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Design of bench–scale auger pyrolysis reactor: Experimental investigation on rice husk biomass

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India has biomass potential of 500 million metric tons per year in the form of agricultural residue. Pyrolysis is one of the extensively studied thermal decomposition for conversion of biomass into various high calorific value products. In this study attempt to address the problem of alternative energy sources and utilizing the biomass potential of India is made. This study examines the influence of temperature (450–600°C) on pyrolysis product yields (bio-oil, biochar, and gases) in a newly designed and fabricated twin-screw auger reactor. A key innovation of this reactor is its integrated provision for catalytic upgrading, facilitated by an attached fixed-bed reactor, enhancing its capability for in-situ bio-oil improvement — a novel feature compared to existing systems. Results indicate that bio-oil yield increases from 27% to 33% as temperature rises from 450°C to 550°C, peaking before declining at 600°C due to secondary cracking. Biochar yield decreases (42% to 36%) with increasing temperature, while gas yield rises, dominated by CO (34.11% to 40.8%) and declining CO_2 (42.18% to 23.7%). Methane and hydrogen production also increase at higher temperatures, driven by cracking and dehydrogenation reactions. These findings, consistent with prior studies, highlight the reactor's potential for optimized pyrolysis and catalytic upgrading, offering a significant advancement in biomass conversion technology.

Keywords: Auger reactor, Biochar, Bio–oil, Design, Pyrolysis, Rice husk

Introduction

India produces 500 million metric tons of agricultural residues annually, but most is burned, causing air pollution and soil degradation[1]. Pyrolysis offers an efficient alternative, converting this biomass into bio-oil (through fast pyrolysis), biochar, and syngas at 300-700°C in oxygen free conditions. This approach creates economic value from waste while reducing environmental harm. Recent advancements in reactor design and catalytic processes have improved the technology's viability for large-scale implementation, addressing both energy needs and agricultural waste management[2].

Significant advancements have been made in pyrolysis reactor designs, including spouted, fluidized bed, rotating cone, and auger systems. Auger reactors offer distinct advantages: simpler scaling, compact design, and minimal inert gas requirements compared to mechanically complex alternatives like rotating cones or ablative systems. According to the Biomass Pyrolysis Network (PyNe) assessment, auger reactors, alongside BFB and CFB, emerge as the most commercially viable options, balancing operational efficiency with scalability for biomass conversion[3,4].

Auger reactors employ screw mechanisms to convey biomass feedstock while utilizing heated walls to achieve pyrolysis temperatures. Industrial pyrolysis facilities lack standard engineering guidelines, often leading to empirical plant designs[5,6]. The market attractiveness and technological strength of technologies available is shown in Fig. 1. For twin-screw auger reactors, key parameters include reactor dimensions, auger configuration, feed capacity, and operational settings. Twin-screw systems outperform single-screw designs in mixing and heat distribution, though scaling challenges persist for high-temperature mechanical components.

The present study aims to design and develop a laboratory-scale twin-screw auger reactor for the pyrolysis of rice husk and to optimise the operating temperature for improved bio-oil yield and quality. The novelty of this work lies in the application of a twin-screw auger reactor for the pyrolysis of rice husk, which, to the best of the authors' knowledge, has not been systematically explored so far. Although twin-screw reactors are known for their advantages such as continuous operation, efficient mixing, and better heat transfer, their potential for handling rice husk (a biomass with high ash and silica content) has not been adequately studied. This research addresses this gap by focusing on temperature as the key parameter for optimisation, thereby contributing to the effective utilisation of rice husk through conversion and promoting sustainable energy generation from agricultural waste.

Experimental Section

Design of bench scale auger pyrolysis reactor

The auger pyrolysis reactor (APR) system shown in Fig. 2 can be divided into four major processes as discussed below: feeding, conveyance, reaction and collection.

Feed hopper: Feed hopper is a funnel-shaped container designed for storing and regulating the flow of bulk materials. The fabricated hopper has a square frustum shape (30 cm × 30 cm top) with a 15° vertical angle, made of 2 mm stainless steel, and is connected to a single screw auger at the bottom to convey biomass into a reactor.

Screw feeder: A screw feeder is a mechanical device that transports bulk materials controllably using a rotating screw inside a tube or trough. The screw's pitch determines its function: short pitches convey small material volumes per revolution,

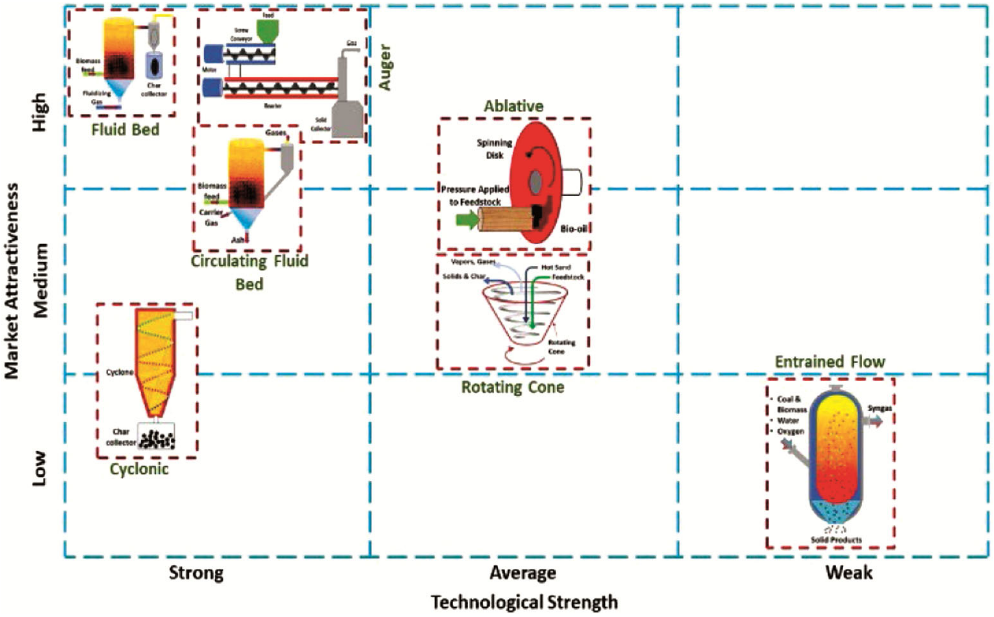

Fig. 1 — Market attractiveness and technological strength of available technologies

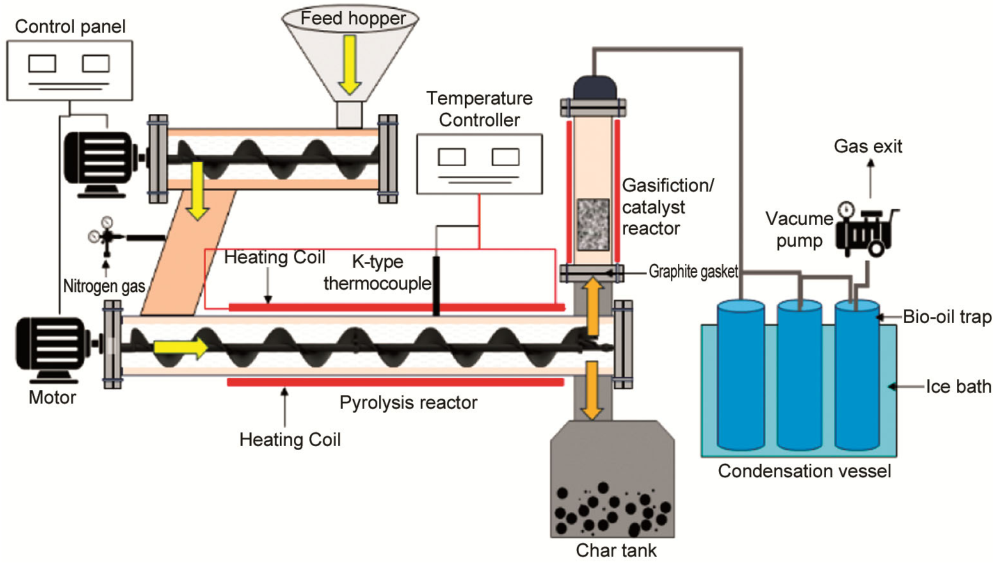

Fig. 2 — Twin screw auger pyrolysis reactor

while long pitches promote mixing over axial movement.[7]. The screw feeder features a standard flight design with a pitch-to-diameter ratio of 1, ensuring efficient biomass conveyance. The 60 mm diameter screw has a 2 mm clearance and is constructed from a solid rod with 10 mm thick, 10 mm deep threads. Powered by a 1 hp motor with a gearbox and VFD-controlled speed (2.5–10 rpm), it achieves a flow rate of 1.5–7 kg/h during trials.

Twin screw auger pyrolysis system: A twin-screw auger is a mechanical device with two intermeshing screws rotating in a barrel, used for conveying, mixing, kneading, or processing materials. During pyrolysis, heat is mainly transferred by radiation, convection, conduction, and pore convection[8]. The length and diameter are considered from the review article by Campuzano et al.[4], where authors reviewed auger reactors necessary design consideration and reactors from different universities and research facilities. The twin-screw pyrolysis reactor features a 100 cm long, 6 cm diameter omega-shaped barrel with 2 mm screw clearance. Constructed from wear-resistant EN 8 steel, it's driven by a 1 hp VFD-controlled motor (2.5-10 rpm). The design includes a 30 cm unheated feed zone and external resistance heating (700°C max) with PID-controlled thermocouples. Process connections include a 6 cm feed pipe and separate outlets for char collection and gas processing (condensation/gasification). The entire reactor is thermally insulated for efficiency.

Fixed bed gasification reactor: The system comprises two integrated sections: a throat section featuring lateral nozzles for precise injection of air, steam, or oxygen to facilitate partial oxidation at the pyrolysis-gasification interface, and a gas cracking section where tars are decomposed into high-energy syngas. Temperature in both sections is independently regulated via PID-controlled resistance heating, while K-type thermocouples ensure accurate monitoring. The insulated reactor body minimizes heat loss and maintains process efficiency. Operational flexibility allows for either heterogeneous mode (using char or catalyst packing) or homogeneous mode (empty) to optimize tar reduction and gas production. A tar trap connected to the top flange captures byproducts, completing the integrated gasification system.

Condenser system: The condenser system plays a crucial role in determining both the yield and quality of bio-oil production. A customized two-stage stainless steel condenser has been developed to address the challenges of bio-oil condensation, particularly its acidic nature (containing acetic and formic acids) and the risk of secondary cracking reactions. This system employs V-shaped stainless steel tubes (2 cm internal diameter, 60 cm submerged length per stage) through which pyrolysis gases pass, while a water/ice coolant mixture in surrounding tanks facilitates efficient heat transfer. Condensed bio-oil is collected from bottom nozzles of each stage, while non-condensable gases are directed for further analysis. This optimized system balances high recovery efficiency with product quality control, overcoming the corrosion challenges posed by bio-oil's acidic composition through its stainless steel construction.

In this research, we utilized rice husk as our feed, which was sourced from a local rice mill in the vicinity. The rice husk underwent a grinding and sieving process to achieve a particle size smaller than 1000 µm. Subsequently, the sample was subjected to oven drying at a temperature of 105°C for duration of 6 h and then carefully stored in an airtight container for use in the experiment. The feed flow rate is in direct correlation with auger rotations. To determine the rpm necessary for achieving the desired flow rate, a procedure was implemented. Initially, 500 g of dry ground biomass were passed through the reactor, while the rpm of the auger was incrementally adjusted in 2.5 rpm increments.

The experiments were conducted within temperature range spanning from 450 to 600°C, with intervals of 50°C. Throughout the reaction process, a specific procedure was meticulously adhered to. Firstly, the feed material was prepared by undergoing a grinding and drying process. Subsequently, the reactor was configured by connecting a condenser and a char collection tank. These condensers were carefully filled with ice to facilitate the condensation process. The reactor was then heated externally using a resistance heating mechanism, as outlined in the preceding section. One liter of nitrogen per minute was added to the reactor, and negative pressure was created inside the reactor using a vacuum pump. This negative pressure was essential for directing the flow of gases along the desired path during the experiments. The gases were collected in tedlar bag at the exit of the vacuum pump. To initiate the reaction, biomass material was introduced into the feed hopper. Concurrently, the rotational speed for the screws in both the conveyor and the pyrolysis reactor was set and the rotation was initiated. This well-structured procedure ensured the precise execution of the experiments. The biomass weighing 500 g was fed into reactor for each experiment. The screw speed was kept at 2.5 rpm which corresponds to 1.5 kg/h feed flow rate. The residence time of biomass in reactor was around 8 to 9 min. The rpm was controlled by the VFD and pyrolysis temperature was controlled by PID controller. After reaction, the heating of reactor and screw rotations were stopped and allowed to cool. The bio-oil was taken out of the condensers and biochar from the char tank. As in our earlier research, the bio-oil that adhered to the condenser tube wall was washed away using a chloroform and methanol (4:1) solvent mixture[9]. The gas collected in tedlar bag was analyzed by gas chromatography instrument. Rice husk biomass was pyrolyzed to obtain bio-oil, biochar and gases by following the reported procedure.

Results and Discussion

The bio-oil, bio-char and gases yield were estimated by conducting experiments on reactor with varying temperature. Fig. 3 shows the product yields for reactions performed at various temperatures at 2.5 rpm in twin screw auger pyrolysis reactor. The figure indicates that bio-oil yield increases from 27% to 33% with increase in temperature from 450 to 550°C. The lower temperature causes the pyrolysis process to be partially completed, meaning that the heat supplied is insufficient to break the biomass bond, which lowers the yield of bio-oil. A temperature increase of upto 550°C makes it easier to complete the process of pyrolysis, which is the intense cracking down of larger molecules of hydrocarbons to produce more bio-oil and gas.After 550°C, the reduction in yield at 600°C can be noticed. This reduction in bio-oil yield is due to secondary cracking of condensable gases or liquid product. This is results are in agreement with our previous studies and other researchers[9,10]. The catalytic cracking of vapour caused by the greater ash content of rice husk is likely one of the additional causes of the lower bio-oil production[11]. The opposite trend was seen for biochar yield. Fig. 3 shows that the biochar yield decreases with increase in temperature. At low temperatures, biomass decomposes incompletely. The pyrolysis process is not powerful enough to convert all of the complex organic molecules in the biomass to volatile gases at lower temperature. This leads to a higher proportion of biomass being converted into solid biochar. Whereas higher temperature facilitates thermal cracking of heavy hydrocarbons causing increase in yield of liquid and gases and reduced biochar yield. The biochar yield decreased from 42% at 450°C to 36% at 600°C.

In contrast to the biochar, the gas yield exhibited the exact opposite trend, increasing as the temperature rose. This is due to intensification in secondary cracking of liquid product. The GC analysis of gases was performed for gases obtained at different temperature. The yield of methane, carbon monoxide, carbon dioxide and hydrogen at different pyrolysis temperatures of 450, 500, 550 and 600°C is shown in Fig. 4. The volume% composition of individual gas component on nitrogen free basis at different temperature is illustrated in Fig. 4. The composition of each can said to be function of temperature. The increase in production of carbon monoxide, methane and hydrogen with increase in temperature can be concluded from the Fig. 4, whereas for carbon dioxide it decreased with temperature.Carbon dioxide and carbon monoxide are the major contributor in gases yield. The carbon dioxide emission is mainly from degradation of hemicellulose at lower temperature, which occured due to primary degradation of carbonaceous compounds and oxygen containing functional groups[12]. The carbon dioxide decreased

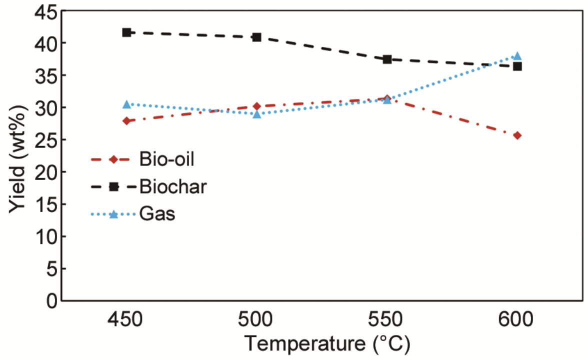

Fig. 3 — Bio-oil, bio-char and gases yield for rice husk at different temperatures

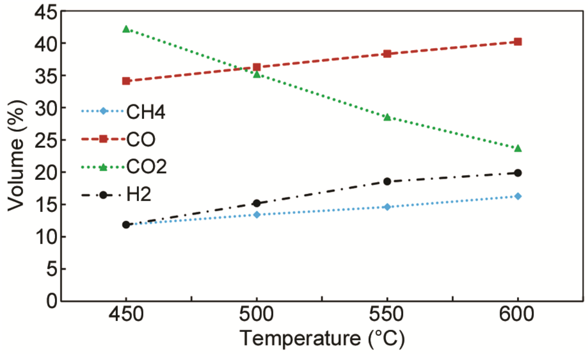

Fig. 4 — Gases yield at different temperatures

from 42.18% at 450 °C to 23.7% at 600°C.The carbonmon-oxide gas yield increased from 34.11% at 450 °C to 40.8% at 600°C due to endothermic reaction where hot carbon reacted with carbon dioxide[9]. Also, due to occurence of reduction reaction between water vapor and hot carbon during pyrolysis resulted in formation of carbon monoxide. The other factors contributing in carbon monoxide yield is cracking of carboxyl, phenolic and hetrerocyclic compounds in tar[13]. The hydrogen and methane concentration is found to be low in this study. It is reported that at lower temperature, reaction of free radical results in production of hydrogen and methane[13,14]. The methane yield increased from 11.87% at 450°C to 16.25 at 600°C due secondary cracking reactions, also thermal decomposition of benzyl and methoxyl groups contributed in methane yield[13,14]. At higer temperature dehydrogenation of aromatics and water shift reaction contributed in increase in hydrogen production[13].

Conclusion

In this study the twin screw auger pyrolysis reactor is designed and initial trials for parameters optimization is done. The fabricated reactor can be operated for feed flow rate of 1.5 to 7 kg/h with solid residence time of approximately 8 min to 1 min, respectively. The reactor is designed considering continous pyrolysis and gasification.When the temperature rises from 450 to 550°C, the bio-oil output rises from 27% to 33%. At 450 °C, the biochar output was 42%; at 600°C, it was 36%. Because of an endothermic reaction involving the reaction of heated carbon with carbon dioxide, the production of carbon monoxide gas increased from 34.11% at 450°C to 40.8% at 600°C[9]. This study finds that the concentrations of methane and hydrogen are low. Secondary cracking processes caused the methane production to rise from 11.87% at 450°C to 16.25 at 600°C. The thermal breakdown of benzyl and methoxyl groups also played a role in the methane yield[13,14]. Higher temperatures led to an increase in hydrogen generation due to the dehydrogenation of aromatics and the water shift reaction[3,7]. Gasification possibility will be checked in our future work. Considering major product as biochar and bio-oil different flow rate at different temperatures needs to be explored. The reactor is suitable for both bio-oil and biochar production. Simultanous removal of char would be helpful to avoid secondary reactions. To reduce moisture in bio-oil fractional condensation can be considered. Further study needs to be done to optimize parameters for different products using different biomass.

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Conflict of interest

The authors declare no conflict of interest.

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