ISSN: 0973-4929, Vol. 17, No. (**3**) 2022, Pg. 634-642

Current World Environment

www.cwejournal.org

Influence of Temperature on the Production of Biochar from Cotton and Castor Feed Stalk in a Pyrolysis Process

U. D. DOBARIYA*, D. K. GOJIYA, J. M. MAKAVANA, S. V. KELAIYA, G. A. GADHIYA, M. S. DULAWAT, K. G. VAJA and P. M. CHAUHAN

Department of Renewable Energy Engineering, College of Agricultural Engineering and Technology, Junagadh Agricultural University, Junagadh, Gujarat, India.

Abstract

Among the various applications of cotton and castor biomass, application of biochar to soil is gaining popularity due to increased crop productivity and CO_2 sequestration. The slow pyrolysis of cotton and castor stalk at 250-500°C was investigated in this study to characterize in terms of production of biochar, bio oil, pyrogases and its chemical properties by using batch type Pyrolyser. The biochar showed a general trend of decreasing biochar production and increasing bio oil, pyro gas production, $_{P}$H, and EC and along with increasing temperature, and CEC decreased with increasing temperature. Out of all the experiments levels the best quality of biochar was found at 500°C temperature and 180 minutes' residence time for the chopped cotton and castor biomass as feed stalk.

Article History

Received: 01 July 2022

Accepted: 16 November 2022

Keywords

Biomass;

Biochar;

Bio Oil;

Pyro Gas and Pyrolyser.

Introduction

Biomass plays an essential role in both energy and environmental problems as a sustainable energy source. Agricultural residues, forestry residues, municipal rubbish, and city products are examples of biomass that can be directly burned, gasified, or pyrolyzed to provide various forms of energy. Biomass is abundant, renewable, and clean, since it emits no carbon and contains low levels of sulphur, nitrogen, and metals.[1]

The residence time, methods of heating and types of pyrolysis process (slow, intermediate, and quick pyrolysis processes) of the pyrolytic material distinguish pyrolysis technologies.[21] Biochar is a fuel-grade charcoal generated from biomass through the pyrolysis process. Thermal degradation of lignocellulose biomass causes a significant loss of volatiles materials, at the end of the process carbon rich hard amorphous biochar is produced and that can be utilized as briquettes or a char-oil water slurry. Pyrolysis is divided into three types based on the operating conditions, traditional, rapid, and flash pyrolysis. The production of biochar varies 12-35 % depending on the temperature, rate of heating, residence time, size of biomass particle,

CONTACT U. D. Dobariya umesh.dobariya@gmail.com Department of Renewable Energy Engineering, College of Agricultural Engineering and Technology, Junagadh Agricultural University, Junagadh, Gujarat, India.

Doi: http://dx.doi.org/10.12944/CWE.17.3.12

and other factors.[10]. Physicochemical components like FC, VM, AC and high calorific value are also used to determine the quaity of biochar for industrial and residential use. Furthermore, the surface characteristics of biochar have an impact on its reactivity and combustion behavior.[26]

Biochar is known as a multi-functional carbonic material, due to it promising wide applications in different field, such as soil amendment, carbon sequestration, and the trapping of organic and inorganic compounds.[21] These applications differ depending on the physio- chemical and thermal degradation conditions, such as reactor system, rate of heating, retention time, and pyrolysis temperature. The pyrolysis temperature is one of these operating conditions that has a significant impact on the end quality and applicability of biochar. The application of biochar to soil which effect on soil physical parameters like porosity, structure & texture of soil and bulk density, all these parameters can be helpful for better plants growth. Biochar can also help to increase soil acidity, capacity for cation exchange (CEC), water holding capacity, and it also provide better condition for beneficial microflora.[20] Biochar produced from sludge can be used for the removing the pollutants from the water.[8] The groundnut shells was pyrolysed at 500°C temperature, 10 mL/min gas flow rate with a ten °C/min rate of heating by using a modified fluidized bed pyrolytic-reactor. It was found that under efficient operating conditions yield of biochar (19.5 wt.%), yield of pyro gas (17.7 wt.%) and yield of pyrolytic-oil (62.8 wt.%).[6]

The goal of this study is to valorization of castor and cotton biomass as feed stalks via pyrolysis process, because it is more reliable techniques to utilize surplus biomass. Selected biomass is available plenty in saurastra region of gujarat.

Experimental Details

Materials Preparation

Whole castor and cotton stalk was collected from the Oil seed research station, JAU, Junagadh. These raw materials were allowed to air dry before being processed into chopped stalks using a shredder machine powered by a 10 hp, 3 phase, and 1450 rpm electric motor.

Pyrolyser Setup

To make biochar from the chopped cotton and castor stalk, slow type small capacity biomass pyrolyser system with a capacity of 5 kg was used. A reactor, hand operated strirrer, electrical coil and glass wool as an insulation, temperature control unit, hopper, chiller, water pump, stand, and other components make up the pyrolyser system.

The biomass pyrolyser chamber is an airtight annular container, where biomass is pyrolyzed without the presence of oxygen. For agricultural residue, developed a batch type biomass pyrolyser as shown in fig.1.[17] The cylindrical reactor's diameter and height were 0.28 m and 0.86 m respectively. The hand operated stirring mechanism was furnished in the reactor to give 1-3 rotation at half an hour to the chopped biomass for uniform heating. The stirrerring system was fitted in to the reactor in such a manner that whole material may under goes the mild rotation. Electrical heaters were mounted on the reactor chamber's exterior surface wall to provide thermal energy to the biomass. Furthermore, for reducing heat loss to the environment, these electrical coils were insulated with 50 mm glass wool. The insulation material was covered with one-millimeter-thick aluminum sheet. For monitoring the temperature of the pyrolyser at the experimental temperature range, a PID unit (UTC 221p, Multisplan, India) was used to control rate of heating along with sensing the temperature. The electrical heaters provided in the reactor were connected to the controller and then electrical mains via MCB. The experimental temperature level of the reactor was set by setting the up-down switches provided on the controller. The temperature was read by thermos couple having measuring range from 0 – 1200 °C. One sensor was fitted at top of the chamber to measured the heat and it is joined with controller unit to display temperature. The chiller is placed in the set-up to condense the volatiles material to convert it into biooil. The volatiles were cooled by circulating the water from the annular space of the chiller with the help of electrical water pump.

Fig.1: Pyrolyser setup[17]

Characterization of Raw Biomass and its Biochars

The characterization of raw biomass and its biochar were carried out in terms of proximate anylysis, thermal properties and chemical properties. The ASTM E870-82[2] which was used for proximate analysis of biomass. For that, we determined the mc%, ac%, vm%, and fc% of raw biomass and its biochar.

Chemical properties of biomass and its biochar were determined as for pH, electrical conductivity (EC) and CEC by using Conductivity/pH measuring device (Cole-Parmer, Mumbai, Model, Oakton PC 2700) and summation method form by Cal Poly's laboratory of soil science was used to obtain the CEC of raw biomass and its biochar.[7,16,18]

CEC_{sum} = Ca +Mg + K +Na

Where,

Ca EXT. Ca in mmolc/ kg
Mg EXT. Mg in mmolc/kg
K EXT. K in mmolc/kg
Na EXT. Na in mmolc/kg

Biochar Production from Chopped Castor and Cotton Stalk

The most common pyrolysis product is biochar. The biochar mainly contains carbon, inorganic elements and mineral i.e ash, which varies depending on temperature and residence time. Because of its higher calorific value, biochar can be utilised as solid fuel. Recently it is also used as adsorbent. Beside biochar, other products include bio oil and pyrogas are byproduct of pyrolysis process. Carbon molecules and water constitute bio oil. Bio oil seems like dark brown liquid that is extremely sticky, dense, and made up of highly oxygenated molecules. The gas composed of non-condens gases like carbon monoxide, carbon dioxide, methane, and other trace elements.

The biochar production decreased with increase in temperature during thermal degradation, resulting in gradual increases productions of bio oil and gas yields for pyrolysis temperatures of 300–700 ^{0}C.[25] High quality charcoal was produced at a temperature of 400 °C from rice husk.[14]

Experimental Design

Using a batch type pyrolyser with a 5kg capacity, chopped castor and cotton stalk were pyrolyzed. The study parametrs and their levels examined are shown in Table 1. Twenty trials were excuted on the pyrolysis of chopped biomass and biochar, bio oil and pyro gas production were determined. The biochar obtained at 200°C can be considered as torrified biomass, so that in this study biochar production was evaluated at only 250°C temperature and 120 min residence time as torrified biomass.[17,18]

Table: 1 Experimental parameters of the study

Sr.No.	Parameters	No.oflevels	Value(s)
1	Biomass material	Two	Choppedcotton& castor biomass
2	Temperature,°C	Four	250, 300, 400, 500
3	Retention period,min	Three	60, 120, 180

Procedure of Experiment

The weighing of biomass was carried out before fed into the reactor chamber through the hopper. Inlet valve was opened then closed for making airtight condition inside the reactor. After the experiment, the pyrolyser was allowed to cool for room temperature for collecting the biochar and biooil. The biochar and biooil were collected from the outlet, which was fitted to bottom of the Pyrolyser and condenser respectively. The amount of biochar and bio oil by using cotton and castor stalk were measured as per method descried.[18,17 and19]

Biochar Production

Biochar production is the quantity of biochar composed at the end of each pyrolysis experiment. It was calculated by using below equation.

Biochar production (%) = (weight of charcaol)/(Initial weight of biomass) x 100

Bio Oil Production

Biooil production is the quantity of bio oil composed at the end of the experiment. It is calculated by using below equation.

Bio oil production (%) = (weight of bio oil)/(Initial weight of biomass) x 100

Pyrogas Production

By deducting the output of biochar and biooil from 100, the production of pyrogas is estimated.

Pyrogas production (%) = 100 − (Biochar production + Bio- oil production)

Results and Discussion

The results of the proximate analysis measured (%, d.b.) in terms of AC, VM , and FC, of raw biomass and its biochar obtained at different experimental levels in Table 2. The FC, VM and AC were found as 16.80; 16.58, 75.06; 76.62, and 6.60; 6.80 (%, d.b) respectively for cotton and castor stalk as presented in Tab. 2. Similar outcome detrmined in terms of FC, VM and AC % of 18.00, 77.04 and 4.96 (% d.b) respectively for chaffed cotton.[23]

The ash content of biochar was found in range from 6.85 to 15.95 and 6.93 to 16.76 at (250 ^{0}c, 120 min ; 500^{0}c, 180 min) temperature and residence time by using cotton and castor stalks respectively as shown in Table 2. Ash content of biochar increased with increased in temperature,[26] The similar trends was found as for different biomass material biochar ash content was increased with increased in temperature.[26] Perhaps cause of this phenomena as the rise in heat, volatile compounds eliminated, reducing weight of biomass, but inorganic portion are preserved in form of solid, thereby increasing the amount of ash.

The value of VM of biochar were ranged from 50.48 % to 75.80 % (d.b) and 51.85 % to 76.66 % (d.b) at (500 °C, 180 min, 250 °C, 120 min) temperature and residence time for cotton and castor stalk respectively as shown in Table 2. The similar trend was found as rise in temperature from 300 to 600°C for various biomass, the VM of their biochar decreased.[31] Pyrolysis tests on normal biomass were carried out in a fixed bed reactor at temperatures ranging from 300 to 350, 400, and 450°C.[3] This might be because the devolatilization reaction takes place when the pyrolysis temperature increases. Due to this, volatile organic molecules were lost, which reduced the amount of volatile matter.

The value of FC of biochar were ranged from 17.35% (d.b) to 33.57 % (d.b) and 16.41% (d.b) to 31.39 % (d.b) at (250°C, 120 min; 500 °C, 180min) temperature and residence time for cotton and castor stalk respectively as shown in table 2. Similar trends found in a study in which FC of different biomass increased as raise in temperature from 300 to 600°C.[31]

VM, FC and AC % for rice husk, rice straw, sugarcane bagasse and cotton stalk were reported as (70.70, 10.7, 18.60), (64.43, 20.37, 15.20), (86.15, 10.62, 3.28) and (96.07, 10.7, 6.93) % d.b. respectively.[15,16] Proximate parameters of different briquettes in terms of calorific value, AC, VM, moisture content and FC differ from 146-200KCal/g, 30.3-40.0%, 15.5-38.5%, 10.5-13.3% and 31.2-50.6% respectively,[418] Similarly, characteristics of raw chopped cotton determined in terms of density (34.92 kg/m^3), moisture (13.63%), VM (74.52%), AC (4.95%), FC (20.53%) and heating value (3827 cal/g) respectively.[28,18]

Table: 2 Proximate analysis raw biomass and it'sbiochar obtained at various temperature and retention time

Temp.(°C)	Retention time(min)	AC(%,d.b)		VM(%,d.b)		FC (%,d.b)	
		Cotton	Castor	Cotton	Castor	Cotton	Castor
Biomass	-	6.60	6.80	75.06	76.62	16.80	16.58
250*	120	6.85	6.93	75.80	76.66	17.35	16.41
300	60	7.25	7.03	73.87	75.88	18.88	17.09
	120	8.36	9.45	71.54	72.33	23.1	18.22
	180	9.05	9.89	69.98	69.98	20.97	20.13
400	60	10.23	10.92	65.55	67.55	24.22	21.53
	120	11.45	12.90	63.43	65.43	25.12	21.67
	180	12.10	13.78	60.12	62.12	27.78	24.10
500	60	13.35	14.88	56.78	58.78	29.87	26.34
	120	14.96	15.96	53.27	55.27	31.77	28.77
	180	15.95	16.76	50.48	51.85	33.57	31.39

*AC-Ash content, VM- Volatile matter, FC- Fixed carbon

Table: 3 pH, EC and CEC values at various temperature and retention period for chopped cotton stalk and its biochar

Temp.(°C)	Retention period (min)	PH		EC dS/m		CEC (cmol/ kg)	
		Cotton	Castor	Cotton	Castor	Cotton	Castor
Biomass	-	6.36	5.90	0.03	0.03	39.84	39.31
250	120	6.47	6.28	0.03	0.03	36.42	34.66
300	60	8.85	8.77	0.04	0.04	35.79	32.19
	120	8.38	8.32	0.05	0.05	34.33	30.99
	180	8.45	8.45	0.05	0.05	35.70	30.46
400	60	9.27	9.18	0.08	0.07	34.23	29.86
	120	9.56	9.47	0.09	0.09	33.10	29.03
	180	8.38	8.29	0.07	0.07	29.38	28.19
500	60	9.63	9.43	0.09	0.09	27.77	27.60
	120	9.82	9.78	0.08	0.08	26.23	26.09
	180	9.58	9.52	0.10	0.10	25.03	25.11

In Tab. 3, it is shown how the pH, EC, and CEC values of cotton and castor biomass and its biochar changed with respect to temperature and residence time. However, no major change or behaviour patterns was noted as residence time increased. Rising temperatures during the pyrolysis process had the major effect on biochar pH, shows that rising temperatures might be induced more volatilization, break down of surface oxygen groups, and dehydroxylation.[16,17] similar result of pH value of biochar varies from of 5.88 at 200°C with a 60-minute retention time to a 9.86 at 500°C with a 240-minute residence time.[18] The accumulation of non-pyrolyzed inorganic elements in biochar may be the cause of dramatic pH increases at high temperatures.[17,18]

EC and CEC value of the chopped cotton and castor biomass were determined as (0.03, 0.03) dS/m and (39.84,39.31) cmol/kg respectively. The EC and CEC value of biochar obtained from pyrolysis of selected biomass was increased in the range of (0.03-0.10) dS/m and decreased in the range (39.84-25.03, 39.31-25.11) cmol/kg with increased in temperature respectively. The EC and CEC value of biochar increased and decresed respectively with increase in temperature.[16,18,19 and 29]

The biochar production were ranged from a minimum of 30.25 % to 51.04 % and 30.21 % to 50.56 % at (500 °C, 180 min, 250 °C, 120 min) temperature and residence time for cotton and castor stalk respectively as shown in Table 4.

Table: 4 Percentage of biochar andbio oil production at various temperature and retention period

Temp.(˚C)	Retention period(min)	Biochar production(%)		Bio oil production(%)		pyro-gas production(%)	
		Cotton	Castor	Cotton	Castor	Cotton	Castor
250*	120	51.04	50.56	12.2	12.0	36.8	37.4
300	60	36.36	41.20	12.4	12.5	51.2	46.3
	120	43.63	42.00	13.3	13.3	43.0	44.7
	180	45.45	42.40	13.7	13.7	59.2	43.9
400	60	36.40	39.25	14.7	14.5	45.8	46.3
	120	39.5	36.20	15.3	15.1	48.3	48.7
	180	35.75	35.75	15.8	15.6	48.4	48.6
500	60	35.5	34.34	17.2	17.0	47.3	48.6
	120	34.0	33.23	17.5	17.3	48.5	49.5
	180	30.25	30.21	18.0	17.8	51.7	51.9

*Biocharproductionis considered as torriefied biomass

Biochar production decreased with increase in heating rate. The experimental data consistence with data observed.[17,18] They observed that as the pyrolysis temperature and residence time elevated from 200°C to 500°C and 60 min to 240 min biochar production was decline from 70.2% to 34.0% for cotton biomass. The biochar production of cotton and castor residue decline from 23.5 to 16.7 % and 24.4 to 17.1 %, respectively as the temp. elevated from 350 to 500°C.[29,30] The biochar production of bagasse decreased from 61.75 to 22.19% as the temperature elevated from 400 to 600°C.[11] According to as the temperature elevated in range from 400 to 650°C, The biochar production from rice husk decreased from 68.36 to 13.45 %.[9] As a result of the loss of volatile organic compounds, biochar production decreased. However, based on visual observation, the biochar production obtained at 25°C may be considered torrefied biomass rather than biochar.

The production of bio oil was ranged from 12.2 % to 18.00 % and 12% to 17.8% at (250 °C, 120 min, 500°C, 180 min) temperature and residence time for cotton and castor stalk respectively as shown in table 4. The production of bio oil was increased from 10.2 % to 19.0% from cotton stalk as the pyrolysis temperature and residence time elevated from 200°C to 500°C and 60 min to 240 min.[16,17] It was discovered that the production of bio oil increases as the temperature rises, and that residence time has less of an impact on the production of bio oil than does the temperature.

The production of pyro gas was ranged from a 36.8 % to 51.7 % and 37.4 % to 51.9 % at (250 °C, 120 min, 500°C, 180 min) temperature and residence time for cotton and castor stalk respectively as shown in table 4. The production of pyro gas was increased from 19.6 % to 47.8% for cotton stalk as the pyrolysis temperature and residence time increased from 200°C to 500°C and 60 min to 240 min.[16,17,18] It was discovered that an increase in temperature and residence time led to an increase in pyro gas output. However, compared to residency duration, the impact of temperature was stronger.

Conclusions

- Proximate parameters for cotton and castor raw biomass in terms percentage of AC, VM, and FC were obtained as, 6.60, 75.06, 16.80 and 6.80, 76.62, 16.58 (%, d.b) respectively. The min. and max. value of biochar obtained at different experimental run were discovered as 6.85 to 15.95 and 6.93 to 16.76, 50.48 to 75.80 and 51.85 to 76.66; 17.35 to 33.57 and 16.41 to 31.39 respectively.
- The chemical properties of cotton and castor raw biomass in terms of pH and EC were discovered as 6.36 and 0.03 dS/m, 5.90 and 0.03 dS/m respectively. The min and max value of chemical properties of biochar obtained at different experiment run were found as 6.47 to 9.58 and 0.03 to 0.10 dS/m, 6.28 to 9.52 and 0.03 to 0.10 dS/m respectively.
- The min. and max. value of biochar production at different experiment run were discovered as 30.25 % and 51.04 %; 30.25 % and 50.56 % for cotton and castor biomass respectively.
- The mini. and maxi. percentages of bio oil production were discovered to be 12.2% and 18.0% for cotton biomass and 12.0% and 17.8% for castor biomass, respectively.

Acknowledgement

This study supported by the authorities of Department of Renewable Energy Engineering, CAET, JAU, Junagadh (Gujarat), India.

Funding

There is funding from Junagadh Agricultural University, Junagadh, Gujarat (Grant No. BH 12567).

Conflict of Interest

There is no conflict of interest.

References

1. Anonymous (2015) World Energy Issues Monitor. Available at https://www.worldenergy.org/publications/2015/world energy issues monitor-2015. Accessed 12 June 2017
2. ASTM E870-82 (2013) Standard Test Methods for Analysis of Wood Fuels. In: ASTM International, West Conshohocken www. astm.org
3. Biswas, B., Pandey, N., Bisht, Y., Singh, R., Kumar, J., & Bhaskar, T. (2017). Pyrolysis of agricultural biomass residues: Comparative study of corn cob, wheat straw, rice straw and rice husk. *Bioresource technology*, 237, 57-63.
4. Dass, P. M., Nkafamiya, I. I., Thliza, B. A., & Joseph, J. I. (2019). Proximate analysis of biomass and cotton stalk charcoal briquettes produced from Biu, Nganzai and Zabarmari in Borno State Using Locally Fabricated Briquetting Machine. International Journal of Progressive Science and Technologies, 16(2), 83-91.
5. Dobariya, U. D., & Sarsavadiya, P. N. (2016). Experimental Investigation and Techno Economic Analysis of Open Core Gasifier by Using Chopped Cotton Stalk as Feedstock. Current World Environment, 11(1), 312.
6. Hai, A., Bharath, G., Daud, M., Rambabu, K., Ali, I., Hasan, S. W. & Banat, F. (2021).

Valorization of groundnut shell via pyrolysis: Product distribution, thermodynamic analysis, kinetic estimation, and artificial neural network modeling. *Chemosphere,* 283, 131162.

7. Herbert L, Hosek I, Kripalani R (2012). The characterization and comparison of biochar produced from a decentralized reactor using forced air and natural draft pyrolysis. Dissertation, California polytechnic state university, San Luis Obispo materials engineering department, pp 0–36.
8. Ihsanullah, I., Khan, M. T., Zubair, M., Bilal, M., & Sajid, M. (2022). Removal of pharmaceuticals from water using sewage sludge-derived biochar: A review. Chemosphere, 289, 133196.
9. Islam, Muhammad & Jamal, M & Sujan, S.M.A. & Ismail, Mohammad & Miah, Md & Saha, M. (2011). Bio oil from pyrolysis of rice husk. Journal of Biofuels.2 (1): 1-7.
10. Jahiru MI, RasulMG, Chowdhury AA, Ashwath N (2012). Biofuels production through biomass pyrolysis. Energies 5(12):4952–5001
11. Jamal, M & Islam, Muhammad & Ismail, Mohammad & Saha, Manoranjan & Miah, Md & kumar Banik, Sujit. (2011). Bio oil from pyrolysis of Bagasse. *DUJASE* vol. 2(1): 17-20.
12. Jindo, Keiji, Hideki Mizumoto, Yoshito Sawada, Miguel A. Sanchez-Monedero, and Tomonori Sonoki., (2014). "Physical and chemical characterization of biochars derived from different agricultural residues." *Biogeosciences* 11, no. 23: 6613-6621.
13. Kumar S,Masto RE, Ram LC, Sarkar P, George J, Selvi VA(2013). Biochar preparation from Parthenium hysterophorus and its potential use in soil application. Ecol Eng 55:67–72
14. Maiti S, Dey S, Purakayastha S, Ghosh B (2006). Physical and thermochemical characterization of rice husk char as a potential biomass energy source. *Bioresour Technol* 97(16):2065–2070
15. Makavana, J. M., Agravat, V. V., Balas, P. R., Makwana, P. J., & Vyas, V. G. (2018). Engineering properties of various agricultural residue. *Int J Curr Microbiol App. Sci,* 7(6), 2362-2367.
16. Makavana, J. M., Sarsavadia, P. N., & Chauhan, P. M. (2020). Effect of Pyrolysis Temperature and Residence Time on Biochar Obtained from Pyrolysis of Chopped Cotton Stalk. *International Research Journal of Pure and Applied Chemistry,* 21(13), 10-28.
17. Makavana, J. M., Kalaiya, S. V., Dulawat, M. S., Sarsavadiya, P. N., & Chauhan, P. M. (2020). Development and performance evaluation of batch type biomass pyrolyser for agricultural residue. *Biomass Conversion and Biorefinery,* 1-8.
18. Makavana, J. M., Sarsavadia, P. N., & Chauhan, P. M. (2020). Effect of Pyrolysis Temperature and Residence Time on Biochar Obtained from Pyrolysis of Chopped Cotton Stalk. *International Research Journal of Pure and Applied Chemistry,* 21(13), 10-28.
19. Makavana, J. M., Sarsavadia, P. N., Chauhan, P. M., Dulawat, M. S., Dobariya, U. D., & Yadav, R. (2021). A Review Pyrolysis: Different Agricultural Residues and Their Biochar Characteristics.
20. McHenry MP (2009) Agricultural Biochar production, renewable energy generation and farm carbon sequestration in Western Australia: certainty, uncertainty and risk. Agric Ecosyst Environ 129:1–7
21. Meyer S, Glaser B, Quicker P (2011). Technical, economical, and climate-related aspects of biochar production technologies: a literature review. *Environ Sci Technol* 45(22):9473–9483
22. Mohan, D., Pittman Jr, C. U., & Steele, P. H. (2006). Pyrolysis of wood/biomass for bio oil: a critical review. *Energy & fuels,* 20(3), 848-889.
23. Nakason, K., Khemthong, P., Kraithong, W., Chukaew, P., Panyapinyopol, B., Kitkaew, D., & Pavasant, P. (2021). Upgrading properties of biochar fuel derived from cassava rhizome via torrefaction: Effect of sweeping gas atmospheres and its economic feasibility. *Case Studies in Thermal Engineering*, 23, 100823.
24. Ortiz, L. R., Torres, E., Zalazar, D., Zhang, H., Rodriguez, R., & Mazza, G. (2020). Influence of pyrolysis temperature and bio-waste composition on biochar characteristics. *Renewable Energy,* 155, 837-847.
25. Park, J., Lee, Y., Ryu, C., & Park, Y. K. (2014). Slow pyrolysis of rice straw: analysis of products properties, carbon and energy

yields. *Bioresource technology,* 155, 63-70.

26. Ronsse, F., Van Hecke, S., Dickinson, D., & Prins, W. (2013). Production and characterization of slow pyrolysis biochar: influence of feedstock type and pyrolysis conditions. *Gcb Bioenergy,* 5(2), 104-115.
27. Titiladunayo, I. F., McDonald, A. G., & Fapetu, O. P. (2012). Effect of temperature on biochar product yield from selected lignocellulosic biomass in a pyrolysis process. *Waste and Biomass Valorization,* 3(3), 311-318.
28. Umesh, D., Sarsavadiya, P., Vaja, K., & Mahadeo, K. (2015). Physiochemical properties of cotton stalk biomass from aricultural residues. *Current World Environment,* 10(1), 343.
29. Venkatesh, G., Srinivarao, Ch., Venkateswarlu, B., Gopinath, K.A., Prasad, J.N.V.S., Raddy, Sanjeeva, B., Sasikala, Ch., Rao, G. R. and Ramesh Babu p. v., (2013a). Operational Process for Biochar Preparation from Castor Bean Stalk and its Characterization for Soil Application. *Central Research Institute for Dryland Agriculture, Hyderabad-500059, Andhra Pradesh. Indian J. dryland Agric. Res. & Dev.*28 (2): 21-26.
30. Venkatesh, G., Srinivasarao, C., Venkateswarlu, B., Gopinath, K. A., Prasad, J. V. N. S., Reddy, B. S., & Babu, P. V. (2013). Operational process for biochar preparation from castor bean stalk and its characterization for soil application. *Indian Journal of Dryland Agricultural Research and Development, 28(2), 21-26.*
31. Yang, H., & Sheng, K. (2012). Characterization of biochar properties affected by different pyrolysis temperatures using visible-near-infrared spectroscopy. *International Scholarly Research Notices,* 2012.