# Biowaste to biochar: development and performance valuation of pilot-scale fixed-bed pyrolysis reactor

Md. Aktarul Islam[1] ,Md.Touhidul Islam[2], Md. Rostom Ali[2*] , Md. Hossain Ali[1],
Ehsanul Kabir[2], Monon Mahboob[3], Mst. Lucky Khatun[2]

*(1. Agricultural Engineering Division, Bangladesh Institute of Nuclear Agriculture, Mymensingh-2202, Bangladesh;*
*2. Department of Farm Power and Machinery, Bangladesh Agricultural University, Mymensingh-2202, Bangladesh;*
*3. Department of Industrial and Production Engineering, AIUB, Dhaka, 1229, Bangladesh)*

**Abstract:** Traditional biomass pyrolysis increases pollutants and reduces charcoal yield. Combustion and gasification produce significant hydrocarbons. Biochar obtained from thermo-chemical conversion of biomass in an oxygen-limited environment can be applied to soil for retaining water and nutrients in soil. This study was initiated to develop and evaluate the performance of a pilot-scale fixed-bed pyrolysis reactor to optimize pyrolysis process, which might minimize $CO_2$ emissions. Mild Steel Sheets (ASTM A36, ASTM 1020) were used to make the double layer combustion chamber having inner volume of 0.35m$^3$. Three heater board (1000W capacity) were laid on the upper surface of the inner cylinder. Non-combustible glass wool was used in the gap between the cylinders to remove heat loss. Rice straw, jute sticks, and mustard stalks were used as possible biochar feed stock in this machine. All feed stocks were burned between 300- 500℃ temperature. The maximum biochar yield was found 54.7% from rice straw at 300℃and average of 45.67% from all feedstock. Maximum percentage of carbon was found 41.1% from jute stick biochar at 500℃. The electric heating coil consumed 1.58 kWh of power on average and the maximum energy consumption was found 1.89 kWh for 300℃ temperature.

**Keywords:** biomass, biochar machine, biochar yield, carbon content

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## 1 Introduction

Bangladesh is one of the most densely populated countries with a 1.04% growth rate in population (Barua, 2022). This significantly increasing population demands increasing agricultural activities to meet food and nutritional requirements. In Bangladesh, the agricultural sector includes subsectors namely crop cultivation, animal farming, fish culture, and foresting to meet the growing population's needs for carbohydrates, vitamins, minerals, and protein (Pamuk et al., 2021). Bangladesh stands third in rice (Al Mamun et al., 2021), third in fruits and vegetables (Pamuk et al., 2021), and third in inland fish culture (DoF, 2022) worldwide and is also self-sufficient in meat and egg production. To meet the food demand of an excessively growing population, increased crop

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***Corresponding author: Md. Rostom Ali.** Department of Farm Power and Machinery, Bangladesh Agricultural University, Mymensingh-2202, Bangladesh. Email: rostomfpm@bau.edu.bd.

production in limited soil areas negatively affected soil health. Continuous crop production in the same soil caused a lowering of soil organic matter which is a matter of great concern for soil health (Ahmmed et al., 2018). On the other hand, every year, a gigantic volume of bio-based waste is generated from different agricultural sectors in Bangladesh (Saha et al., 2024a). Improper handling of these wastes causes bio-degradation of these wastes and emission of greenhouse gas directly to the environment (Kabir et al., 2023). Open burning of crop-based biomass in cooking stoves causes heat loss to the environment and emission of combustion gases (Saha et al., 2024b). So, alternative management of crop-based biomass is a crucial need for environmental protection. Production of biochar from crop-based biomass can be a remedy for waste management problems and the production of quality fertilizer which can improve soil health. Biochar acts as a carbon sink, sequestering carbon in a stable form for an extended period (Shoudho et al., 2024). This can contribute to mitigating climate change by reducing the amount of carbon dioxide released into the atmosphere.

Biochar is a porous carbonaceous solid that is very resistant to decomposition and has a high degree of aromatization. It is created when biomass from plant or animal waste is thermally broken down in the absence of oxygen or in an atmosphere with oxygen shortage (Yadav et al., 2022; Kumar et al., 2021). Biochar, a product with additional value, has numerous applications. Properties of biochar especially its high carbon content, porosity, stability, bulk density, low heat conductivity, and increased surface area make it a great amendment to improve soil health (Seow et al., 2022). Biochar has a great capacity to hold nutrients in the soil which is beneficial for soil fertility and crop production (Domingues et al., 2017). Baquy et al. (2021) reported around 54%- 61% nutrient (NPK) recovery in soil using biochar as a soil element. Torrefaction, gasification, hydrothermal carbonization, and pyrolysis are the major thermochemical processes used to produce biochar (Iwuozor et al., 2023). Yaashikaa et al. (2020) reported pyrolysis as the most suitable techniques to produce biochar compared to other technology.

Pyrolysis is a thermochemical waste-to-energy conversion technology that produces solid biochar, gases, and oil from biomass. These products are value-added and in high demand in the industry. They create less NOx and SOx emissions than combustion processes (Premalatha et al., 2021), require less pressure than hydrothermal liquefaction (Prathiba et al., 2018), produce less tar than torrefaction (Sanjeevi et al., 2021), and consume less energy than gasification (Shankar et al., 2023). Pyrolysis is categorized into six classes namely: slow, first, flash, vacuum, intermediate, and hydro pyrolysis (Armah et al., 2022). These vary in terms of biomass particle size, heating rate, solid residence time, process temperature, and so on. The composition of pyrolytic products and their quality are also affected by different process parameters including temperature, retention time heating rate, and type of biomass (Cha et al., 2016; Yaashikaa et al., 2019). Hence, the design and development of a pyrolysis reactor to produce biochar considering process parameters is essential for cost-effective and efficient biochar production.

Sanahuja-Parejo et al. (2022) analysed co-pyrolysis of lignocellulosic biomass with polymer wastes in pilot-scale reactor. Soni and Karmee (2020) was pyrolyzed sawdust at first in a fixed bed batch scale reactor to know the temperature effect on yield and then pyrolyzed sawdust in a pilot-scale continuous pyrolysis system at 500ºC. Bangladesh is an agricultural country, where a gigantic volume of different agricultural waste and by-products is produced every day. To the best of our knowledge, research on utilizing this enormous quantity of waste to produce value-added products, such as biochar, is limited. The implementation of a pilot-scale fixed-bed pyrolysis reactor in developing countries like Bangladesh offers numerous benefits from both environmental and agricultural perspectives. Firstly, this reactor efficiently converts available crop-based biomass into biochar. This not only reduces waste and associated greenhouse gas emissions but also produces a valuable carbon-rich product that can enhance soil fertility and sequester carbon in the long term. Additionally, pilot-scale fixed-bed pyrolysis reactor provide an opportunity for local communities to generate income through the sale of biochar and promote sustainable practices, contributing to rural development and poverty alleviation in Bangladesh (Ge et al., 2021). Thus, this study aimed to design and develop a pilot-scale fixed-bed pyrolysis reactor that optimizes the pyrolysis process and evaluates its performance. By understanding the machine's capabilities and efficiency, it is possible to assess its potential to contribute to sustainable agriculture and environmental conservation.

## 2 Design and development of pilot-scale fixed-bed pyrolysis reactor

### 2.1 Design consideration

The reactor was designed considering some parameters to develop a cost-effective and environmentally friendly machine. An electric heating system with temperature control was considered in this study to ensure interrupted heat supply during pyrolysis. An insulator was used in the machine to reduce heat loss and emergency shut-off switches, overheat protection, and ventilation was also considered during fabrication.

### 2.2 Materials for pilot-scale fixed-bed pyrolysis reactor

The reactor was developed using locally available, low-cost materials that were procured from the local market. Most parts of the reactor were fabricated in the local workshop in Rangpur town, Bangladesh. Mild steel sheets of ASTM A36 and ASTM 1020 were used to make the double-layer combustion chamber having an inner volume of 0.35m$^3$. Three heater boards were prepared with 1000W capacity each and laid on the upper surface of the inner cylinder. Non-combustible glass wool was used in the gap between the cylinders to reduce heat loss in the combustion chamber. Temperature sensor and temperature controller (up to 1300℃) were used to measure the temperature and control the temperature of the chamber. Glass wool from glass fiber was used as insulator and was attached to the inner reactor so that the heat generated in the inner reactor could not escape and could not be lost.

### 2.3 Electrical connection diagram of pilot-scale fixed-bed pyrolysis reactor

AC voltage (220 V) was supplied to electric heating coils of the reactor. The schematic diagram of the electric connection of the biochar machine is shown in Figure 1. Three 1000-watt coils were connected in parallel. Circuit breakers were used to link the coil and power supply lines. The reactor's inside was fitted with a thermocouple, which measures temperature. The temperature was monitored and controlled using a temperature controller. Cables were used to link the temperature controller and circuit breaker.

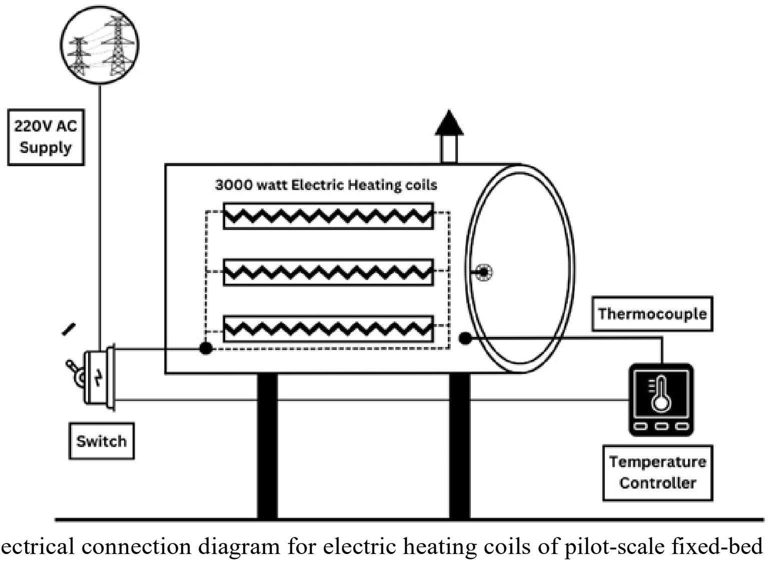


Figure 1 Electrical connection diagram for electric heating coils of pilot-scale fixed-bed pyrolysis reactor

### 2.5 Fabrication of pilot-scale fixed-bed pyrolysis reactor

This compressive procedure describes the steps involved in fabricating a reactor, such as the fabrication of the outer cylinder, inserting the reactor cylinder inside the outer cylinder, attaching the coil to the reactor cylinder, connecting the power source to the coil, and attaching the temperature sensor and controller. At first outer body of the biochar machine was fabricated by rolling AISI 1020 steel and its two ends were joined by electric arc welding. A36 carbon steel sheets were arranged to ensure proper alignment (Figure 2a). Then inner layer was fabricated by rolling AISI 1020 steel sheet. A total of three heater boards were connected to the inner reactor by screwing through a carbon steel sheet (Figure 2b). Finally, the three heater boards were connected in series by electrical wires. Then glass wool was placed on the reactor, the inner reactor was placed inside the outer body (Figure 2c), and the temperature sensor was connected to the reactor chamber. The inner layer consisted of a heating chamber used to perform agricultural biomass pyrolysis (Figure 2d). It was also outfitted with a thermocouple and temperature controller to measure and adjust the chamber's temperature. Then the reactor under went renovations to enhance its efficiency and productivity, including the replacement of heat gaskets and cement reinforcing to seal off any leaks.

(a) outer cylinder (b) heater board

(c) glass wool between inner and outer cylinder (d) pyrolysis chamber

Figure 2 Fabrication of pilot-scale fixed-bed pyrolysis reactor

## 3 Performance evaluation of pilot-scale fixed-bed pyrolysis reactor

### 3.1 Feedstock preparation for biochar production

Three crop-based biomasses were selected for biochar production. These biomasses were rice straw, jute stick, and mustard plant. All of these biomasses were collected from the nearby local market and agricultural field in Mymensingh, Bangladesh. The feedstock was sun-dried for several days before the pyrolysis to bring the moisture content of each biomass between 12% to 15%.

### 3.2 Production of biochar

The reactor is likely to utilize a pyrolysis process to convert agricultural residues into biochar, through an electric heater. The process flow diagram of biochar production is shown in Figure 3. Three kg of each sample was taken as a feedstock, and the prepared biomass was placed at the bottom of the reactor. A homogeneous mixture of the feedstock was achieved for uniform heating during pyrolysis to ensure quality biochar. The reactor was operated for 60 to 90 min at 300°C to 500°C. The reactor was operated for 90, 75, and 60 min retention time at 300°C, 400°C and 500°C, respectively. After completion of the pyrolysis process, the biochar was cooled and the final product was collected. Then carbon content of biochar was determined following wet oxidation method following Walkley and Black (1934).

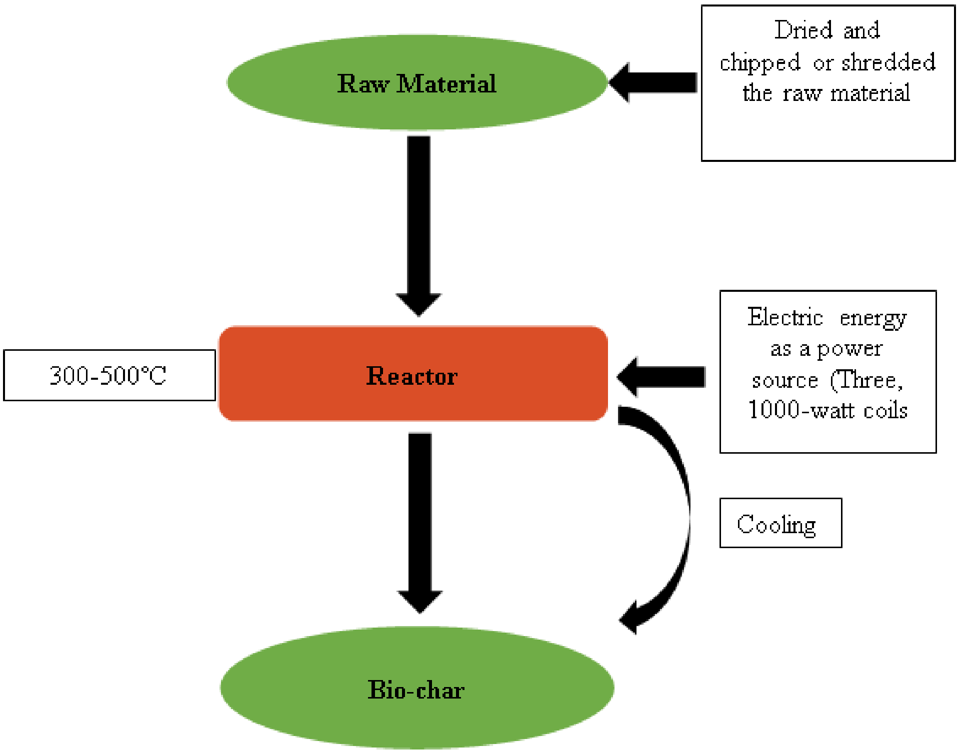


Figure 3 Flow diagram of the biochar production process

The biochar yield was calculated using the following Equation (1) (Cao et al., 2016).

$$Y = \frac{W_{Biochar}}{W_{Feedstock}} \times 100 \tag{1}$$

where,

Y is the percent biochar yield;

$W_{Feedstock}$ is the weight of the raw feedstock on an air-dried basis (kg);

$W_{Biochar}$is the weight of the produced biochar (kg).

**Energy consumption:** Energy consumption can be calculated based on the power rating of the heating coil and the duration of the pyrolysis process. The energy consumption can be calculated using following Equation (2).

$$E = P_{Coil} \times T_{Pyrolysis} \tag{2}$$

where,

$E$ is the energy consumption ($kWhr^{-1}$);

$P_{Coil}$ is the power rating of the electric heating coil system in kW;

$T_{pyrolysis}$ is the duration of the pyrolysis process in hrs.

## 4 Results and discussion

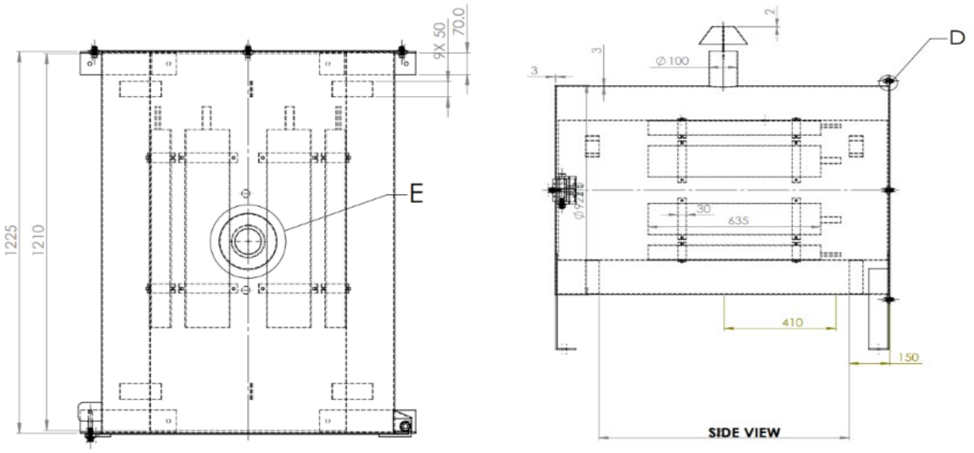
### 4.1 Design and dimension of the pilot-scale fixed-bed pyrolysis reactor

Appropriate dimensions of a biochar machine for fabrication are crucial for optimum production of biochar. A specific design considered dimensions of 1.225 m in length, 0.908 m in diameter, and a sheet metal with 5 mm thickness. Inside, a cylindrical reactor with dimensions of 1.210 m length, 0.610 m diameter, and 3 mm thickness was incorporated. These measurements provide a benchmark for future machine development, but may need adjustments based on factors like desired output, feedstock characteristics, and available space. The heater boards were rectangular, measuring 0.635 m by 0.152 m with a thickness of 2 mm. They were arranged around the inner reactor, which had a circumference of 1.917 m.

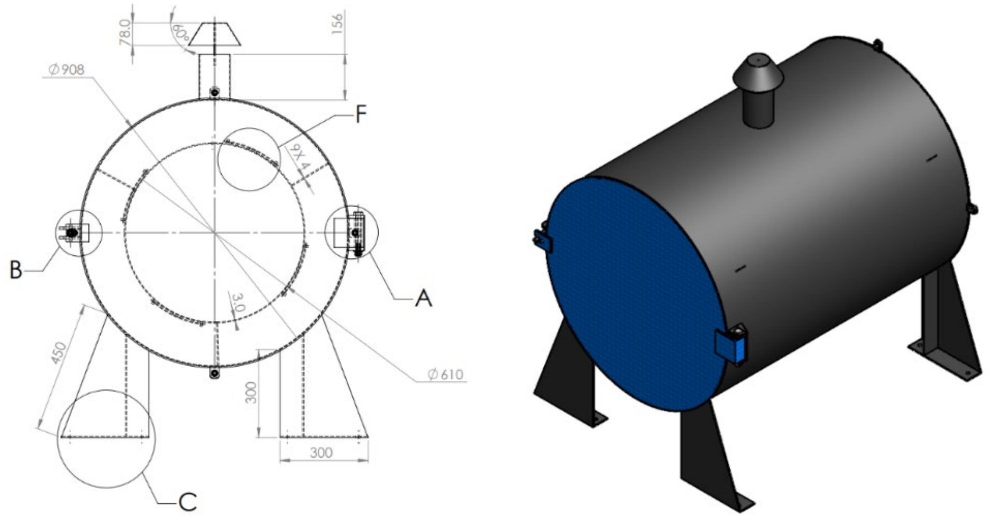
Three heater boards were connected to the reactor, spaced 0.487 mm apart. Mild steel sheets and screws were used to secure the heater boards in place. Figure 4 illustrates the biochar machine from various perspectives. The specifications of the developed reactor is also shown in Table 1.

**Table 1 Specifications of fixed-bed pilot-scale pyrolysis reactor**

| Specifications Parameter | Value / Description |
|---|---|
| Reactor type | Batch |
| Feedstock type | Agricultural waste and by-product |
| Reactor capacity | 48 kghr$^{-1}$ |
| Reactor material | Mild Steel |
| Reactor volume | 0.35m$^3$ |
| Heating method | Electrical |
| Heating rate | 7.05 °Cmin$^{-1}$ |
| Operating temperature range | 300°C-500°C |
| Insulation type | Glass wool |
| Feed method | Manual batch |



(a) Top view (b) Side view



(c) Front view (d) Isometric view

Figure 4 Different views of the pilot-scale fixed-bed pyrolysis reactor

### 4.2 Biochar yield from different biomass

The physio-chemical characteristics of biochar have a great impact on the de-volatilization, product yield, and form of the biochar created during the pyrolysis procedure. The pyrolysis process of each biomass was carried out at a temperature of 300°C–500°C for 60 to 90 min retention time. The effect of temperature on the yield and characteristics of biochar is demonstrated in Figure 5.

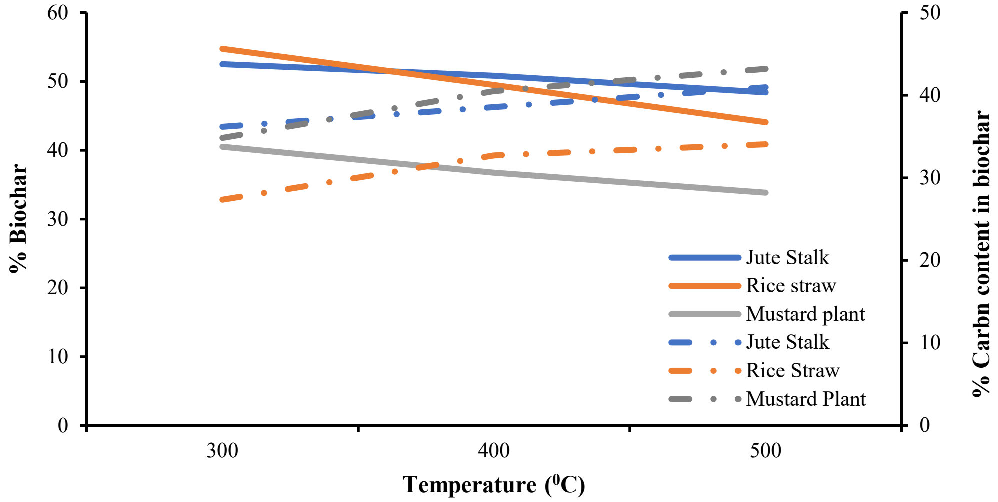


Figure 5 Variation of biochar yield (solid line) and percentage of carbon (dotted line) at different temperature

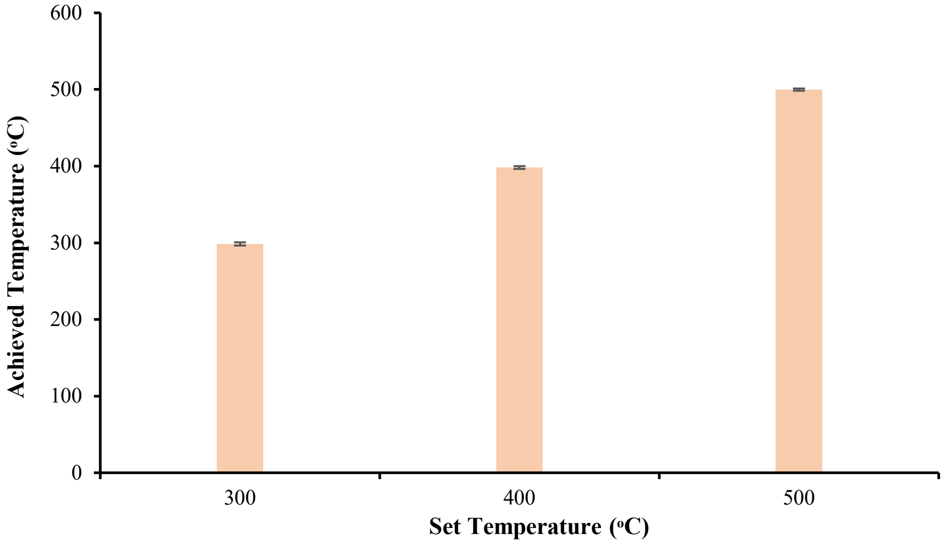


Figure 6 Plot of set temperature and mean achieved temperature

According to Figure 5 biochar obtained from rice straw, jute sticks, and mustard stalks with pyrolysis processes have a high yield at low temperatures. With an increase in temperature of pyrolysis process, the yield of the biochar product decreased. Maximum yield percentage was found 54.73%, 52.50%, and 40.50% from rice straw, jute stick, and mustard plant, respectively at 300°C temperature and 90 min retention time. Peng et al. (2011) found pyrolysis of rice straw at 300°C for 120 min produces 49.2% yield where increasing temperature to 400°C causes 37.5% yield. In the case of mustard, Singh et al. (2013) found highest percentage of yield at 250°C but highest carbon content in biochar was found at 500°C. Altıkat et al.(2024) also reported lowering of biochar yield with increasing temperature during pyrolysis of woody biomass. Hence, according to the experiment results the machine and setting conditions could be considered for biochar production from agricultural residues. It can also be seen from Figure 5 that the percentage of carbon in produced biochar from each feedstock increased with an increasing temperature, which is in line with the research findings of Altıkat et al.(2024). Zhao et al.(2018) also found an increase in carbon content increased with temperature during pyrolysis of rapeseed stem. According to the experiment, 60 min pyrolysis at 500°C is appropriate for producing the maximum carbon percentage from the selected agricultural residues. Intani et al.(2016) used external heating source to pyrolyze maize cobs, successfully producing 22%–33.8% biochar. The obtained yield (33%-54%) (Figure 5) demonstrated the efficiency of the biochar synthesis apparatus designed for this investigation. As production of biochar was a medium of waste management instead of landfilling and burning, it may reduce greenhouse gas emissions.

### 4.3 Heating efficiency

A heating coil was used to reach the pyrolysis temperatures. Hence, maintaining a stable temperature during pyrolysis was essential. Figure 6 demonstrates the set temperature and extent of achieved temperature throughout the pyrolysis process with standard deviation for all biomasses.

The electric heating coil proved to be incredibly effective in reaching pyrolysis temperature and maintaining it during the experiment, as the standard deviation was negligible (less than 2.1ºC). The slight changes in the performance of the heating coil might be due to intrinsic flaws in the experimental arrangement and transient thermal dynamics in the pyrolysis chamber. The close relationship between the set and attained temperatures emphasized how well the heating coil supports the efficient conversion of biomass from agricultural leftovers into biochar. The electric heating coil showed precise temperature control throughout the pyrolysis process to maximize energy economy and ensure the consistent quality of the biochar generated.

### 4.4 Energy consumption during pyrolysis process

Energy consumption was closely observed during the pyrolysis of biomass in the developed biochar machine and is listed in Table 2. Energy consumption decreased by 33.86% and 22.36% at 300°C and 400°C, respectively, compared to 500°C (Table 2). This was due to reduced electricity supply duration and retention time.

**Table 2 Energy consumption of biochar machine during pyrolysis**

| Temperature (°C) | Duration for pyrolysis (min) | Duration of electricity supply (min) | Energy consumption (kWh) | Average energy consumption (kWh) |
|---|---|---|---|---|
| 300 | 90 | 38.00 | 1.89 | 1.58 |
| 400 | 75 | 32.15 | 1.61 | |
| 500 | 60 | 25.00 | 1.25 | |

## 5 Conclusion

Sustainable and efficient design and development of a reactor help to produce quality biochar and reduce biowaste management problems, consequently. This 1.225 m long reactor, having a diameter of 0.908 m, produces biochar effectively with an average 1.58kWh energy consumption. Biochar produced in this machine has also comparatively high biochar yield percentage (40.50%-54.73%). Carbon content and total yield varied depending on the type of biomass, retention time, and temperature. In this study, raw substrates were used, and there was no catalyst. The addition of a catalyst and pretreatment of substrates might increase efficiency. Techno-economic analysis of the utilization of this reactor for different biomass may promote its field-level application. The findings of this study might help to further improve and commercialize a locally manufactured pilot-scale fixed-bed pyrolysis reactor.

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## References

Ahmmed, S., M. Jahiruddin, S. Razia, R. A. Begum, J. C. Biswas, A.S.M. M. Rahman, M. M. Ali, K. M. S. Islam, M. M. Hossain, M. N. Gani, G. M. A. Hossain, and M. A. Satter. 2018. Fertilizer Recomendation Guide- 2018. Available at: http://barc.portal.gov.bd/sites/default/files/files/barc.portal.gov.bd/page/4adead4d_6e17_4d74_b5bd_e86e46c059ad/88c1738fe0618daef286ef3d27c95423.pdf. Accessed 25 December 2024.

Al Mamun, M. A., S. A. I. Nihad, M. A. R. Sarkar, M. A. Aziz, M. A. Qayum, R. Ahmed, N. M. F. Rahman, M. I. Hossain, and M. S. Kabir.2021. Growth and Trend Analysis of Area, Production and Yield of rice: A Scenario of Rice Security in Bangladesh. *PLoS One*, 16(12): e0261128.

Altıkat, A., M. H. Alma, A. Altıkat, M. E. Bilgili, and S. Altıkat.2024. A Comprehensive Study of Biochar Yield and Quality Concerning Pyrolysis Conditions: A Multifaceted Approach. *Sustainability*, 16(2):937.

Armah, E. K.,M. Chetty, J. A. Adedeji, D. E. Estrice, B. Mutsvene, N. Singh, and Z. Tshemese.2022. Biochar: Production, Application and the Future.In *Biochar - Productive Technologies, Properties and Applications*, eds. M. Bartoli, M. Giorcelli, and A. Tagliaferro,ch. 2, 105070. London, UK: IntechOpen.

Baquy, M. A., M. A. Al Mamun, S. Mia, M. M. Alam, M. S. H. Khan, and S. M. Rahman.2021. Biochar Research Advancement in Bangladesh : Challenges and Opportunities of Biochar in Improving Soil Health. *SAINS TANAH – Journal of Soil Science and Agroclimatology*, 19(2): 145–159.

Barua, S. 2022. Over Population Problem of Bangladesh.Available at: https://www.researchgate.net/publication/361439003. Accessed 15 December 2024.

Cao, H., Y. Xin, and Q. Yuan.2016. Prediction of Biochar Yield from Cattle Manure Pyrolysis via Least Squares Support Vector Machine Intelligent Approach. *Bioresource Technology*, 202: 158–164.

Cha, J. S., S. H. Park, S. C. Jung, C. Ryu, J. K. Jeon, M. C. Shin, and Y. K. Park.2016. Production and Utilization of Biochar: A Review. *Journal of Industrial and Engineering Chemistry*, 40: 1-15.

Department of Fisheries (DoF). 2022. Annual Report. Available at: http://fisheries.portal.gov.bd/sites/default/files/files/fisheries.portal.gov.bd/annual_reports/bd7e72fb_fedf_4023_9736_0a16dcafcba0/2022-03-01-08-59-c31b9943fd74d886f4edf29b22110773.pdf. Accessed 10 December 2024.

Domingues, R. R., P. F. Trugilho, C. A. Silva, I. C. N. A. Melo, L. C. A. Melo, Z. M. Magriotis, and M. A. Sánchez-Monedero.2017. Properties of Biochar Derived from Wood and High-Nutrient Biomasses with the Aim of Agronomic and Environmental Benefits. *PLoS One*, 12(5): e0176884.

Ge, S.,P. N. Y. Yek, Y. W. Cheng, C. Xia, W. A. W. Mahari, R. K. Liew, W. Peng, T. Q. Yuan, M. Tabatabaei, M. Aghbashlo, C. Sonne, and S. S. Lam. 2021. Progress in Microwave Pyrolysis Conversion of Agricultural Waste to Value-Added Biofuels: A Batch to Continuous Approach. *Renewable and Sustainable Energy Reviews*, 135: 110148.

Intani, K., S. Latif, A. K. M. R. Kabir, and J. Müller.2016. Effect of Self-Purging Pyrolysis on Yield of Biochar from Maize Cobs, Husks and Leaves. *Bioresource Technology*, 218: 541–551.

Iwuozor, K. O., E. C. Emenike, E. O. Omonayin,J. O. Bamigbola, H. T. Ojo, A. A. Awoyale,O. A.A. Eletta, and A. G. Adeniyi.2023. Unlocking the Hidden Value of Pods: A Review of Thermochemical Conversion Processes for Biochar Production. *Bioresource Technology Reports*, 22: 101488.

Kabir, E., K. H. Kim, and E. E. Kwon.2023. Biochar as a Tool for the Improvement of Soil and Environment. *Frontiers in Environmental Science*, 11:1324533.

Kumar, M.,S. Dutta, S. You, G. Luo, S. Zhang, P. L. Show, A. D. Sawarkar, L. Singh, and D. C. W. Tsang.2021. A Critical Review on Biochar for Enhancing Biogas Production from Anaerobic Digestion of Food Waste and Sludge. *Journal of Cleaner Production*, 305: 127143.

Pamuk, H., M. J. Alam, and T. Tichar. 2021. Scoping Study on Fruits and Vegetables : Results from Bangladesh.Wageningen, The Netherlands: Wageningen Environmental Research.

Peng, X., L. Ye, C. Wang, H. Zhou, and B. Sun.2011. Temperature- and Duration-Dependent Rice Straw-Derived Biochar: Characteristics and its Effects on Soil Properties of an Ultisol in Southern China. *Soil and Tillage Research*, 112(2): 159–166.

Prathiba, R., M. Shruthi, and L. R. Miranda.2018. Pyrolysis of Polystyrene Waste in the Presence of Activated Carbon in Conventional and Microwave Heating using Modified Thermocouple. *Waste Management*, 76: 528–536.

Premalatha, N., R. Prathiba, M. A. Miranda, and L. R. Miranda. 2021. Pyrolysis of Polypropylene Waste Using Sulfonated Carbon Catalyst Synthesized from Sugarcane Bagasse. *Journal of Material Cycles and Waste Management*, 23(3): 1002–1014.

Saha, C. K.,R. Nandi, S. Akter, S. Hossain, K. B. Kabir, K. Kirtania, M. T. Islam, L. Guidugli, M. T. Reza, and M. M. Alam.2024a. Technical Prospects and Challenges of Anaerobic Co-Digestion in Bangladesh: A Review. *Renewable and Sustainable Energy Reviews*, 197: 114412.

Saha, C. K.,M. L. Khatun, J. Nime, K. Kirtania, and M. M. Alam.2024b. Co-Digestion-Based Circular Bio-Economy to Improve Biomethane Generation and Production of Nutrient-Enriched Digestate in Bangladesh. *Sustainability*, 16(1):104.

Sanahuja-Parejo, O. A. Veses, A. Sanchís, M. S. Callén, R.

Murillo, and T. García.2022. Recent Advances in the Catalytic Co-pyrolysis of Lignocellulosic Biomass and Different Polymer Wastes from Laboratory Scale to Pilot Plant. In *Production of Biofuels and Chemicals from Sustainable Recycling of Organic Solid Waste*, eds. Z. Fang, R. L. Smith Jr., and L. Xu,ch. 2, 33-73. Singapore:Springer.

Sanjeevi,S., V. Shanmugam, S. Kumar, V. Ganesan, G. Sas, D. J. Johnson, M. Shanmugam, A. Ayyanar, K. Naresh, R. E. Neisiany,and O. Das. 2021. Effects of Water Absorption on the Mechanical Properties of Hybrid Natural Fibre/Phenol Formaldehyde Composites. *Scientific Reports*, 11: 13385.

Seow, Y. X.,Y. H. Tan, N. M. Mubarak, J. Kansedo, M. Khalid, M. L. Ibrahim, and M. Ghasemi. 2022. A Review on Biochar Production from Different Biomass Wastes by Recent Carbonization Technologies and its Sustainable Applications. *Journal of Environmental Chemical Engineering*, 10(1): 107017.

Shankar, V. S., G. Velmurugan, R. Prathiba, D. S. Poornima, M. Suvetha, and V. Keerthiga 2023. Effect of On-Farm Storage Structure on Physical and Bio-Chemical Changes in Aggregatum Onion. *Materials Today: Proceedings*, 72: 2417–2422.

Shoudho, K. N.,T. H. Khan, U. R. Ara, M. R. Khan, Z. B. Z. Shawon, and M. E. Hoque.2024. Biochar in Global Carbon Cycle: Towards Sustainable Development Goals. *Current Researchin Green and Sustainable Chemistry*, 8:100409.

Singh, A., R. Singhai, A. K. Biswas, and A. K. Dubey. 2013. Production of Biochar from Mustard for Agriculture Use and Carbon Sequestration. *International Journal of Chem Tech Research*, 5(2): 844–848.

Soni, B., and S. K. Karmee.2020. Towards a Continuous Pilot Scale Pyrolysis Based Biorefinery for Production of Biooil and Biochar from Sawdust. *Fuel*, 271: 117570.

Walkley, A., and I. A. Black.1934. An Examination of the Degtjareff Method for Determining Soil Organic Matter and a Proposed Modification of the Chromic Acid Titration method. *Soil Science*, 37(1):29-38.

Yaashikaa, P. R., P. S. Kumar, S. Varjani, and A. Saravanan.2020. A Critical Review on the Biochar Production Techniques, Characterization, Stability and Applications for Circular Bioeconomy. *Biotechnology Reports*, 28: e00570.

Yaashikaa, P. R., P. S. Kumar, S. J. Varjani, and A. Saravanan.2019. Advances in Production and Application of Biochar from Lignocellulosic Feedstocks for Remediation of Environmental Pollutants. *Bioresource Technology*, 292: 122030.

Yadav, M.,C. Joshi, K. Paritosh, J. Thakur, N. Pareek, S. K. Masakapalli, and V. Vivekanand. 2022. Reprint of Organic Waste Conversion through Anaerobic Digestion: A Critical Insight into the Metabolic Pathways and Microbial Interactions. *Metabolic Engineering*, 71:62–76.

Zhao, B., D. O'Connor, J. Zhang, T. Peng, Z. Shen, D. C. W Tsang, and D. Hou.2018. Effect of Pyrolysis Temperature, Heating Rate, and Residence Time on Rapeseed Stem Derived Biochar. *Jrounal of Cleaner Production*, 174: 977–987.