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REVIEW

Optimizing biochar production: a review of recent progress in lignocellulosic biomass pyrolysis

Nguyen Xuan LOC[1], Do Thi My PHUONG (✉)[2]

1 Department of Environmental Sciences, Can Tho University, Can Tho 900000, Vietnam.

2 Department of Environmental Engineering, Can Tho University, Can Tho 900000, Vietnam.

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Correspondence: dtmphuong@ctu.edu.vn
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SUPPLEMENTARY MATERIALS

Table S1 Established and new pyrolysis processes, along with their respective strengths and limitations

Pyrolysis method	Production conditions and product yield	Scalability, efficiency and environmental impact			Limitations	Scale achieved	Barriers to expanded scale
		Scalability	Efficiency	Environmental impact			

Established pyrolysis methods	*Slow pyrolysis*	*Pyrolysis conditions*: Temperature: 300–700 °C Heating rate: 1–10 °C $\cdot$min^{-1} Residence time: > 1 h *Product yield* (%): Bio-oil: ~30 wt% Biochar: ~35 wt% Gases: ~35 wt%	• Being scaled to accommodate various feedstock types and production capacities • Adaptable to different production scenarios and resource availability, offering flexibility in its application	• Slow heating rates and longer residence time, facilitating more complete carbonization of the feedstock and resulting in higher biochar production compared to other pyrolysis methods • Ensuring the feedstock undergoes efficient carbonization through prolonged duration and precise heat control	• Properly designed slow pyrolysis processes can minimize emissions of harmful pollutants through effective combustion and gas cleaning systems • Biochar, when applied to soils, serves as a long-term carbon sink, assisting in climate change mitigation by capturing carbon from the atmosphere	• Certain biomass materials with high moisture content or low carbon content may not undergo efficient pyrolysis or yield biochar of desired quality, limiting the range of feedstocks that can be effectively utilized • Potential to generate emissions of volatile organic compounds and other pollutants during the pyrolysis process	Suitable for implementation in both small-scale systems, such as on-farm or community-level biochar production, and larger industrial-scale facilities	• Extended heating periods and precise temperature control increase energy use and operational costs • Long processing times reduce efficiency and complicate large-scale production • Achieving consistent feedstock quality and size on a large scale is challenging • Significant investment in large-scale equipment and infrastructure is required

	Fast pyrolysis	*Pyrolysis conditions*: Temperature: 400–800 °C Heating rate: 20–200 °C·min^{-1} Residence time: <10 min *Product yield* (%): Bio-oil: ~50 wt%; Biochar: ~ 20 wt%; Gases: ~30 wt%	- Applicability in various contexts, including agricultural settings and waste management facilities - Facilitating the conversion of different feedstocks into biochar, contributing to sustainable practices in agriculture and waste management	- Rapid heating rates and short residence times, leading to accelerated thermal decomposition and vaporization of organic matter - Efficient thermal decomposition of organic matter, maximizing bio-oil production efficiency	- Minimization of harmful pollutants by integrating advanced combustion and gas cleaning technologies - Promotion of sustainable practices by converting biomass waste into valuable resources, minimizing environmental impacts associated with traditional waste disposal methods	- Rapid heating rates and short residence times favor the production of volatile compounds, leading to lower biochar yield compared to slow pyrolysis - High energy input is needed to maintain rapid heating rates and optimal process conditions, which can raise operational costs and reduce efficiency, especially without renewable energy sources	Adaptable to different production capacities, ranging from small-scale operations suitable for localized biochar production to larger industrial-scale facilities	- Extended heating and precise control lead to high energy consumption and costs - Consistent feedstock quality and size are challenging at scale - Large-scale operations face difficulties in efficient heat and mass transfer - Significant investment in large-scale equipment and infrastructure is required

	Flash pyrolysis	*Pyrolysis conditions*: Temperature: 900–1300 °C Heating rate: >1000 °C·s^{-1} Residence time: <10 s *Product yield* (%): Bio-oil: ~75 wt%; Biochar: ~12 wt%; Gases: ~13 wt%	• Versatile feedstock handling, providing flexibility in material sourcing • By facilitating small-scale operations, decentralized processing promotes local economic development and reduces transportation costs	• Rapid heating rates and short residence times minimize secondary reactions, ensuring efficient conversion of biomass into desired products without significant by-product formation • Integration with downstream processes to recover additional products such as biochar and syngas, enhancing overall process efficiency and resource utilization	• Converting to renewable bio-oil reduces greenhouse gas emissions and lessens dependence on non-renewable resources • Promotion of sustainable practices by converting biomass into renewable energy sources (bio-oil) and soil amendments (biochar)	• The complex product mixture necessitates additional processing steps, leading to increased overall complexity and cost • The composition of bio-oil, containing elevated levels of oxygen, water, impurities, and contaminants, limits its quality and applicability, necessitating additional refining and upgrading processes	Scalability and adaptability in various contexts, allowing for implementation in diverse contexts and industries	• Flash pyrolysis demands expensive, specialized equipment for rapid heating and processing • Consistently preparing and managing feedstock poses challenges • Separating bio-oil, char, and gas efficiently is technically challenging • Maintaining precise conditions and rapid processing adds operational complexity

New pyrolysis methods	*Microwave pyrolysis*	*Pyrolysis conditions*: Temperature: 300–600 °C Heating rate: 15–30 min *Product yield* (%): Bio-oil: ~15 wt%; Biochar: ~50 wt%; Gases: ~35 wt%	• Flexibility in processing different types of biomass feedstocks • Efficient and controlled processing of biomass feedstocks, leading to the production of biochar, bio-oil, and syngas while minimizing energy consumption and emissions	• High heating rates and rapid thermal decomposition of biomass feedstocks, resulting in shorter processing times and higher biochar yields compared to established pyrolysis methods • Efficient energy transfer mechanism of microwaves enables uniform heating of the biomass material, promoting more complete pyrolysis and enhancing the quality of the produced biochar	• Compared to established methods, microwave heating provides faster pyrolysis, selective material heating, and better process control, potentially increasing yields of biochar, bio-oil, and syngas while reducing impurities • Microwave pyrolysis can quickly achieve the desired temperature and requires minimal power to maintain the reaction once initiated	• Specialized microwave reactors and control systems are necessary to ensure efficient and safe operation, potentially increasing overall capital expenses compared to established heating systems • Calibrating and optimizing microwave power and frequency are essential for achieving uniform heating and maximizing process efficiency, adding complexity to operations	Scalability across production capacities, ranging from small-scale laboratory setups to large industrial facilities	• Low product yield and quality, coupled with high power consumption, specialized and costly equipment are the primary challenges in scaling up equipment • Ensuring even heating across feedstock can be challenging • Feedstock must be specifically prepared for microwave heating, adding complexity • Maintaining uniform microwave distribution and process control is difficult at large-scale

	Co-pyrolysis	*Pyrolysis conditions*: Temperature: 300–1200 °C Heating rate: varied Residence time: varied *Product yield* (%): Bio-oil: ~32 wt%; Biochar: ~40 wt%; Gases: ~28% wt%	• Employing a variety of feedstocks enhances the flexibility of co-pyrolysis processes, enabling them to adapt to diverse production scenarios and resource availability • Integration with existing infrastructure and processes, facilitating its adoption and implementation in diverse settings • Promotion of resource efficiency by enabling the utilization of various feedstocks and byproducts, contributing to sustainable resource management and	• Strategic selection of complementary feedstocks with diverse chemical compositions and thermal decomposition characteristics enables co-pyrolysis processes to achieve higher biochar yields and superior product quality compared to single-feedstock pyrolysis • Co-pyrolysis of various biomass feedstocks lowers production costs, enhances process convenience and efficiency, and minimizes waste formation.	• Utilizing biomass residues and waste materials reduces dependence on fossil fuels for energy production, thereby mitigating greenhouse gas emissions associated with both waste decomposition and fossil fuel combustion • Co-pyrolysis offers an effective waste management solution by reducing waste volume, saving landfill space, cutting waste management costs, and mitigating environmental issues associated with landfills, all	• The quality and composition of feedstocks can vary, leading to inconsistent outcomes and operational challenges • Co-pyrolysis setups often require sophisticated equipment for handling multiple feedstocks simultaneously, which can increase costs and maintenance requirements • Co-pyrolysis may generate various byproducts that require proper handling and disposal, adding complexity to the process	• Co-pyrolysis for biochar production is currently at the lab scale, and addressing various challenges is crucial for advancing the technology to commercial-scale production • The reactor choice for co-pyrolysis varies by product and conditions: slow pyrolysis reactors (drum, rotary, screw-fed) are used for biochar, while fast reactors (fixed, fluidized bed, vacuum, rotating cones, auger, ablative) are suited for oil and gas production	• Ensuring and verifying the quality and efficiency of biochar from diverse feedstocks and processes is challenging on a large scale, with the goal of maximizing its benefits for agriculture, the environment, and the economy • Ensuring consistent conditions for mixed feedstocks is complex • Separating byproducts from various feedstocks is technically demanding • Transitioning from laboratory-scale to industrial-scale operations can pose difficulties in maintaining process efficiency and consistency

			waste valorization efforts		while generating an alternative energy source			

	Hydrothermal carbonization (HTC)	*Pyrolysis conditions*: Temperature: 220–240 ºC Pressure: 2–10 MPa Residence time: 1–72 h *Product yield* (%): Bio-oil: ~25 wt%; Hydrochar: ~65 wt%; Gases: ~10 wt%	• Uniform heating, mixing, and reaction conditions across larger volumes is crucial for maintaining process efficiency and product quality during scale-up • Need for innovative engineering solutions to overcome challenges such as heat and mass transfer limitations and reactor design complexities	• High carbon conversion efficiencies, transforming biomass into valuable products such as hydrochar, bio-oil, and biogas • Operating at moderate conditions results in lower energy consumption compared to alternative thermochemical conversion methods	• HTC can produce hydrochar, a versatile material with a range of applications • Upscaling HTC technology can convert substantial amounts of organic waste from landfills into valuable products, thereby reducing greenhouse gas emissions and lessening environmental impact	• HTC efficacy can vary depending on the feedstock used. Some materials may not undergo effective carbonization or may produce low-quality hydrochar • HTC typically requires longer reaction times compared to other thermochemical processes, which can affect production efficiency and throughput	HTC technologies are predominantly applied in batch mode using lab-scale autoclaves, bench-scale reactors, and a few pilot-scale systems	• Pre-drying biomass before HTC aids in processing but may not reflect large-scale conditions. Assuming rehydrated feedstock retains original properties can cause scaling issues, as industrial reactors use biomass at its natural moisture content • In large-scale HTC production, stirring lacks standardization, leading to discrepancies from variations in reactor sizes, process conditions, feedstock types, and output measures

	Autothermal pyrolysis methods	*Pyrolysis conditions*: Temperature for pre-heat: ~450 °C Heating rate: ~10 °C·min^{-1}) Residence time: ~10 min; Carrier gas: N$_2$ mixed with 3 %, 5 %, or 10 % O$_2$ *Product Yield* (%): Bio-oil: ~50 wt%; Biochar: ~30 wt%; Gases: ~20 wt%	• Suitability for various contexts, including decentralized biomass processing, waste-to-energy facilities, and industrial-scale biochar production • Promotion of sustainable practices by converting biomass and waste materials into valuable products while minimizing environmental impacts. This supports efforts to transition towards a circular economy and reduce reliance on fossil fuels	• Self-sustained thermal decomposition of biomass by utilizing internal heat generated from exothermic reactions within the system • Enhanced overall process efficiency compared to established pyrolysis methods, as it harnesses the energy released during pyrolysis • Reduction of external energy requirements and operational costs by utilizing the energy generated internally, leading to improved efficiency, lower environmental impact and carbon footprint associated	• Autothermal pyrolysis can address the energy supply challenges of established pyrolysis, offering a promising method for converting biomass into valuable products	• Complexity of design to achieve self-sustained thermal decomposition of biomass. Designing reactors capable of efficiently harnessing internal heat generation while maintaining process control can be challenging and may require specialized expertise • Achieving optimal operating conditions is complex. Balancing factors such as feedstock composition, heating rates, residence times, and gas composition to	With scalability across production capacities, the autothermal methods gain versatility and applicability across various fields	• Efficiently managing the energy required to sustain the autothermal reaction can be challenging, especially as scale increases. Maintaining the balance between energy input and output is crucial for process stability • A thorough understanding of the kinetic behaviors of autothermal pyrolysis is required for effective reactor design and successful process scaling

				with energy consumption		achieve stable and efficient operation requires careful process optimization and control • Supplementary energy inputs may still be required, particularly during startup or under variable operating conditions		