pith etc [6]. Ma et al.[7] specified bio-oil extraction from rice husk in which fixed-bed pyrolysis reactor incorporated with three-stage condensation columns. Crop residues in fields can cause considerable crop management problems as they accumulate.

There are various generic waste/residue processing technologies. The thermo-chemical technology [8] is one of them, which comprises direct combustion [9] for power, pyrolysis [10], for biochar, gas and oils, and gasification [11] (for carbon monoxide and hydrogen-rich syngas). Panwar et al. [12] exclusively elaborated the thermo-chemical conversions of biomass to produce different end products as showed in the Fig.2.

Biochar is a carbon rich, fine grained, porous substance produced under oxygen limiting conditions at temperatures between range 350℃

- 700℃ for the zero-carbon biochar process pyrolysis is the best system to conduct. The slow pyrolysis and intermediate pyrolysis both result in higher biochar yields, while fast pyrolysis gives higher liquid (bio-oil) yields [13,14]. This paper representing the slow pyrolysis system with three types of feed stocks of GS, CS and WS was fed into the pyrolysis reactor. This feedstock yields the biochar, bio-oil and syngas, in particular, average. The reviews said that, biochar production with slow pyrolysis process will produce 35% biochar, 30%liquid(bio-oil) and 35% gas(syngas) [15,16]. The smoke contains some amount of bio-oil so that liquid (bio-oil) can be condensed and also the non-condensable gases combust using suitable burner to produce process heat [12,17]. The process heat can used for preheating of biomass which help to improve working efficiency of biochar production unit. Before this study, the gases from this biochar unit directly expel into the atmosphere[18–20]. These gases was utilized and bio-oil and syngas was recovered by condensing these hot gas. The study shows that the gases which are non-condensable are combustible in nature that can be used for secondary heat generation [21,22].
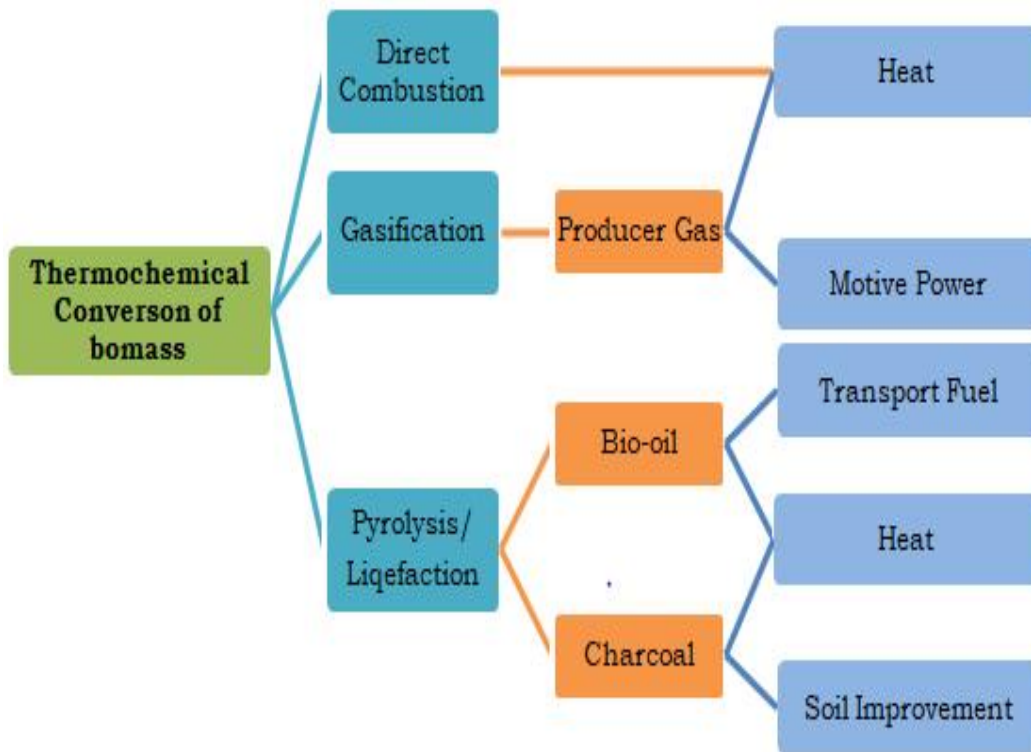

Fig. 2. Thermo-chemical conversion of biomass

2. MATERIALS AND METHODS

2.1 Feedstock

The process flow chart is described in Fig.3.The present study was conducted with three different crop residues such as GS, CS and WS residues used as a feedstock (shown in Fig. 4).

2.2 Experimental Setup

The Energy Recovery System was specially developed and coupled with the existing continuous biochar production system Pratap Kiln) having the working capacity of 1-30 kg of biomass per hour. Raw biomass (crop residues) as GS, CS and WS was feed through the hopper and slowly pyrolyzed for the residence time of about 4min at temperature 450°C on left side of the cooling chamber, in which the biochar discharge from the bottom side of the reactor. The pyrolysis reactor converted biomass into bio-char while the cyclone separator were provided at the end of the reactor for biochar collection and hot gas feed into the cooling chamber then hot gas condensed, converted into the bio-oil. However, non-condensable gas (syngas) feed into the premixed type burner for secondary uses of heat generation. The cooling chamber containing 5 baffles arranged in zigzag position to increasing residence time which help to maintain the 5°C temperature. The outlets of cooling chamber having two purposes, collecting the oil by condensable gas and extracting non-condensable gas. The premixed type burner was designed based on the stoichiometric air requirements for the burning of the gas, and the gas composition was calculated by Gas Chromatography (GC-Trace1110).

The schematic view of Energy Recovery system coupled with biochar production unit is depicted in Fig. 5.
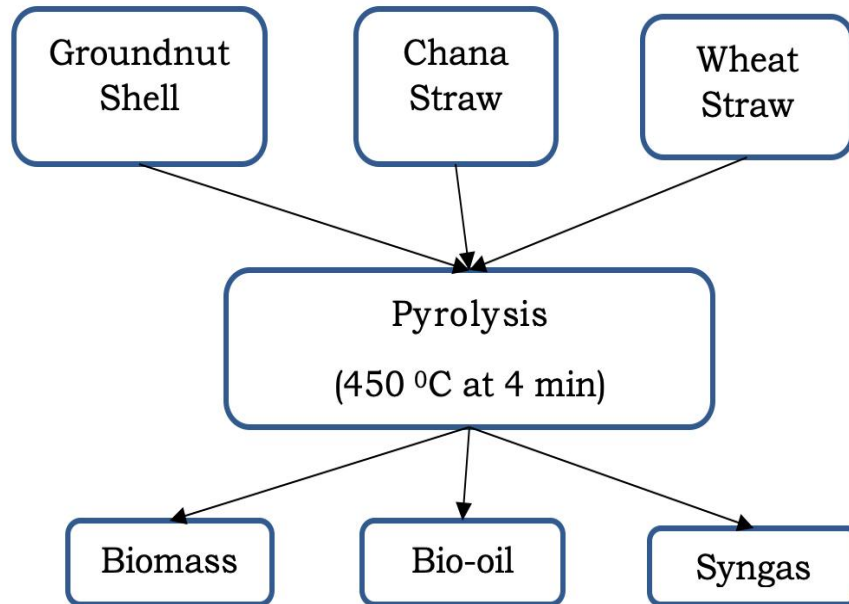
2.3 Products Yield

The product yield which is calculated during performance of the developed energy recovery system was evaluated by the following formula:

2.3.1. Biochar and bio-oil yield

$$Biochar/bio-oil\ yield(\%)$$
$$= \frac{Total\ mass\ of\ biochar/bio-oil\ produced(kg)}{Total\ mass\ of\ biomass(kg)} \times 100$$

2.3.2 Syngas yield

$$Syngas\ yield(\%) = 100 - [Biochar\ yield(\%) + Bio-oil\ yield(\%)]$$

Fig. 3. Flow chart of the methodology

Groundnut Shell   **Chana Straw**   **Wheat Straw**

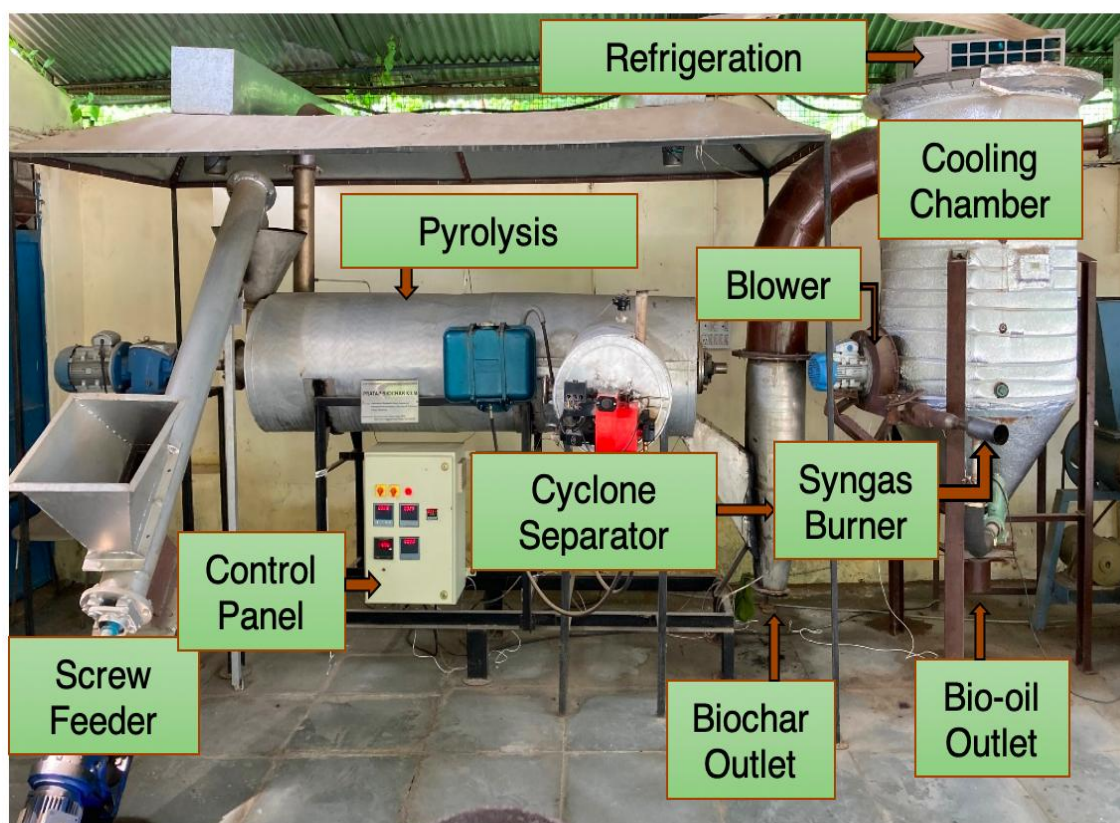**Fig. 4. Crop residues used as feedstock for pyrolysis**

Fig. 5. Energy recovery system coupled biochar production system

3. RESULTS AND DISCUSSION

The pyrolysis system was set at temperature of 450 ºCat 4 minutes of residence time. The performance of the developed energy recovery system was evaluated product yield as presented in Table 1.

The biochar yield was maximum found in CS followed by the WS and GS while the bio-oil yield was maximum in GS followed by WS and CS also the syngas yield was maximum in GS followed by the CS and WS. The different types of feedstock have produced a different char, condensate and varying gas composition was

observed due to their different ash content and lignocellulosic compositional variation [23], and also the liquid yield depended on biomass type, temperature, vapour residence time, and biomass ash content, which have wide influence towards vapour cracking [24,25]. The product yield was verified with the [26] similar product yield percentage was found.

3.1 Proximate Analysis of the Biomass

Proximate analyses of the feed stocks (GS, CS, and WS) were experimentally analyses using standard protocols [27]. The results obtained from the proximate analysis of the biomass are tabulated as in Table 2.

3.2 TGA-DTG Analysis of Biomass

The thermogravimetric analysis (TGA) of biomass shows the mass loss takes place during the slow pyrolysis as a function of temperature and it was taken at the heating rate of 20°C/min and the maximum temperature of 700°C. The pyrolysis product formation by the pyrolysis totally depends on the hemicellulose, cellulose and lignin content of the biomass [28].

Fig. 6 shows the TG and DTG curves of the GS, CS and WS sample. The mass loss took place in three different stages: moisture content removal, hemicellulose, cellulose, lignin degradation and char formation.

Stage 1:This stage was conducted from room temperature 180°C for removing moisture content and volatile matter form the mass, this degradation higher in groundnut shell.

Stage 2:This stage was conducted temperature range 180 to 380°C which covert mass product hemicellulose, cellulose and lignin into pyrolysis product: biochar, bio-oil and syngas. Maximum degradation was found mostly higher in Groundnut Shell.

Stage 3:This stage called the lignin degradation starts from 380 to 535°C, lower percentage of the weight loss was observed as compared to previous stage due to lower reaction rate.

Fig. 7 shows the TG-DTG analysis curve of biochar produced from the biomass feedstock (GS, CS and WS) at 450 °C. The TG analysis of biochar done to analyse the thermal resistance and pyrolytic performance. When temperature range started from 400 to 450 ^{o}C, small amount

of mass loss was occurred (8 – 22%) due to higher thermal stability. The thermal degradations of all the biochar samples were started from 450 0C and ended at 750 ^{o}C with average mass loss of 58% in all the samples[29]. TG-DTG curves showed that the maximum mass loss occurs between the 500-550 0C was about GS followed by CS and WS.

Due to the presence of the water and macromolecule such as cellulose, hemicellulose, oligomeric phenolic compounds the density of the bio-oil is larger than the petrol and diesel [30]. The pH content of the bio-oil was found high acidic in the CS followed by WS and GS.

3.3 Bio-oil Properties

The hot gases which were condensed by the cooling chamber converted into the form of bio-oil. This condensed bio-oil was analysed in the departmental laboratory and its properties like viscosity, density and pH were determined and tabulated in Table 3.

3.4 Syngas Composition

The hot syngas was condensed in the cooling chamber. The non-condensable gas was collected into the 2 *lit* glass bottle by waster displacement method. The sample bottle was then attached to the Gas Chromatography (GC) by Thermo Fisher Scientific GC Trace-1110. The gas composition was found by this instrument is given in the Table 4.

3.5 Higher Heating Value of the Biomass and Pyrolysis Product

The calorific value of the biomass, biochar and bio-oil was determined using the bomb calorimeter. The higher heating value of the biomass, biochar and bio-oil with the crop residues was given in the Table 5.

The calorific value of the syngas was determined by the composition of the syngas. The syngas was consisting of H_2, CO, CH_4, N_2, CO_2, and lower C_nH_n gaseous streams (where, n < 4).

3.6 Economic Feasibility of the Developed System

The economic feasibility of the developed energy recovery system for continuous biochar production as Table 6 which was accessed after analyzing the various economic parameter [31].

The cost analysis of a developed energy recovery system was considering the present investment, and the assumption where the capital cost of Energy Recovery system is Rs. 1,75,000, while the total capital costs of the developed system Rs. 9,25,000 for operating period of 300 days in a year which was recovered in 10 months only. The total cost of Production per annum including repair and maintenance is Rs. 9,11,650.

The system was design for the agricultural waste biomass however few operation precautions has to be taken care like: at the moisture content has to be maintain the biomass. The low density agrowaste biomass has the issue with the flowability therefore it was necessary to maintain the uniform flow of the biomass during the experimentation. The operation must be purely under the anaerobic condition to avoid the combustion of the biomass during the operation.

Table 1. Overall product yield obtained from the developed energy recovery system

Product yield	Product Yield (%)		
	GS	CS	WS
Biochar	29±0.25	35±0.3	33±0.5
Bio-oil	31±0.75	26±0.4	30±0.2
Syngas	40±0.5	39±0.7	37±0.8

Table 2. Proximate analysis of the biomass

Parameters	Feedstock		
	GS	CS	WS
Moisture Content (%)	6.5±1.0	10.2±1.0	8.6±1.2
Volatile Content (%)	68.1±1.8	67.6±3.0	69.7±1.0
Ash Content (%)	9.1±0.5	6.8±0.7	7.3±0.6
Fixed Carbon (%)	16.3±1.0	15.4±1.5	14.6±2.0
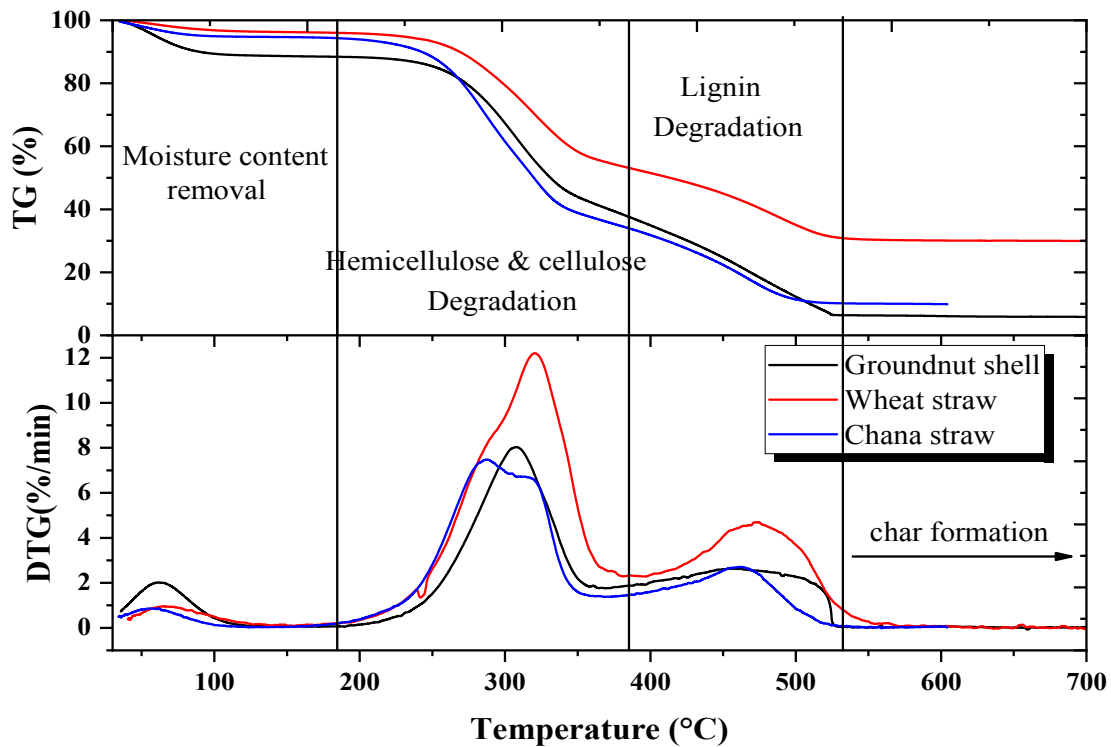
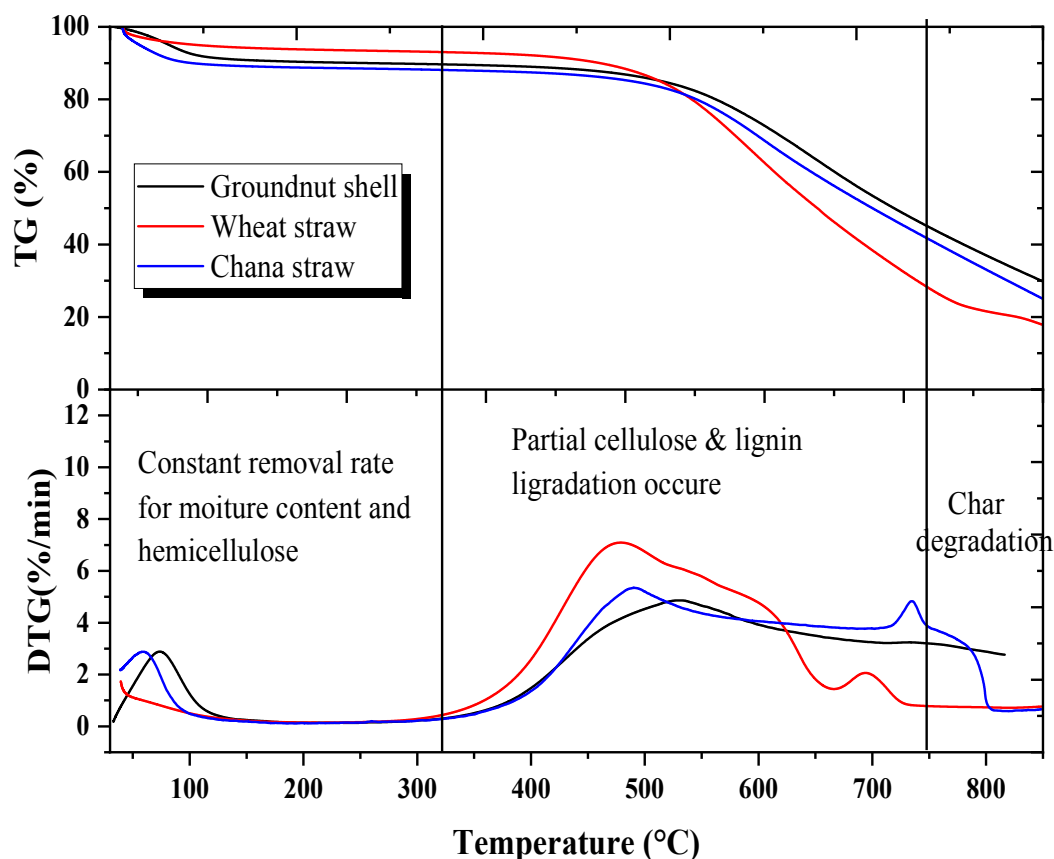**Fig. 6. TG-DTG analysis curve for biomass feedstocks**

Fig. 7. TG-DTG analysis curve of biochar

Table 3. Physicochemical properties of the bio-oil recovered from the pyrolysis

Biomass Names	Physical Properties of Bio-oil		
	Viscosity (cSt at 40ºC)	Density (kg/m³)	pH
GS	32.3±0.12	1.04±0.12	4±0.05
CS	30.1±0.2	1.02±0.3	3.1±0.1
WS	29.9±0.14	1.01±0.05	3.6±0.1

Table 4. Gas composition of non-condensed gases from the cooling chamber

Biomass	H_2 (%)	CO (%)	CH_4 (%)	N_2 (%)	CO_2 (%)
GS	2.74±0.8	7.2±1	1.02±0.1	70.2±1.2	12.6±1
CS	2.8±1	6.9±1	1.03±0.1	71.7±1.6	14.4±0.5
WS	2.53±1	6.7±1	1.01±0.2	72.36±0.9	13.8±1

Table 5. Calorific value of the biomass and pyrolysis product i.e. biochar, bio-oil and syngas

Biomass	Calorific Value			
	Biomass (MJ/kg)	Biochar (MJ/kg)	Bio-oil (MJ/kg)	Syngas (MJ/m³)
GS	15.90	23.79	20.63	4.91
CS	15.77	20.91	20.41	5.49
WS	14.60	22.88	21.76	5.02

Table 6. Economic of the developed energy recovery system

S. No.	Economic Indicators	Values
1.	Net Present Worth (NPW)	Rs. **59,71,354.9**
2.	Benefit Cost Ratio (BCR)	1.91
3.	Payback Period	10 Months
4.	Internal Rate of Return (IRR)	121.10%

4. CONCLUSION

In this study Pratap kiln slow pyrolysis continuous biochar production system for energy recovery of biomass of crop residues like GS, CS and WS was used for the experiment. The cooling chamber containing the 5 baffles arranged in zig-zag position for increasing the residence time for condensing hot gas having two outlet of 100 mm for collecting bio-oil and another for burning non-condensable gas. Condensable gas used for production of oil while non condensable gas is also employed for heat generation using premixed type burner. The biochar yield was found maximum in CS followed by WS and GS i.e. 35, 33 and 29 percent respectively. The bio-oil yield was found maximum in GS followed by WS and CS i.e. 31, 30, 26 percent respectively. The syngas yield was found maximum in GS followed by CS and WS i.e. 40,39 and 37% respectively. The combustible gases remaining after the condensation of the bio-oil was utilized for secondary heat source for slow pyrolysis process.

The economic indicators shows that the developed system has the NPW of Rs. 59,71,354.9, Benefit Cost ratio is 1.98 and IRR of 121.1 %. By selling the biochar at Rs. 60/kg and bio-oil at Rs. 30/kg the payback period was calculated for the developed system is 11 months. The utilization of the waste heat from the syngas produced during the process can be used back in to the pyrolysis process which could improve the overall efficiency of the pyrolysis system.

ACKNOWLEDGEMENTS

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Monlau F, Sambusiti C, Antoniou N, Barakat A, Zabaniotou A. A new concept for enhancing energy recovery from agricultural residues by coupling anaerobic digestion and pyrolysis process. Appl Energy. 2015;148:32–38.
DOI: 10.1016/j.apenergy.2015.03.024.
2. Huang Y, Anderson M, McIlveen-Wright D, Lyons GA, Mc Roberts WC, Wang YD et al. Biochar and renewable energy generation from poultry litter waste: A technical and economic analysis based on computational simulations. Appl. Energy. 2015;160:656–663.
DOI: 10.1016/j.apenergy.2015.01.029.
3. MNRE ministry of new and renewable energy; 2020.
Available:https://mnre.gov.in/physical-progress-achievements.
4. Kumar A, Kumar N, Baredar P, Shukla A. A review on biomass energy resources, potential, conversion and policy in India. Renew Sustain Energy Rev. 2015;530–539.
5. Williams CL, Westover TL, Emerson RM, Tumuluru JS, Li C. Sources of biomass feedstock variability and the potential impact on biofuels production. Bioenergy Res. 2016;1–14.
6. Sugumaran P, Seshadri S. Evaluation of selected biomass for charcoal production India. J Sci Ind Res. 2009;68:719–723.
7. Ma S, Zhang L, Zhu L, Zhu X. Preparation of multipurpose bio-oil from rice husk by pyrolysis and fractional condensation. J Anal Appl Pyrolysis. 2018;131:113–119.
DOI:10.1016/j.jaap.2018.02.017.
8. Van de Kaa G, Kamp L, Rezaei J. Selection of biomass thermochemical conversion technology in the Netherlands: A best worst method approach. J Clean Prod. 2017;166:32–39.

DOI:10.1016/j.jclepro.2017.07.052.

9. Francisco RW, Rua F, Costa M, Catapan RC, Olivrira AAM. No combustion characteristics of gaseous fuels with low calorific value in a porous burner. In proceedings of the European combustion meeting. 2009;103–109.

10. Brown TR, Wright, MM, Brown RC. Estimating profitability of two biochar production scenarios: Slow pyrolysis vs fast pyrolysis. Biofuels, Bioprod. Biorefining. 2011;5:54–68.
DOI:10.1002/bbb.254.

11. Makwana JP, Pandey J, Mishra G. Improving the properties of producer gas using high temperature gasification of rice husk in a pilot scale fluidized bed gasifier (FBG). Renew Energy. 2019;130:943–951.
DOI:10.1016/j.renene.2018.07.011.

12. Panwar NL, Pawar A, Salvi BL. Comprehensive review on production and utilization of biochar. SN Appl Sci. 2019;1.
DOI:10.1007/s42452-019-0172-6.

13. Bernardino CAR, Mahler CF, Veloso MCC, Romeiro GA. Preparation of biochar from sugarcane by-product filter mud by slow pyrolysis and its use like adsorbent. Waste and Biomass Valorization. 2017;8:2511–2521.
DOI:10.1007/s12649-016-9728-5.

14. Lédé J, Broust F, Ndiaye FT, Ferrer M. Properties of bio-oils produced by biomass fast pyrolysis in a cyclone reactor. Fuel. 2007;86:1800–1810.
DOI:10.1016/j.fuel.2006.12.024.

15. Jaroenkhasemmeesuk C, Tippayawong N. Technical and economic analysis of a biomass pyrolysis plant. In proceedings of the energy procedia. 2015;950–955.

16. Nsamba HK, Hale SE, Cornelissen G, Bachmann RT. Sustainable technologies for small-scale biochar production — A Review. 2015;10–31.

17. Hlavsová A, Corsaro A, Raclavská H, Juchelková D, Škrobánková H, Frydrych J. Syngas production from pyrolysis of nine composts obtained from nonhybrid and hybrid perennial grasses. Sci World J. 2014;1–11.
DOI:10.1155/2014/723092.

18. Nasir Uddin M, Daud WMAW, Abbas HF. Potential hydrogen and non-condensable gases production from biomass pyrolysis: Insights into the process variables. Renew Sustain Energy Rev. 2013;204–224.

19. Paul AS, Panwar NL, Salvi BL, Jain S, Sharma D. Experimental investigation on the production of bio-oil from wheat straw. Energy sources, Part A Recover Util Environ Eff. 2020;1–16.
DOI:10.1080/15567036.2020.1779416.

20. Pawar A, Panwar NL. Experimental investigation on biochar from groundnut shell in a continuous production system. Biomass Convers Biorefinery; 2020.
DOI:10.1007/s13399-020-00675-4.

21. Muvhiiwa RF, Sempuga B, Hildebrandt D, Van Der Walt J. Study of the effects of temperature on syngas composition from pyrolysis of wood pellets using a nitrogen plasma torch reactor. J Anal Appl Pyrolysis. 2018;130:159–168.
DOI:10.1016/j.jaap.2018.01.014.

22. Ash N. Generation of electricity and heat from biomass: Technology options and potential pitfalls. In Proceedings of the Utility Week Africa; 2018.

23. Yue Y, Lin Q, Irfan M, Chen Q, Zhao X. Characteristics and potential values of bio-oil, syngas and biochar derived from Salsola collina Pall. in a fixed bed slow pyrolysis system. Bioresour Technol. 2016;220,378–383.
DOI:10.1016/j.biortech.2016.08.028.

24. Tröger N, Richter D, Stahl R. Effect of feedstock composition on product yields and energy recovery rates of fast pyrolysis products from different straw types. J Anal Appl Pyrolysis. 2013;100:158–165.
DOI:10.1016/j.jaap.2012.12.012.

25. Choi HS, Choi YS, Park HC. The influence of fast pyrolysis condition on biocrude-oil yield and homogeneity. Korean J Chem Eng. 2010;27:1164–1169.
DOI: 10.1007/s11814-010-0213-8.

26. Wang ZX, Dong T, Yuan LX, Kan T, Zhu XF, Torimoto Y et al. Characteristics of bio-oil-syngas and its utilization in Fischer-Tropsch synthesis. Energy and Fuels. 2007;21:2421–2432.
DOI: 10.1021/ef0700275.

27. Tinwala F, Mohanty P, Parmar S, Patel A, Pant KK. Intermediate pyrolysis of agro-industrial biomasses in bench-scale pyrolyser: Product yields and its characterization. Bioresour Technol. 2015; 188:258–264.
DOI: 10.1016/j.biortech.2015.02.006.

28. Gajera B, Panwar NL. Pyrolysis and kinetic behaviour of black gram straw using thermogravimetric analysis. Energy

sources, part A recover util environ eff. 2019;1–15.
DOI:10.1080/15567036.2019.1662138.

29. Ghani WAWAK, Mohd A, da Silva G, Bachmann RT, Taufiq-Yap YH, Rashid U, Al-Muhtaseb AH. Biochar production from waste rubber-wood-sawdust and its potential use in C sequestration: Chemical and physical characterization Ind Crops Prod. 2013;44:18–24.
DOI:10.1016/j.indcrop.2012.10.017.

30. Xu Y, Hu X, Li W, Shi Y. Preparation and characterization of bio-oil from biomass. In Progress in Biomass and Bioenergy Production. 2011;1–28.

31. Paul AS, Panwar NL, Salvi BL, Jain S, Sharma D. Experimental investigation on the production of bio-oil from wheat straw. Energy sources, part A recover. util. environ. eff. 2020;1–16.
DOI:10.1080/15567036.2020.1779416.

Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sdiarticle4.com/review-history/64545