Heliyon 9 (2023) e16864

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Conversion of cud and paper waste to biochar using slow pyrolysis process and effects of parameters

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A R T I C L E I N F O

Keywords:
Char production
The effect of airflow rate on char yield
The effect of heating rate on char yield

A B S T R A C T

A series of laboratory studies were undertaken in Gondar to explore the effects of temperature, air mass flow rate, heating rate, and residence duration on cud and waste paper char yields in slow pyrolysis. Cud and waste paper were burned at a low pyrolysis temperature to generate biochar (167 °C). The rate of decomposition depends on the feedstock and the process conditions. The biochar yield is mostly governed by the applied regulated temperature and airflow rate, according to the data. During the experiment, the main airflow rate delays the pyrolysis process.

The temperature rises when both the primary and secondary air inlets open at the same time, resulting in lesser biochar output. The experiment was carried out at a slow pyrolysis temperature of 167 °C, with 15% biomass moisture, 60% humidity, and a 0.35–1.5 kg/s air mass flow rate. At this temperature, 30 kg of feedstock, cup, and paper in the reactor generate 10 kg–23kg and 10–20 kg of biochar, respectively, at a 0.35 m/s airflow rate. As the airflow rate increases within the restricted values, a temperature gradient appears and tends to increase. However, as the pyrolysis temperature and airflow rate rise, the biochar yield decreases.

1. Introduction

Cud residual wastes found in a slaughterhouse or meat industry is the Couse of groundwater pollution. The Converting of the waste to char for use as a soil fertilizer application is an indirectways to mitigate pollution. A gradual pyrolysis process produce a char that restores and maintains the nutrients in the soil [30]. Pyrolysis is one of the most effective and efficient methods for producing char from energy [9]. It is a thermochemical process in which biomass is thermally decomposed into its chemical constituents in the presence of inert or very low stoichiometry oxygen. It is the conventional type of pyrolysis which is characterized by a slow heating rate and long residence time [28]. In the slow Pyrolysis process, a limited or low-temperature thermal conversion process was embroiled to convert waste into char [21]. To minimize the high-temperature impact on the product, the pyrolysis process was carried out under the temperatures of 350 °C. Usually, biomass decomposed under an oxygen-limited process [4,8] The degree of biomass decomposition depends on the feedstock used and process temperature [17,26]. In the slow pyrolysis process, biomass moisture removes, and the

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https://doi.org/10.1016/j.heliyon.2023.e16864
Received 21 April 2022; Received in revised form 24 April 2023; Accepted 31 May 2023
Available online 6 June 2023
2405-8440/

cellulose and lignin are broken down from long to short carbon structures [13]. The thermal bonds are cracked (lysis) under the action of heat (pyro) [2] and carbonaceous material biochar is a typical product during the process [1,11,29]. Biochar's acceptance as a beneficial soil amendment and carbon sink around the world would provide the pyrolysis process economic value and encourage increased waste usage [14]. Pyrolysis is a more cost-effective way to turn waste paper to char than recycling it into paper. Depending on the operating conditions used, Pyrolysis processes are classified as fast pyrolysis and slow pyrolysis [18]. The term "slow pyrolysis" is arbitrarily used with no particular definition with reference tied to the holding period or the rate of heating [7]. The slow pyrolysis condition typically employs heating rates of ($1 \leq 350$ °C minute-1) in the absence of oxygen, and long char residence times (hours to days) [25]. However, the pyrolysis parameters: air flow rate, temperature, humidity, and pressure can be varied to change the relative quantities and quality of the resulting products [6,25]. Biochar can be produced from different waste materials [27]. In this study, it was produced from waste animal cud and paper. The carbon-rich biochar can be used in varying applications such as carbon sequestration, soil conditioning, and filtration of pollutants from aqueous and gas media [24]. The pyrolysis process was affected by temperature, moisture content, particle size, and biomass physical properties [19]. The pyrolysis condition was determined the production of char yields, and the properties it has [10]. Specifically, heating rate and temperature were the most influential pyrolysis parameters affecting the amount of char product [16,19]. The primary goal of this study is to see how slow pyrolysis reactor factors like airflow rate, temperature, particle size, heating rate, and flue gas circulation affect biochar yield. A lot of work has gone into evaluating pyrolysis conditions in order to identify the best biochar production

2. Materials and methods

2.1. Feedstock preparation

The paper was manufactured in a briquette shape and dried to below 15% moisture content before heating. Biochar is produced using two separate feedstocks: animal cud and waste paper. In Ethiopia, there are both prospective and accessible resources that could be used as an input for biochar production. Animal cud discovered at slaughterhouses and in the countryside was used, as was waste paper obtained from the University and other sector offices. The cud was originally obtained from a slaughterhouse in downtown Gondar (12,044′59.99″ N, 37° 00′ 0.00″ E), Ethiopia, then sun-dried to a moisture content of 15%. The waste paper was first gathered in the workplace as a sheet and then made as a mold briquette with water and dried using the same cud technique. Fig. 1 depicts molded paper, while Fig. 2 depicts cud biomass drying. The distribution and removal of moisture content is influenced by the environment's humidity, temperature, and pressure, as well as accumulated procedures. The feedstock creates precipitation and gains moisture as the humidity rises at night. To avoid this, the first moisture removal or drying biomass is stored. Humidity varies throughout the day, especially in the morning, middle, and evening. The feedstock is dried to a moisture level of less than 15% with no water vapor. The flue gas cycle eliminates all leftover moisture from the feedstock and converts it to char. The reactor was manually loaded with the prepared biomass. The rate of loading is determined by availability, weather forecasts, and the pyrolysis process. Mold paper takes 13 days to dry below 15% moisture level, while cud biomass dries to the same moisture percentage in 5 days.

To prepare a paper in the form of briquette mold improves the carbon and heat-storing and water holding capacity of the char. As char Kruger studied (2020), biochar production via pyrolysis still provides a large C sequestration potential and heating value even after emissions from process energy are subtracted, which represents a counterbalance of about 2.93 MT CO_2 per MT biochar applied to the soil. (MT = metric, ton = 1000 kg or 2200 l b), and can substitute for agricultural lime by raising soil pH. This can make biochar profitable when trading prices per metric ton of CO_2 $16.44 for smaller mobile and $3.39 for transportable facilities [32].

2.93 MT CO_2 per MT biochar is offset by the difference between the sum of input, process, biomass, and carbon sequestration energy and the sum of all release gas energy (SO_2, CO, NO_2, Ar, CO_2, etc …).

2.2. Pyrolysis system design

A high-temperature core of the pyrolysis process, a reactor, was required to carry out the pyrolysis experiment. At a temperature of

Fig. 1. Preparation of a paper mold.

Fig. 2. Dried form of animal cud.

167 °C, 30 kg of feedstock with a moisture content of less than 15% can be pyrolyzed and transformed into char every run in the reactor. The pyrolysis system described in (Fig. 3) comprises of a secondary air inlet and an internal pipe that was extended up to the bottom of a reactor. To form char, the dense collected cud biomass necessitates a secondary air mass flow rate. The air from the surroundings enters the reactor through the intake at a mass flow rate of 0.35 kg/s. The produced biochar was physically a black carbon material from the decomposition of biomass organic matter in a low- or zero-oxygen environment (pyrolysis) useful for soil amendment, heat generation, and other benefits [3,22]. Process temperature impacted the amount of biochar generated and its properties. The secondary and primary airflow rates via the inlets were controlled to maintain the slow pyrolysis temperature range.

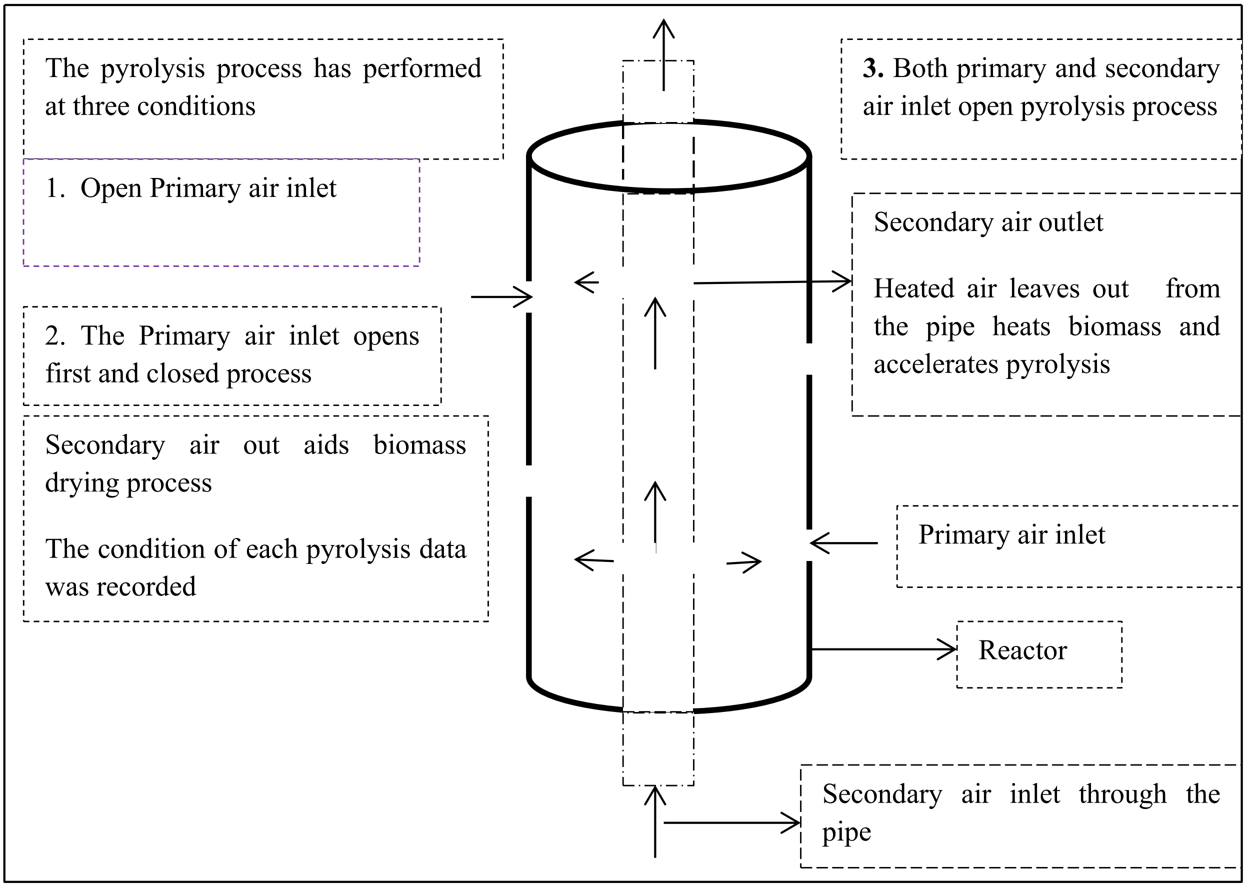

Fig. 3. Schematic diagrams of the system.

The amount of biochar produced is determined by the reactor's airflow rate and temperature. Intervals of temperature, feedstock particle size, airflow rate, and heating rate in the pyrolysis process were examined in the system. The roasting of biomass and the conversion process are aided by transferring heat through biomass in the reactor. Small heating rates at the start of the pyrolysis process guaranteed that the pyrolyzing biomass removed moisture, reduced air flow into the reactor, and kept the temperature below the slow pyrolysis temperature. The temperature at which biochar is formed rises as the airflow rate in the process rises. The pyrolysis temperature rises as the air-flow rate increases, and the biochar is exposed to a greater temperature, yielding less biochar. The temperature in the reactor is controlled by controlling the air flow rate through the inlet. The biochar is completely converted into ash due to the high temperature.

2.3. Design of pyrolysis experiment

A 1 m long stainless steel reactor was used in the slow pyrolysis arrangement. Before being placed into the reactor for the process, the dry feedstock was measured using a digital balance. An infrared thermometer was used to determine the temperature of the starting environment. An external source of energy hatch fire was used to begin or ignite manually supplied feedstocks into the pyrolysis reactor. The pyrolysis process temperature change in the reactor was begun to record after 20 min. In the reactor, the maximum temperature (167 °C) was measured. Because of the primary and secondary air inlet apertures (shown in Fig. 4), the process temperature changed. Different pyrolysis experiments were done and repeated at various temperatures during biochar synthesis in the case of both waste paper and cud feedstock to determine the temperature variation in the reactor. The temperature was measured at the same air mass flow rate (0.35 kg/s) and moisture content as before (15%). The amount of char yield is determined by the weight of the biochar obtained in comparison to the initial feedstock. Pyrolysis conditions must be carefully monitored in order to produce high-quality biochar. During the pyrolysis process, the most essential factors to regulate were the reactor temperature and airflow rate. Pyrolysis can be controlled in two ways: (1) moist biomass should be provided to reduce the high temperature produced in the reactor; (2) both the primary and secondary air inlets should be closed, making the system totally non-oxygen process. Even when the whole air intake ports are sealed, the chimney must stay open until the flue gas in the system has stopped. This quickly closes, preventing any incoming air from the outside and limiting the amount of high-temperature flue gas in the system.

For biomass with a long length and stem, size consideration is recommended. However, to improve pyrolysis, densification is contemplated and mold is made.

2.4. Air mass flow rate calculation

During the experiment, the air was supplied to the pyrolysis reactor through the inlets at a controlled rate. All air inlets have the same cross-sectional area and which determines the flow rate of air into the reactor. The ideal gas law relation was considered to

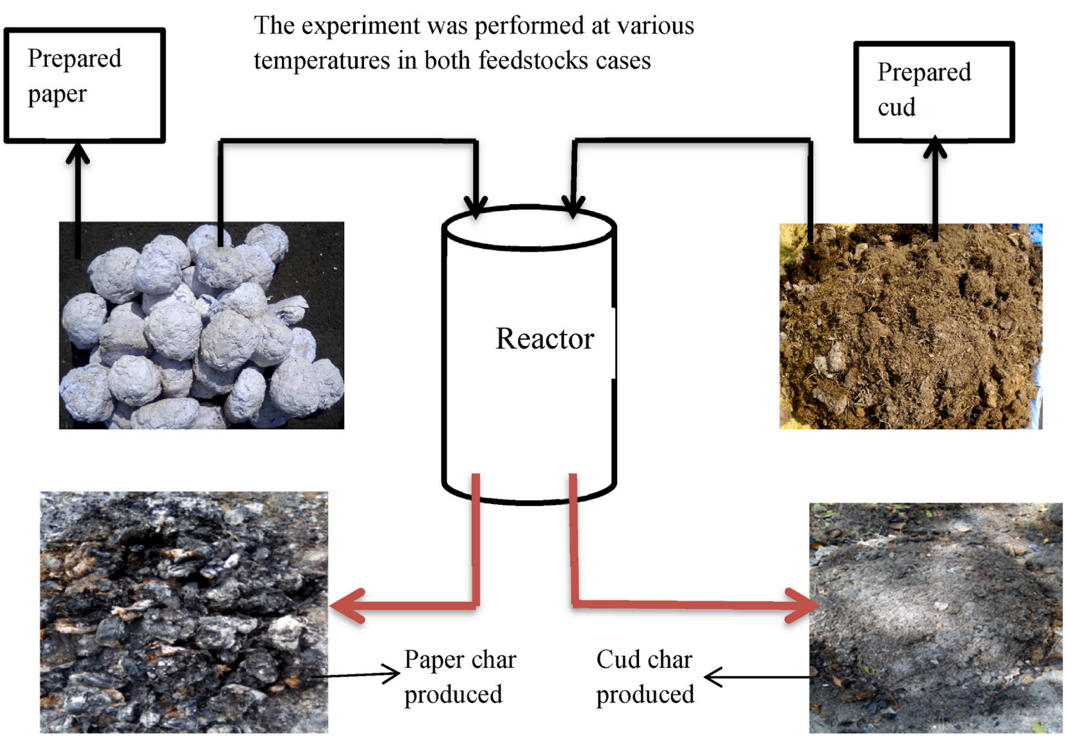

Fig. 4. Schematic diagrams of Conversion techniques of biomass to the char.

calculate the flow rate of air into the reactor. Air mass flow rate was an independent variable and an ideal substitute in this work as its value remains constant through the inlet [31]. The airflow rate was often better to expressin volumetric terms (Eq. (1)) [27].

$$\dot{m}_a = \frac{P\dot{V}}{RT}\ \mathrm{kg}\Big/\mathrm{s} \tag{1}$$

Where P = atmospheric pressure (1 atm).

$\dot{V}$ = volumetric flow rate (m^3/s)
R = gas constant (kJ/kg.k)
T = temperature (k)

Based on the flow situation, the volumetric flow rate can be expressed by.

$\dot{V}$ = velocity × flow area = C $\times \frac{\pi d^2}{4}\ m^3/s$
Where C velocity of air in m/s (0.35 m/s)

Before the experiment, the starting parameters (Table 1) are measured and energy was temporarily generated by exothermic combustion reactions. However, after oxygen was limited, pyrolysis and endothermic reduction reaction were dominated. Correspondingly, the mass reduction rate of biomass (feedstock) particles is closely related to the gaseous species concentration and the temperature distribution profile inside the reactor. In the natural convection region, there is a fast mass loss for biomass particles since volatiles are released by pyrolysis reactions. In the mixed convection region, which is near the air inlet, the heterogeneous reactions between carbon and gaseous species occur quickly leading to a higher temperature and higher oxygen concentration. In addition, it was noted that there was a similar trend for the particle mass change across the different ER conditions and the particle mass decreased with the increase of ER [12].

3. Result and discussion

3.1. Effects of pyrolysis operating parameters on biochar yield

During pyrolysis, temperature, process time, airflow rate, and heating rate all have an impact on biochar production. The quality of the pyrolysis products as well as the char yield is influenced by these operating parameters. The goal of pyrolysis is usually to maximize product output, so it's crucial to talk about how these process variables affect biochar synthesis [1].

To prevent carbon pollution, biochar is made by a slow pyrolysis method [10]. and is efficient to convert biochar carbon into a stable form. During pyrolysis, animal cud was burnt with very little oxygen. It produces very few polluting smokes or gases while it burns. The chemical composition varies depending on the feedstock and processing methods employed. The pyrolysis process, temperature, and ambient variables all influence the carbonization and stability of biochar [15]. During the experiment, alter the pyrolysis time, Figs. 5 and 6 shows the resulting char product of paper and cud.

At different pyrolysis temperatures of 167 °C, biochar was made from the two feedstocks. Thirty kilograms of each feedstock were pyrolyzed per run, providing 10–23 kg of biochar from animal cud and 10–21 kg of biochar from paper. The pyrolysis temperature determines how much biochar is produced from each source. The lower the reactor temperature, the less biochar is produced. Cud feedstock collects tightly in biomass, reducing temperature dispersion and increasing char.

3.2. Effects of operating parameters

3.2.1. Effects of air flow rate

The quality, characteristics, composition of the biochar products, and carbon sequestration ability were influenced by pyrolysis parameters [23]. The airflow rate through the primary air inlet was heated biomass and removed the moisture it contains. The airflow rate through the secondary air inlet can further increase the temperature in the reactor which determines the quantity of biochar produced. The more the airflow rate, the temperature reached its peak value and the less biochar was obtained. This is because the higher airflow rate promotes the exothermic combustion reactions and more reaction heat was generated and hence the temperature inside the reactor increased. The amount of biochar yield also depends on the moisture contents of feedstock contain and the airflow

Table 1
Air flow rate and equivalence ratio (ER) calculating data.

Parameters	Values	parameter	Values
Pressure	1 atm (1.01325 bar)	diameter of inlets	50 mm
Average temperature	295 K	gas constant (R)	8.314 kJ/kg.k
Average velocity of air	0.35 m/s	Mass of feedstock	30kg/run
Density of air	1.125 kg/m^3	Mass of biochar produced	19 kg

Fig. 5. Waste paper biochar product.

Fig. 6. Animal cud biochar at different temperature.

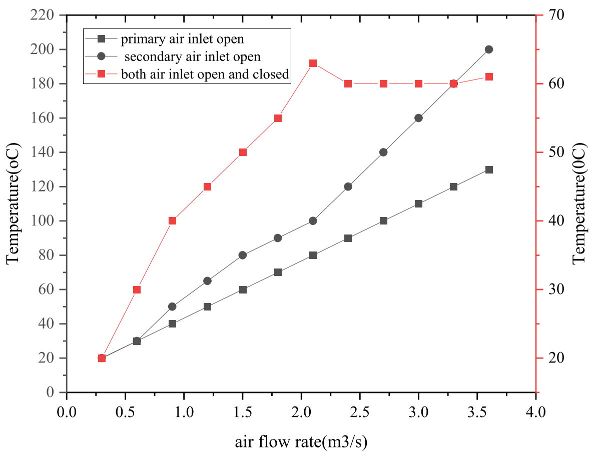

Fig. 7. Effects of airflow rate and temperature on biochar yield.

rate to the reactor. During the experiment, the primary airflow rate makes the process a slower pyrolysis process and provides more biochar yield than the secondary air flow rate process. Both primary and secondary air inlet opening at the same time process gives less biochar and more ash product. In the waste paper feedstock char production process, the black ink product was observed on the pan of the reactor by secondary air inlet hole opening practice. However, the primary and secondary air inlet hole closed process circulates the flue gas more times and increases the temperature of biochar inside the reactor. The experiment was conducted with pyrolysis temperature (75, 85, 105, 125, 132, 148,155 and 167 °C), 15% moisture, an airflow rate of 0.35, 0.6, 0.92, 1.5, 1.75, 2.5, 2.75, and 3 mˆ3/s respectively. The higher the airflow rate into the reactor, the higher the temperature and the lower the biomass yields in the process. In the reactor produces 11 kg–25 kg of biochar yield was obtained from 30 kg of feedstock. The result depends on the feedstock types and processes. The effect of air flow rate on the char yield was clearly shown in Fig. 7.

Temperature data was recorded at the end of the chimney at various intervals throughout the heating operation to manage the temperature. The reactor's pyrolysis temperature is cost-effective, and it may be simply constructed by farmers using locally available materials and biomass. To increase biochar formation, both the primary and secondary air input holes should be initially opened and closed at the same time when cud biomass is pyrolyzed. Different reactions may occur, but it is difficult to evaluate their contribution to the carbonization process without conducting experiments. This is frequently determined indirectly by estimating the system's energy and mass balance. Biochar's stability, on the other hand, varies depending on the type of biomass, the pyrolysis method, and the surrounding environment.

3.3. Residence time and biochar yield

Cud feedstock is being dense in accumulation which may create difficulties in the transfer of heat during the pyrolysis process and to provide more biochar yield. Since low temperature associated with long residence time is required for high biochar production. Increasing the vapor residence time helps the biomass constituents to pyrolyze and remove the moisture by taking sufficient time during the process.

Residence time affects not only biochar yield (Fig. 8) but also biochar quality and features by stimulating the formation of micro and macro-pores. An increase in charcoal output has been reported with long residence times.

3.4. Effect of heating rate

Heating rate is significant in biomass pyrolysis because the rate of change of heat affects the nature and composition of the end product to some extent. The potential of secondary biomass pyrolysis reaction can be reduced when the heating rate is modest. A modest heating rate also prevents thermal cracking of the biomass, resulting in a higher biochar production. However, a high heating rate promotes biomass fragmentation and increases gaseous and liquid yield, limiting biomass formation. The roasting of biomass is facilitated by heat transfer through biomass in the reactor. The first 20 min of low heating rate measurement revealed that the feedstock needed more heat to evaporate the moisture. The heating rate in the reactor was changed dependent on the airflow rate, as indicated in Table 2. The amount of biochar produced and its characteristics are determined by the heating rate. When both primary and secondary air inlets were opened, the maximum heating rate (1.550c/min) was achieved. Further increases in heating rate have an impact on char production because the process becomes fast pyrolysis and transforms biomass into oil at a high heating rate.

A high heating rate raises the temperature (Table 2), causing gaseous and liquid production. Slow pyrolysis, on the other hand, requires a lower temperature and a longer residence time to produce char. The charred quality and reduction of moisture content below 10% are also determined by the heating rate distribution through the reactor. A portion of the energy released during biomass combustion at the ignition point is frequently used to heat the pyrolysis feedstock. To produce higher biochar yield, the airflow rate

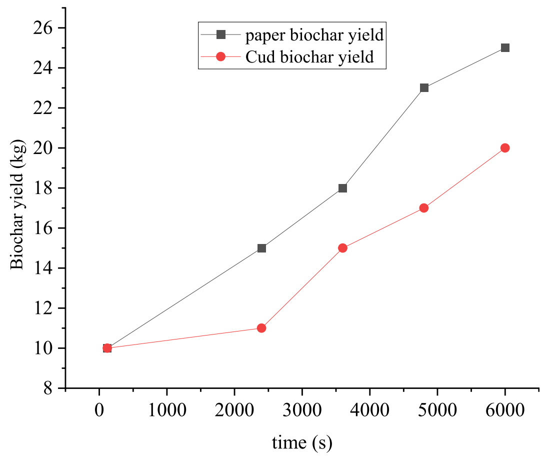

Fig. 8. Heat distributions through feedstock during the biochar production process.

Table 2
Experimental results of heating rate during paper and cud biochar production.

Heating rate (^{0}c/min) during waste paper biochar production			
Primary air inlet open	Secondary air inlet open	Both inlets closed	Both inlets open
0.6	0.75	1.2	1.7
1.25	1.4	0.3	1.15
0.6	0.5	0.6	1.05
0.5	0.7	0.75	1.55
Heating rate (^{0}c/min) during cud biochar production			
0.3	0.75	0.15	0.7
0.5	0.85	0.25	0.95
0.45	0.35	0.35	0.75
0.95	0.9	0.9	1.45

should be greatly reduced after the biomass has been dried by heating rate.

3.5. Effect of temperature on biochar yield

During the pyrolysis process, the heat generated by the torch on the biomass was transferred to the biomass's bottom sections. Biochar is produced first by the ignition side of biomass heat. However, the side farthest from the starting point dries out until the flame reaches it, yielding less biochar. The charcoal roasting process in the reactor is affected by temperature and time. Fig. 9 shows the temperature and biochar yield counter graphs for air flow rates of 0.35, 0.65, 0.95, and 1.25 kg/s. Temperature trends grow as the airflow rate increases within the specified values during pyrolysis, as can be shown. However, as the pyrolysis temperature and airflow rate rise, the biochar yield decreases. This results in a non-uniform pyrolysis profile, with the bottom of the feedstock pyrolyzing last. Because of the particle's structural evolution and heat transport conditions, several heating zones occur inside the particle. The regions with the highest heating rates were near the reactor's surface, where the biomass ignites first and biochar formed quickly, with a short residence period, and those particles that do not decompose produce more biochar. As increasing the temperature in pyrolysis reduces the biochar output (Fig. 9).

As can be observed, when the airflow rate is high, the temperature is high, but the biochar yield is low. At high temperatures, energy exchange is high in the reactor. At the top of the biomass, the pyrolysis experiment was carried out at atmospheric pressure and vacuum. Conducting under atmospheric pressure is straightforward and cost-effective. The pyrolysis temperature is negatively connected with the biochar product, as seen in Fig. 9. The thermal cracking of molecular weight in biomass feedstock may increase and lower the biochar output as the reactor temperature rises. The biochar production drops to 9 kg when the temperature rises from 30 to 167 °C. While at low temperatures, the yield of biochar was found to be high. As the temperature of the pyrolysis process increases above 167 °C, the biochar yield becomes ash. In a similar study of wood pellets and grass straw, the temperature has the opposite effect on the biochar production between the temperature ranges 350–600 °C [20], and as Browsort, Peter has studied, higher temperature gives less char in all types of the pyrolysis process. With a higher temperature, more volatile material is forced out of the biomass (feedstock), and therefore the number of char decreases [5].

4. Conclusions and recommendations

The pyrolysis process experiment was carried out in this paper to manufacture biochar at various temperatures and airflow rates. Temperature, feedstock type, airflow rate, and moisture content are the primary factors that influence biochar creation. The higher the airflow rate, the faster the pyrolysis and the lower the charcoal output. The period of biochar production and the velocity of airflow into the reactor are both reduced as the feedstock is dried (less moisture). To improve the char product, the densely accumulated feedstock (cud) requires molding and an internal secondary airflow rate. The paper produced 10–25 kg of biochar and 10–21 kg of animal cud at thesame kilos of feedstock (30 kg) and pyrolysis te mperature (167 °C). Both primary and secondary air inlets are shut, the temperature rises steadily, and more time is needed to produce more char. The biochar production increases to 25 kg and the temperature drops to 200C when the air flow rate drops from 2.5 to 0.35 kg/s. Further research on thechemical composition and final analysis of the cud is proposed.

Author contribution statement

Tayachew Nega: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Kirubeil Awoke, Aboytu Sisay: Performed the experiments; Contributed reagents, materials, analysis tools or data.
Ashenafi Tesfaye Bicks, Ashager shimelash Admasu: Analyzed and interpreted the data.
Endale Getu Mengstie: Contributed reagents, materials, analysis tools or data.
Getahun Tassew Melese: Contributed reagents, materials, analysis tools or data; Wrote the paper.

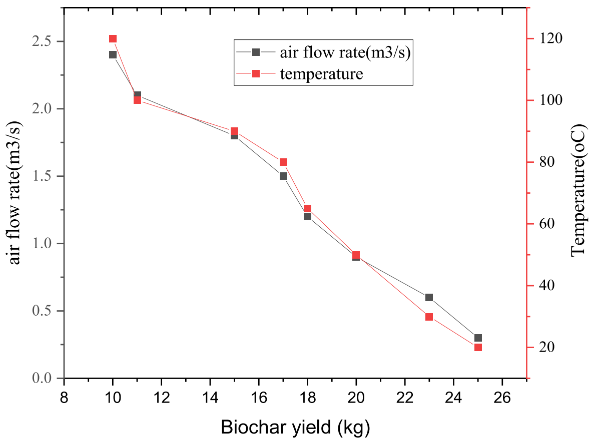

Fig. 9. Effects of temperature on biochar yield.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Acknowledgments

The authors would like to acknowledge University of Gondar Institute of Technology for the materials and computer and simulation laboratory support and facilities throughout this research work.

References

[1] B. Balagurumurthy, V. Srivastava, J. Kumar, B. Biswas, R. Singh, P. Gupta, K.S. Kumar, R. Singh, T. Bhaskar, Value addition to rice straw through pyrolysis in hydrogen and nitrogen environments, Bioresour. Technol. 188 (2015) 273–279.

[2] F.D. Boer, J. Valette, J.-M. Commandre, M. Fournier, M.-F. Thevenon, Slow pyrolysis of sugarcane bagasse for the production of char and the potential of its by-product for wood protection, J. Renewab. Mater. 9 (2021) 97.

[3] A.V. Bridgwater, Review of fast pyrolysis of biomass and product upgrading, Biomass Bioenergy 38 (2012) 68–94.

[4] P.A. Brownsort, Biomass Pyrolysis Processes: Performance Parameters and Their Influence on Biochar System Benefits, 2009.

[5] S. Carter, S. Shackley, S. Sohi, T.B. Suy, S. Haefele, The impact of biochar application on soil properties and plant growth of pot grown lettuce (Lactuca sativa) and cabbage (Brassica chinensis), Agronomy 3 (2013) 404–418.

[6] D. Chen, J. Zhou, Q. Zhang, Effects of heating rate on slow pyrolysis behavior, kinetic parameters and products properties of moso bamboo, Bioresour. Technol. 169 (2014) 313–319.

[7] S. Danje, Fast Pyrolysis of Corn Residues for Energy Production, Stellenbosch University, Stellenbosch, 2011.

[8] B. Dutta, Development and Optimization of Pyrolysis Biochar Production Systems towards Advanced Carbon Management, 2014.

[9] S.A. El-Sayed, M.E. Mostafa, Thermal pyrolysis and kinetic parameter determination of mango leaves using common and new proposed parallel kinetic models, RSC Adv. 10 (2020) 18160–18179.

[10] C. Fogarassy, L. Toth, M. Czikkely, D.C. Finger, Improving the Efficiency of pyrolysis and increasing the quality of gas production through optimization of prototype systems, Resources 8 (2019) 182.

[11] L. Fryda, R. Visser, Biochar for soil improvement: evaluation of biochar from gasification and slow pyrolysis, Agriculture 5 (2015) 1076–1115.

[12] D. Granatstein, C. Kruger, H. Collins, M. Garcia-Perez, J. Yoder, Use of Biochar from the Pyrolysis of Waste Organic Material as a Soil Amendment, Washington State University, 2009.

[13] M. Gustafsson, Pyrolysis for Heat Production-Biochar the Primary Byproduct, Master's Thesis, University of Gavle, 2013.

[14] S. Kern, M. Halwachs, G. Kampichler, C. Pfeifer, T. Proll, H. Hofbauer, Rotary kiln pyrolysis of straw and fermentation residues in a 3 MW pilot plant–Influence of pyrolysis temperature on pyrolysis product performance, J. Anal. Appl. Pyrol. 97 (2012) 1–10.

[15] H.W. Lee, H. Lee, Y.-M. Kim, R.-S. Park, Y.-K. Park, Recent application of biochar on the catalytic biorefinery and environmental processes, Chin. Chem. Lett. 30 (2019) 2147–2150.

[16] S.Y. Lee, R. Sankaran, K.W. Chew, C.H. Tan, R. Krishnamoorthy, D.-T. Chu, P.-L. Show, Waste to bioenergy: a review on the recent conversion technologies, Bmc Energy 1 (2019) 1–22.

[17] R.B. Madsen, M. Glasius, How do hydrothermal liquefaction conditions and feedstock type influence product distribution and elemental composition? Ind. Eng. Chem. Res. 58 (2019) 17583–17600.

[18] L. Matsakas, Q. Gao, S. Jansson, U. Rova, P. Christakopoulos, Green conversion of municipal solid wastes into fuels and chemicals, Electron. J. Biotechnol. 26 (2017) 69–83.
[19] R. Mehrabian, R. Scharler, I. Obernberger, Effects of pyrolysis conditions on the heating rate in biomass particles and applicability of TGA kinetic parameters in particle thermal conversion modelling, Fuel 93 (2012) 567–575.
[20] A.K. Mensah, K.A. Frimpong, Biochar And/or Compost Applications Improve Soil Properties, Growth, and Yield of Maize Grown in Acidic Rainforest and Coastal Savannah Soils in Ghana, International Journal of Agronomy, 2018.
[21] S. Naqvi, H.M. Prabhakara, E. Bramer, W. Dierkes, R. Akkerman, G. Brem, A critical review on recycling of end-of-life carbon fibre/glass fibre reinforced composites waste using pyrolysis towards a circular economy, Resour. Conserv. Recycl. 136 (2018) 118–129.
[22] B.A. Oni, O. Oziegbe, O.O. Olawole, Significance of biochar application to the environment and economy, Ann. Agric. Sci. (Cairo) 64 (2019) 222–236.
[23] F. Ronsse, S. van Hecke, D. Dickinson, W. Prins, Production and characterization of slow pyrolysis biochar: influence of feedstock type and pyrolysis conditions, Gcb Bioenergy 5 (2013) 104–115.
[24] J.K. Sarkar, Q. Wang, Different pyrolysis process conditions of south Asian waste coconut Shell and characterization of gas, bio-char, and bio-oil, Energies 13 (2020) 1970.
[25] S.B. Scholz, T. Sembres, K. Roberts, T. Whitman, K. Wilson, J. Lehmann, Biochar Systems for Smallholders in Developing Countries: Leveraging Current Knowledge and Exploring Future Potential for Climate-Smart Agriculture, World Bank Publications, 2014.
[26] M. Shahbaz, A. Alnouss, P. Parthasarathy, A.H. Abdelaal, H. Mackey, G. Mckay, T. Al-Ansari, Investigation of Biomass Components on the Slow Pyrolysis Products Yield Using Aspen Plus for Techno-Economic Analysis, Biomass Conversion and Biorefinery, 2020, pp. 1–13.
[27] A. Tomczyk, Z. Sokolowska, P. Boguta, Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects, Rev. Environ. Sci. Biotechnol. 19 (2020) 191–215.
[28] M. Tripathi, J.N. Sahu, P. Ganesan, Effect of process parameters on production of biochar from biomass waste through pyrolysis: a review, Renew. Sustain. Energy Rev. 55 (2016) 467–481.
[29] F.R. Vieira, C.M.R. Luna, G.L. Arce, I. Ávila, Optimization of slow pyrolysis process parameters using a fixed bed reactor for biochar yield from rice husk, Biomass Bioenergy 132 (2020), 105412.
[30] S. Wijitkosum, P. Jiwnok, Elemental composition of biochar obtained from agricultural waste for soil amendment and carbon sequestration, Appl. Sci. 9 (2019) 3980.
[31] Z. Yao, S. You, T. Ge, C.-H. Wang, Biomass gasification for syngas and biochar co-production: energy application and economic evaluation, Appl. Energy 209 (2018) 43–55.
[32] S. Yorgun, D. Yildiz, Slow pyrolysis of paulownia wood: effects of pyrolysis parameters on product yields and bio-oil characterization, J. Anal. Appl. Pyrol. 114 (2015) 68–78.