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Review

Comparative assessment of biochar reactor technologies for biomass conversion: Design, performance, and application suitability

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ABSTRACT

The effectiveness of biochar for ecological restoration, toxicity remediation and carbon sequestration are fundamentally dependent on the biochar production technology. This review provides a systematic comparison of thermochemical conversion techniques such as pyrolysis (slow, rotary kiln, auger-based), gasification (downdraft and fluidized bed) and hydrothermal carbonization (HTC). Key performance metrics such as temperature profile, residence time, emissions regulation, and scalability are evaluated alongside critical biochar qualities such as surface area, porosity, fixed carbon content, cation exchange capacity, and polycyclic aromatic hydrocarbon. Priority has been given to aligning the biochar produced from each reactor with their respective environmental applications based on the biochar functions, such as nutrient retention, pH adjustment, and carbon fixation. The reactor performances have been summarized in context with production capacity, capital cost, and other variables related to system selection. The review uniquely integrates technical, environmental, and agronomic factors to propose a decision framework that aligns biochar production technologies with appropriate feedstocks, logistical settings, and long-term sustainability goals. In conclusion, this interdisciplinary approach fills a gap in literature by linking reactor engineering with functional outcomes in land management and climate resilience.

1. Introduction

The ongoing global challenges of climate change, natural and anthropogenic land degradation and waste accumulation has led to a global interest towards carbon neutral or negative technologies that are driven by circularity. Biochar, a carbonaceous, recalcitrant and highly porous by-product of pyrolytic conversion of biomass, has emerged as a multi-faceted solution at the intersection of land restoration, carbon sequestration, and sustainable waste valorization (Lehmann and Joseph, 2015; Lal, 2016; Ghosh et al., 2025; Rodriguez Franco et al., 2024). The large volume of woody biomass generated from forest restoration thinning, logging residues, and wildfire risk reduction treatments present both a biomass waste management challenge and an opportunity for biochar production. These materials are often underutilized due to high transportation and processing costs, resulting in open pile burning, which contributes to greenhouse gas emissions and air quality degradation (Han et al., 2018). Historically inspired by the high-fertility Amazonian Terra Preta soils, modern biochar technologies are now engineered to provide a range of environmental services, including soil fertility improvement, cleanup of pollutants, greenhouse gas reduction, and enabling long-term carbon sequestration (Lehmann and Joseph, 2015; IPCC, 2018). Many of these systems also provide usable energy in the form of heat, electricity and even liquid fuels. The performance, scalability and mobility of biochar production largely depend on the reactor technology and production conditions, which determine biochar physicochemical properties and potential for various end uses.

Biochar is predominantly produced through pyrolysis, a thermochemical conversion carried out under low-oxygen conditions that converts biomass into biochar and a combination of condensable and non-condensable gases (Santos et al., 2024; Ippolito et al., 2015; Ronsse et al., 2013; Crombie et al., 2013). Pyrolysis reactor systems employed differ greatly in terms of scale, configuration, heating rate, and recovery of energy (Fryda and Visser, 2015). Some of them are fixed-bed, rotary kiln, fluidized-bed, auger, and microwave-assisted reactors, which have some merits in terms of energy efficiency, product homogeneity, and feedstock compatibility (Tripathi et al., 2016; Jerzak et al., 2024; Vieira

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et al., 2020). Energy recovery can include heat (especially process heat), bio-oil, methane and syngas that can be used in the production of liquid fuels and chemicals, especially using the Fischer–Tropsch process. The selection of an appropriate pyrolysis reactor is critical not only for ensuring process efficiency but also for tailoring biochar characteristics such as porosity, pH, nutrient content, and carbon stability, factors that directly affect biochar's suitability for soil amendment or remediation applications (Sharma et al., 2024; Santos et al., 2024; Ippolito et al., 2015).

The bioreactor technology selection is driven by factors like feedstock, target throughput, operating temperature range (typically 350–700 °C), residence time, energy recovery needs, degree of automation, capital cost and cost-effectiveness (Safarian, 2023; Al-Rumaihi et al., 2022). For example, agricultural settings can host dispersed, low-tech, inexpensive batch kilns for processing crop residues and woody biomass from orchards, while centralized, continuous rotary or auger kilns suit industrial-scale operations with heat recovery from mill residues (Shackley et al., 2011; Fehmi et al., 2020).

Heavily forested areas have high biomass fuel load and often prone to wildfires. Mobile pyrolysis systems like CharBoss, Charm Industrial Pyrolyzer, Tigercat Carbonizer can provide an effective solution for biomass valorization by producing biochar on-site, which increases transportation efficiency, reduces hauling cost and lowers fire risks while maintaining environmental compliance (Page-Dumroese et al., 2024; Oyier et al., 2024; Pierson et al., 2024). Furthermore, in cases where sustainable soil rehabilitation is the primary objective, reactor system selection should prioritize the production of biochar with high cation exchange capacity, nutrient adsorption, low contaminant levels, and a high recalcitrant carbon (Ippolito et al., 2020; Santos et al., 2025). Different applications require specific biochar properties; for example, a large surface area to enhance pollutant adsorption or a high mineral content to ameliorate acidic soils; making reactor design critical in ensuring that biochar characteristics are tailored to performance requirements in targeted applications (Ganesapillai et al., 2023; Ronsse, 2016). Apart from the end product requirements, other important factors that influence system selection are economics and logistics. For example, while centralized biomass processing facilities can reduce the per-ton handling costs and benefit from economies of scale, they often incur higher transportation costs. In contrast, decentralized pyrolysis systems, situated closer to biomass sources and end-use sites, may provide greater economic and environmental feasibility, particularly in remote or difficult-to-access regions (Kizha and Han, 2016). In conclusion, aligning reactor technology with site-specific conditions, biomass characteristics, and end-use objectives is key to maximizing both the environmental and economic benefits of biochar systems.

Benefits of biochar in soil environments have been extensively researched and are well-supported under diverse soils and climates (Joseph et al., 2018; Sarauer et al., 2019; Ghosh et al., 2020). Application of biochar can enhance soil structure, water retention, microbial activity, and nutrient cycling and concurrently mitigate nitrous oxide and methane emissions (Jeffery et al., 2017). In both polluted and degraded soils, biochar can immobilize heavy metals, restrict leachate toxicity, and enhance the effectiveness of phytoremediation (Ghosh and Maiti, 2020). These outcomes heavily rely on the quality of biochar and the compatibility between biochar properties and soil conditions. There have also been recent findings that highlight biochar efficiency in restoring forest soils following wildfires by stabilizing soil structure, resisting erosion, facilitating water infiltration, and improving microbial and vegetative recovery (Ghosh et al., 2025; Wittenberg & Shtober-Zisu, 2023; Prats et al., 2021; Fehmi et al., 2020). Similarly, in mine-degraded soils, biochar has been reported to be effective at reversing soil acidity, immobilizing remaining toxic metals such as arsenic and cadmium, and improving adsorption of nutrients, thereby facilitating the re-growth of vegetation and improving long-term soil health (Ghosh and Maiti, 2020; Ippolito et al., 2019). These specialized applications further underscore the importance of tailoring biochar properties such as ash content, pH, and surface functional groups to address the specific challenges of post-disturbance or chemically degraded soils.

With the rapid expansion of the biochar and carbon-rich soil amendment market, there is a growing demand for standardized quality benchmarks and certified production processes. International standardization such as the European Biochar Certificate (EBC) and IBI Biochar Standards, now offers thresholds for elemental content, carbon stability, and contaminant safety (IBI, 2012). Quality assurance, however, extends beyond the lab; it begins with reactor design and operational consistency. A range of industrial-scale reactor systems is now commercially available, tailored to handle specific biomass types and aligned with regional regulatory standards (Fryda and Visser, 2015). Many of these systems are equipped with features such as integrated energy recovery and digital monitoring and process controls that enhance carbon yield, operational efficiency, and traceability throughout the production process. Due to the wide variation in reactor technologies and the diverse end-use requirements for biochar, there remains a strong need for multidisciplinary approaches to develop optimized selection frameworks tailored to specific environmental applications. Soil restoration, for instance, demands biochar that is not only effective in nutrient retention and structural amendment but also economically viable and locally produced to reduce life-cycle emissions. Therefore, this paper seeks to provide a comprehensive review and analytical framework for selecting pyrolysis reactor systems optimized for sustainable soil remediation, integrating considerations of production efficiency, environmental benefit, regulatory compliance, and deployment scalability.

While previous studies have explored biochar properties (Ippolito et al., 2020), reactor performance (Ronsse et al., 2013), or environmental applications independently (Al-Rumaihi et al., 2022), few have integrated these dimensions into a unified assessment. This paper addresses that gap by offering a reactor-specific comparison framework that connects design parameters with biochar functionality, operational scale, and application suitability for soil restoration. The main objectives of the study are: (1) Assess biochar production techniques and the relationship between reactor design and char characteristics; (2) Identify and elaborate key reactor selection criteria, including technical, economic, and environmental dimensions. (3) Map current pyrolysis reactor technologies and companies, analyzing their suitability for targeted use cases in sustainable soil restoration.

2. Biochar production techniques and the relationship between reactor design and biochar characteristics

As mentioned earlier, the type of reactor significantly influences the physicochemical characteristics of the biochar produced. It has been reported that a biochar produced in a auger-type reactor with slow pyrolysis typically yields higher amounts of biochar but with smaller surface areas and elevated levels of polycyclic aromatic hydrocarbons (PAHs) compared to fluidized bed gasification reactor (Santos et al., 2024; Fryda and Visser, 2015). Similarly, studies on fixed bed reactors show that increasing the pyrolysis temperature enhances the fixed carbon content and surface area of the biochar, while rotary kiln reactors provide valuable insights into how temperature affects biochar quality, particularly PAH concentrations and the presence of toxic elements (Lataf et al., 2022). In downdraft gasifiers, the slightest variation in temperature can affect biochar properties, underlining the need for precise thermal controls (Rollinson, 2016). Nitrogen plasma reactors, which facilitate both pyrolysis and gasification, reveal complex interdependencies amongst temperature, yield, and biochar characteristics (Muvhiiwa et al., 2019). Additionally, entrained-flow reactors, which operate across a broad temperature range, demonstrate strong temperature-driven changes in yield, chemical composition, and reactivity of the produced biochar.

Studies report a rise in surface area due to the increase in pyrolysis temperature, due to the aromatic rings formed through the volatilization of organics (Ghosh and Maiti, 2020; Roshan et al., 2023). Similarly, the proportion of fixed carbon and stable carbon typically increases with temperature, enhancing the recalcitrant carbon content, which in turn improves the carbon sequestration potential of biochar (Ronsse et al., 2013). However, this relationship may become more nuanced under certain conditions, such as in nitrogen plasma reactors, where carbon proportion increases with temperature during pyrolysis but decreases during gasification when oxygen flow is introduced (Muvhiiwa et al., 2019). The pH of the biochar has been reported to rise with temperature due to the thermal degradation of acidic functional groups and the concentration of basic mineral components (Fryda and Visser, 2015). Similarly, polycyclic aromatic hydrocarbon (PAH) content increases significantly at temperatures >750 °C, however gasification process often reduces the PAH levels in biochar compared to slow pyrolysis biochar. Pore characteristics such as volume and size have also been reported to increase with rising temperature (Lataf et al., 2022). On the contrary, the biochar yield has an inverse relationship with temperature, as the higher temperature drives off the volatile matter, which reduces the solid residues (Ghosh et al., 2020). Overall, optimizing pyrolysis parameters is critical for achieving desired biochar qualities for specific soil restoration and remediation goals (Table 1). Another important factor that influences biochar properties is the feedstock material used for its production (Ippolito et al., 2020; Tomczyk et al., 2020; Mishra et al., 2023; Hassan et al., 2020). Among biochar standards established by trade associations and carbon offset credit registries, some feedstocks do not meet specifications, including some types of manure, municipal sewage sludge, some aquaculture and meat processing wastes, biological medical waste, and some partially processed industrial biomass wastes (Climate Action Reserve, 2024; Puro.earth, 2025; Voluntary Carbon Standard, 2025). This is often due to the common presence of contaminants or other properties that make the resulting biochar inappropriate for soil amendment. Though many of the aspects of pyrolysis described here apply to these challenging feedstocks, a detailed discussion of pyrolysis with a waste disposal focus is beyond the scope of this paper and can be found elsewhere (Paz-Ferreiro et al., 2018; Qureshi et al., 2020).

Biochar characteristics, such as surface area, carbon stability, and contaminant levels are strongly influenced by the feedstock used for production. For example, feedstocks with high ash content, like rice husk yield varying stable carbon than those with poor ash content like pine or wheat straw. Additionally, minor differences in the feedstock moisture content can influence the biochar surface area and the PAH contents, indicating the sensitivity of the biochar properties to the feedstock material properties. Optimal pyrolysis conditions are also feedstock-specific, a study conducted on the use of shredded cotton stalk feedstock showed that even optimum temperature and residence time maximized the desirable biochar properties (Makavana et al., 2020). Moreover, stability in the resultant biochar, indicated by elemental ratios like O/C and H/C, is determined by the interaction between feedstock chemistry and pyrolysis temperature, demonstrating a synergistic relationship between material and thermal conditions. Overall, these findings underscore the importance of proper feedstock selection and characterization, together with reactor design and process optimization to tailor biochar properties for specific applications.

3. Types of biochar production reactors

The reactor type used for biochar production plays an important role in determining its physicochemical characteristics and, hence its suitability for specific end-use applications. Reactor designs such as slow pyrolysis, fixed-bed, entrained-flow, and nitrogen plasma reactors produce biochar with distinct properties. (Santos et al., 2024; Fryda and Visser, 2015). For example, nitrogen plasma reactors produce biochar by thermal decomposition of biomass under closed conditions using nitrogen gas as the plasma-forming gas. Plasma, which is created by electrical discharges, facilitates the formation of biochar in inert or semi-inert conditions, inhibiting unwanted oxidation and allowing for the control of desired biochar properties. The choice of biochar production reactors such as slow pyrolysis, fixed bed, entrained flow, or nitrogen plasma, implicitly determines the properties of biochar, tailoring applications like soil amendment or wastewater treatment. Fixed-bed systems with continuous and centralized configurations often support large-scale biochar production. However, for heterogeneous biomass, broader thermochemical conversion processes such as pyrolysis, gasification, and hydrothermal carbonization are typically employed, and are discussed in detail in the subsequent sections.

3.1. Pyrolysis reactors

Pyrolysis is a thermochemical conversion process that decomposes organic biomass at high temperature (typically 300–700 °C) in the absence or limited supply of oxygen to yield three principal products: solid biochar, condensable bio-oil, and syngas (Ahmed et al., 2025; Raza et al., 2021). The relative yield and nature of the products are governed by key operation parameters such as temperature, heating rate, residence time, and reactor type. In particular, the design of the pyrolysis reactor is the most important factor for process efficiency, product distribution, and environmental performance. The types of reactors include fixed-bed, fluidized-bed, rotary kiln, auger, and entrained-flow systems, which can be optimized for specific feedstocks and capacities. For instance, fixed-bed reactors are simple and usually low capital cost, widely used for small-scale batch operation, while fluidized-bed and rotary kilns offer higher throughput and even heat distribution, but are generally higher cost, and hence better suited to continuous industrial operation. Recent innovations have also included modular and mobile pyrolysis units (e.g., CharBoss, Charm Industrial) that allow decentralized waste processing and in-field biochar production. Moreover, developments in emissions controls and integration with energy recovery systems have significantly enhanced the sustainability of modern pyrolysis platforms. Studies have further highlighted the importance of synchronizing reactor design with feedstock properties (e.g., particle size, moisture content, lignocellulosic composition) to optimize carbon yield, energy efficiency, and the functional properties of biochar for soil amendment, carbon sequestration, and environmental remediation. For example, gasifiers typically require smaller, more uniform feedstock particles, as opposed to some mobile units, which cannot process chipped, ground or pulverized materials. Rotary kilns provide continuous processing with uniform heating and temperature control, which is valuable in minimizing toxic compounds such as polycyclic aromatic hydrocarbons (PAHs) (Moser et al., 2023). Table 2 provides an overview of commercial pyrolysis reactors with a focus on reactor types, scales, feedstock compatibility, and emission controls, covering laboratories to industrial systems used in agriculture, forestry, and waste-to-biochar applications.

Slow Pyrolysis Reactors, such as auger and fixed-bed types, operate at relatively low temperatures (300–600 °C) and long residence times, which favor higher biochar yields. However, biochar from slow pyrolysis often exhibits lower surface areas and can contain elevated levels of PAHs when processed above 500 °C (Moser et al., 2023). Similarly, fixed-bed reactors are known for their design simplicity and scalability and demonstrate consistent increases in fixed carbon and porosity as pyrolysis temperature rises. These are often used in both experimental and decentralized production settings (Vieira et al., 2020). In contrast, rotary kiln reactors are designed for better mixing and thermal uniformity; and are suited for industrial-scale operations. Temperature control is critical in these systems, as it strongly influences PAH content and trace element behavior in the resulting biochar (Moser et al., 2023).

3.2. Gasification reactors

Gasification reactors operate at elevated temperatures (approximately 700–1200 °C) and with minimal oxygen or steam, producing syngas and minor solid residues called biochar (Fryda and Visser, 2015;

Table 1
Overview of common biochar reactor designs, operating conditions, and their effects on surface area, chemical properties, and suitability for environmental applications.

Reactor type	Design Features	Operating Parameters	Key Advantages	Biochar Characteristics		Quality Indicator	Challenge/ Disadvantage	References
				Surface Area and Pore Characteristics	Chemical Properties			
Fixed bed slow pyrolysis	Stationary biomass bed, gas flow through the bed	Temperature: 350–750 °C, residence time: minutes to days	Simple design, suitable for slow pyrolysis	Increases with temperature	Fixed carbon content increases with temperature. Higher N, S, available-P, Ca, Mg, higher cation exchange capacity	Suitable for soil amendment	Limited feedstock flexibility, uneven heating, batch operation; emission control, periodic cleaning	Santos et al. (2024); Ippolito et al. (2015); Ronsse et al. (2013); Crombie et al. (2013)
Gasification (Fluidized bed)	Suspended solid particles in gas/ liquid	Temperature: 600–750 °C (gasification)	Efficient heat transfer, high reaction rates	Large compared to slow pyrolysis	Lower PAH content, higher pH, and ash content; very low tar content	Potential for diverse applications	Needs uniform feedstock, strict emission control for syngas; high maintenance for moving parts and temperature control	Fryda and Visser (2015);
Slow pyrolysis (Auger reactor)	Rotating screw mechanism	Temperature: 450–550 °C, biomass flow rate: up to 1 kg/ h, residence time: 5 min	Continuous operation, good residence time control	Smaller compared to gasification	Higher PAH content	Appropriate for environmental applications	Needs uniform feedstock, regular auger maintenance, potential emission spikes if not sealed well; throughput limitations	Santos et al. (2024); Fryda and Visser (2015)
Downdraft gasifier	Downward gas flow, reduction zone	Operates under slight negative pressure	Suitable for small-scale electricity production	Higher for lower moisture content feedstock	Higher PAH content for lower moisture content biomass	Potential for high-value applications	Low-moisture feedstock, tar risk, regular cleaning needed, emission control vital for gases produced	Rollinson (2016)
Nitrogen plasma reactor	Use of plasma technology	Temperature: 400–1000 °C	Novel approach, potential for unique biochar properties	Pore volume and size increased with temperature.	Carbon content increases with pyrolysis temperature, and decreases with oxygen flow in gasification.	High carbon purity and porosity, with potential for advanced environmental applications (e.g., pollutant adsorption)	Needs pure, dry feedstock; high energy/ maintenance, advanced emission control	Muvhiiwa et al. (2019)
Batch Pyrolyser	Closed system, oxygen-limited, manually loaded, batch operation.	Temperature: 300–700 °C	Excellent control over residence time	Variable, dependent on feedstock	Variable PAH; stable carbon at higher temperatures	Appropriate for on-farm use	Small, uniform feedstock, batch cleaning, maintenance to avoid blockages, emission peaks possible when opening chambers	Joseph et al. (2018); Oyier et al. (2024); Wilson et al. (2024)
Continuous Pyrolysers	Biomass is fed into one end while biochar is continuously discharged from the other.	Temperature: 300–800 °C	More control over the process conditions of the biochar, lower emissions	Moderate–high, depending on feedstock	Consistent quality; reduced PAHs	Suitable for commercial operations	Uniform feedstock, expertise needed; costly scaling, regular checks	Joseph et al. (2018)
Stove (TLUD, Luau, etc.)	Updraft or top-lit micro-scale	300–600 °C	Low-tech, portable, cooking dual use	Limited unless optimized	Variable: high ash content	Rural & smallholder settings	Dried feedstock, no emission control, frequent ash cleaning	Ghosh and Maiti (2020)
Kiln (Kon-Tiki, Pit)	Open batch system, semi-buried or cone-shaped	400–700 °C	Low cost, easy to construct	Variable; depends on oxygen control	PAH content above 750 °C, some toxic elements decreased above 600 °C	Suitable for low-resource contexts	Accepts diverse feedstock, but oxygen/ temperature control difficult; open burn can lead to high uncontrolled emissions, regular maintenance to remove clogs	Lataf et al. (2022); Joseph et al. (2018)

(continued on next page)

Table 1 (*continued*)

Reactor type	Design Features	Operating Parameters	Key Advantages	Biochar Characteristics		Quality Indicator	Challenge/ Disadvantage	References
				Surface Area and Pore Characteristics	Chemical Properties			
Retort	Closed system with external heat source	400–700 °C	Controlled burn, gas recycling	Good pore development	Cleaner burn, lower emissions	Ideal for artisanal production	Requires uniform feedstock, temperature management, periodic cleaning, and emission control	Joseph et al. (2018); Crombie et al. (2013)

Muvhiiwa et al., 2019; Rollinson, 2016). Gasification involves four stages: drying, pyrolysis, oxidation, and reduction, each leading to the transformation of biomass to syngas (Situmorang et al., 2020). Unlike pyrolysis, gasification is more about the production of energy-dense gases, typically yielding lower but more reactive and cleaner biochar. Table 3 summarizes key features of optimal gasification technologies, spanning from small modules to industrial platforms, highlighting feedstock compatibility, emission control systems, and biochar productivity potential.

- Downdraft Gasifiers: The most common gasification technology that is used for small-to medium-scale biochar production. They pull gases downward through the biomass bed, allowing for high-temperature reaction and relatively low tar syngas (Indrawan et al., 2020). Biochar produced by downdraft gasifiers are extremely sensitive to temperatures, and precise thermal control is essential for consistency in carbon content, surface area, and levels of contamination.
- Fluidized Bed Gasifiers: These reactors are known for the uniform temperature distribution and enhanced mixing of feedstock, leading to effective burners and more homogenized biochar (Nam et al., 2016). They are most used in pilot-scale commercial plants and research, and the biochar produced by this process generally has lower PAH content compared to slow pyrolysis products and provides greater surface area, hence can be potentially used for environmental remediation.
- Updraft and Crossdraft Gasifiers: Not widely utilized in biochar-focused manufacturing, these types of gasifiers can yield biochar as a by-product, but the quality and consistency of the material may vary based on unstable temperature distribution or ash buildup. Updraft gasifiers are effective and can handle wet biomass but have tar-rich syngas, while crossdraft gasifiers yield clean syngas with faster response times but require dry low-ash fuel. The cross/updraft hybrid system unifies the advantages of both, yielding high cold gas efficiency (~94 %), tar content minimization, and improved operation flexibility (Čespiva et al., 2022).

Several new companies are applying gasification technologies to produce high-quality biochar alongside renewable energy. Aries Clean Technologies (USA) specializes in fluidized bed gasification of biosolids and wood biomass, generating energy and biochar for industrial and agronomic uses. Similarly, All Power Labs (USA) offers downdraft gasifier modules, such as their PowerPallet systems, which are ideally suited for decentralized combined heat and power (CHP) and small-scale biochar manufacture. Carbon Lock Technologies in Canada uses downdraft gasification to make carbon-negative biochar from forest and agricultural residues with a focus on carbon removal and soil improvement. France-based Biogreen Energy provides adaptable thermochemical platforms like gasification for conversion of variable biomass feedstocks to syngas, bio-oil, and biochar. In contrast, 3R-Bio-Phosphate Ltd. (EU) employs EU biochar certification-grade high-temperature rotary kiln gasification systems that complement European circular economy and sustainable agriculture paradigms. These companies are examples of the growing commercial interest in scalable, carbon-negative gasification technologies that integrate waste valorization with sound environmental management.

Biochar from gasification, especially from downdraft and fluidized bed gasifiers, has shown great potential for use in soil amendment (Fryda and Visser, 2015). With lower production yields than pyrolysis, gasification-based biochar generally has a higher surface area, higher porosity, and higher reactivity, which are characteristics that make it more effective in improving soil aeration, water retention, and nutrient holding capacity (Hansen et al., 2015). Moreover, the relatively low PAH content and homogeneous carbon composition make it safe for application in agriculture, especially if treated under controlled temperature. Cross/updraft or nitrogen plasma reactor gasification biochar, which is highly porous (up to 0.188 m^3g^{-1}) and has low tar production (0.1–0.5 g $N^{-1}m^{-3}$), enhances degraded soil water retention and microbial populations, particularly with the addition of organic amendments, due to its unique structural and chemical characteristics (Čespiva et al., 2022; Hansen et al., 2015; Fryda and Visser, 2015). Its alkalinity also serves to correct pH in acidic soils, and its high cation exchange capacity (CEC) ensures nutrient retention with minimal leaching losses (Wang et al., 2020).

3.3. Hydrothermal carbonization (HTC) reactors

Hydrothermal carbonization (HTC) is a thermochemical conversion process that converts wet biomass into hydrochar using heat (180–250 °C) under autogenous pressure, with residence times ranging from 0.5 to 8 h (Libra et al., 2011; Lucian and Fiori, 2017). Unlike traditional pyrolysis, HTC successfully processes high-moisture feedstocks without energy-intensive drying and is well-adapted to the conversion of wet biomass. Reactor scales vary widely,from laboratory systems like the Parr Instrument Hydrothermal Reactor used for research, to medium-scale units such as the Hydrothermal Biochar Reactor (HBR-1000) supporting farm-based waste management, and large industrial systems like HTCycle, TerraNova Ultra, and SunCoal HTC designed for continuous processing of municipal sludge, food waste, and digestate (Table 4).

A key advantage of HTC is its broad feedstock compatibility, capable of handling wet biomass types including wet waste, agricultural residues, and organic municipal waste (Jiang et al., 2025). For example, CarboCat and TerraNova Ultra target wastewater sludge, while HTCycle and SunCoal focus on food and green waste. The ability to convert more than 70 % water content feedstocks to stable carbonaceous hydrochar without drying enhances HTC energy balance and its sustainability for various waste streams. Additionally, the closed, high-pressure system of the HTC reactor minimizes direct air emissions when compared to dry thermal processes. Industrial systems often incorporate integrated emission controls and nutrient recovery technologies to comply with environmental standards and reclaim valuable resources from process water.

Although hydrocar and biochar might have some physio-chemical differences, HTC is included in reviews of biochar production technologies because it represents a complementary thermochemical

Table 2
Overview of commercial pyrolysis reactors with focus on reactor types, scales, feedstock compatibility, and emission controls, covering lab to industrial systems used in agriculture, forestry, and waste-to-biochar applications.

Reactor Name	Company/ Manufacturer	Scalability	Feedstock compatibility	Emission Control	Description	References
AGRA marketing	Agricultural Waste Solutions (California)	Large-scale	Dairy manure, agricultural residues	Integrated GHG and emission capture	Converts dairy/agricultural waste into jet fuel and biochar	(Agra Marketing Group)
Abritech Mobile & Stationary Pyrolysis Systems	Abritech Inc. (Quebec, Canada)	Small to large scale, modular and upgradable	Woody biomass, agricultural residues,	Cyclone separators and condensers reduce PM, VOCs, and CO emissions	Patented auger-based pyrolysis unit uses steel shot as a heat carrier, paired with a chain-flail biomass dryer for in-line moisture reduction, producing biochar, bio-oil, and syngas	(Abritech Inc. Products – Abritech)
Airex Energie Inc.	Airex Energie (Canada)	Large-scale	Woody biomass	Fast pyrolysis; gas cleanup	Torrefaction and fast pyrolysis technology	(Airex Energy Tech)
Ankur Rotary Kiln Pyrolyzer	Ankur Scientific (India)	Industrial-scale	Agricultural residues, wood chips, mixed biomass	Cyclone and scrubber systems can be integrated	Industrial rotary kiln for continuous biochar production.	(Ankur Scientific)
ARTi Modular Pyrolysis Reactor	Advanced Renewable Technology International (USA)	Modular design; scalable by adding reactor trains	Forestry residues, agricultural waste, food waste, woodchips, mushroom substrate	Afterburners, gas scrubbing, particulate filters, heat recovery for VOC and CO control	Containerized, modular, and transportable systems that can house up to five pyrolysis trains per container.	(ARTi)
BC Biocarbon	BC Biocarbon (Canada)	Medium	Forestry/agricultural waste	Standard gas cleanup	Batch/continuous systems	(Biocarbon)
Best Biochar Garden Kiln	–	Small	Garden biomass, wood	None	Cone kiln for hobby or household-scale production	United States Biochar Initiative (2023)
Big Box Biochar	Open-source/ Independent	Small–Medium (up to 40 TPD)	Woody biomass	Minimal, flame cap	Scalable open firebox flame-cap design; modifiable	United States Biochar Initiative (2023)
Biochar Solutions (B-1000)	Biochar Solutions Inc. (USA)	Small to medium; up to 500 lbs/hr dry biomass per unit; multiple units for higher throughput	Forestry/agricultural residues	Controlled oxygen-limited environment reduces CO/ NOx/PM	Two-stage continuous process carbonizes woodchips at 500–700 °C for <1 min followed by a hold of 300–550 °C for14 min produces biochar with high fixed carbon and surface area.	(Biochar Solutions Inc)
BiocharNow	BiocharNow (USA)	Medium	Agricultural and forestry residues	Patented stack assembly purifies the emissions of smoke and CO/NOx/PM	Commercial-scale batch pyrolyzers with multi-zone combustion, airflow, negative pressure and allows modifications for machine functioning.	(BiocharNow)
Bioforcetech	Bioforcetech (California, USA)	Medium	Wet waste, organics	Low-emission + drying integrated	Drying and carbonization system	(Bioforcetech)
Biogreen Pyrolysis Reactor	Biogreen North America (New York, NY)	Industrial, continuous	Wide feedstock range: wood, sludge, RDF	Sophisticated emission controls with condensers and filters	Continuous pyrolysis system for industrial biochar applications.	(Biogreen North America)
Bühler Aeroglide Fluidized Bed Pyrolysis System	Bühler Group (Switzerland)	Large-scale (commercial)	Uniform-sized feedstock like pellets, chips	Advanced control with gas cleanup, heat recovery systems	High-efficiency fluidized bed pyrolysis for large-scale production.	(Bühler Group)
Carbolite Gero Horizontal Tube Furnace	Carbolite Gero (UK)	Lab-scale only	Small, dry, uniform samples (e.g., powders, chips)	Not intended for emission control; used in fume hood	Lab-scale pyrolysis system for research applications.	(Carbolite Gero)
CarbonZero Biochar Reactor	CarbonZero (Oregon)	Small to medium	Agricultural waste, wood chips	Low emission burners and optional gas scrubbing units	Small to medium-scale pyrolysis system for sustainable farming.	(CarbonZero)
Char Technologies	Char Technologies (Canada)	Industrial	Industrial carbon streams	High-temp gas cleaning	Biocarbons for filtration, odor, metallurgy	(Char Technologies)
CharBoss	Air Burners Inc. (Florida, USA)	Medium (mobile, field-scale)	Forestry residues, woody biomass, agricultural residues	Integrated with air curtain technology to reduce smoke and PM emissions	Mobile pyrolysis unit designed for converting biomass waste into biochar.	Oyier et al. (2024); (Air Burner Power Series, 2025)
Charm Industrial Pyrolyzer	Charm Industrial (USA)	Mobile, scalable	Agricultural residues, woody biomass	Designed for carbon-negative process; CO_2 captured and injected into wells	Mobile pyrolysis unit for carbon-negative biochar production.	(Charm Industrial)
Coaltec Energy	Coaltec Energy USA (Indiana, USA)	Large-scale	Agricultural/woody biomass, manures	Gas cleanup + heat recovery (optional)	Industrial drying and batch pyrolysis for biochar and energy	(Coaltec Energy)

(continued on next page)

Table 2 (*continued*)

Reactor Name	Company/ Manufacturer	Scalability	Feedstock compatibility	Emission Control	Description	References
Earthcare LLC	Earthcare LLC (Indiana, USA)	Industrial	Agricultural/forestry waste	Custom emission controls	Heat, drying, and carbonization systems	(Earthcare)
ECHO-TECH Pyrolysis Reactor	ECHO-TECH (France)	Modular (medium to large)	Variety of dry biomass feedstocks	Comes with flue gas cleaning and heat recovery systems	Modular pyrolysis reactor for sustainable biochar and energy generation.	(Echo-Tech)
Ecochar Biochar Kiln	Ecochar (California)	Small, portable	Agricultural byproducts, manures	Limited emission controls; typically used in rural settings	Portable batch kiln designed for small-scale biochar producers.	(Ecochar)
Genesis Industries	Genesis Industries (USA)	Medium-scale industrial	Forest biomass: sawmill waste, logging residues, wood chips/forest wood waste sawmills	–	Pyrolysis technology with industrial partnerships	(Genesis Biochar)
Heyl & Patterson	Heyl & Patterson (USA)	Large	Waste and biomass	Industrial standard emission systems	High-throughput pyrolysis systems	(Heyl & Patterson)
High Plains Biochar	High Plains Biochar (USA)	Small to Medium	Chips, pellets, ag waste	Limited control	Stationary continuous pyrolysis systems	(HPBiochar)
Kon-Tiki Kiln	Ithaka Institute (Switzerland)	Small-scale, decentralized	Woody biomass, garden waste	Open kiln—produces smoke; minimal emission controls	Open-source, farmer-friendly biochar kiln.	Ithaka Institute (2023)
NetZero	NetZero/Ithaka Network	Small	Various biomass types	Low-emission designs (retort)	Small-scale retort systems	(NetZero et al., 2015)
Commercial HTL facility)	Nulife GreenTech (Canada)	Medium	Agricultural biomass	Contaminant removal (e. g. PFAS removal >95 %)	Produces biofuel with biochar co-products	(Nulife GreenTech.)
Off-grid BioCharger/ On-grid PGFireBox	Air Burners Inc. (Florida, USA)	Modular and portable; can be deployed as single or multiple units, easily relocated within days	Whole logs, root balls, untreated pallets, wooden crates, and other woody or vegetative waste without preprocessing	Integrated Air Curtain technology minimizes particulate emissions; operates without smokestacks or fossil fuel supplements	Mobile air curtain burner with built-in power generation (up to 100 kW); processes up to 8 tons (7.2 metric tons) of waste per hour on-site	Air Burner Power Series, (2025)
Pi Fabricators	–	Small	Wood, garden waste	None	Backyard fire pit kiln	United States Biochar Initiative (2023)
Pyreg PX 1500	Pyreg GmbH (Germany)	Modular industrial-scale	Broad range: wood waste, wet waste, green waste	Low-emission system with integrated gas cleaning; EU/EPA-compliant	Continuous pyrolysis reactor for carbon sequestration and biochar production.	(Pyreg GmbH)
Pyrocal Pty Ltd.	Pyrocal (Australia)	Medium to Large	Biomass residues, waste	CCT emission controls	Continuous carbonization technology	(Pyrocal)
Pyrovac	Pyrovac (Canada)	Large	Biomass residues	Fast pyrolysis system	Bio-oil and char co-product system	(Pyrovac)
ROCC Biochar Kiln	Community-driven designs	Small	Woody biomass	None	Rotatable, covered flame-cap cavity kiln	Anderson (2020)
Smartcare Terra LLC	Smartcare Terra LLC (Kansas, USA)	Medium to Large	Biomass, manures	Thermal oxidizers; integrated scrubbers	Modular pyrolysis systems with heat recovery	(Smart Terra Care)
Tigercat 6040 Carbonizer	Tigercat	Medium (mobile, field-scale)	Wood debris	Air curtain, controlled combustion zone	On site conversion of wood waste	(Tigercat)
Wilson Biochar/ Ring of Fire	Wilson Biochar/ Ring of Fire Kilns (USA)	Small	Forestry/ag biomass	Minimal, flame cap	DIY kiln kits for orchards, forests	(Wilson et al., 2024)

conversion pathway capable of producing carbon-rich solid products from wet biomass streams that are otherwise challenging to process by conventional pyrolysis. While biochar and hydrochar differ in structure and properties, hydrochar offers distinct advantages such as higher yields, lower ash content, and superior adsorption capacity for specific contaminants (Table 5). Its integration broadens the carbonization technology horizon, with emphasis on diverse alternatives of valorization of sustainable biomass and waste management (Lucian and Fiori, 2017; Jiang et al., 2025).

The basic difference between biochar and hydrocar is that biochar is thermally more stable, aromatic, and porous, which makes it better suited for long-term soil amendment, carbon sequestration, and solid fuel (Table 5). Hydrochar on the other hand generally have more yield, lower ash content, and the presence of higher oxygen-containing functional groups promotes better adsorption capacity for certain pollutants. However, hydrochars tend to be typically less thermally stable and moister. Hence, hydrochar and biochar are generally not interchangeable for most applications and must be selected based on specific needs, e.g., contaminant adsorption, energy production, or soil amendment. Few direct comparisons exist, though one recent paper by Jiang et al. (2025) compared biochar and hydrochar from leaves, bark, and wood and reported hydrochar has higher yields, lower ash content, and enhanced adsorption properties, while biochar is more thermally stable, with the type of feedstock being a significant factor for their environmental benefits and usability. Generally, HTC provides scalable, versatile technology for converting wet biomass into hydrochar with reduced environmental impacts. Its versatility in feedstock types and quantities—from laboratory-scale research to industrial waste management positions HTC as an asset technology in green waste-to-carbon strategies. Table 4 summarizes HTC reactors from lab to industrial scale, highlighting their feedstock flexibility and emission limitations. These include lab-scale reactors like Parr Instrument for research, and large

Table 3
Gasification biomass gasification systems, including scalability, feedstock compatibility, emission controls, and primary applications.

Reactor Name	Company/ Manufacturer	Scalability	Feedstock Compatibility	Emission Controls	Description	References
3R-BioPhosphate Kiln	3R-BioPhosphate Ltd. (EU)	Commercial-scale	Agricultural/forest waste	EU-compliant emissions; closed system	High-temp kiln for EU-certified biochar	(3R-BioPhosphate Ltd)
All Power Labs PP30 Gasifier	All Power Labs (USA)	Small-scale (25 kW); modular	Hardwood chips, nut shells; moisture <30 %; size 1–4 cm	Integrated emissions control; meets modern power standards	Compact gasifier for syngas and biochar production.	(All Power Labs)
Ankur Updraft Gasifier	Ankur Scientific (India)	Small to medium-scale	Agricultural residues, wood chips; moisture <20 %	Basic filtration systems; may require additional controls for stringent standards	Small-scale updraft gasifier for energy and biochar production.	(Ankur Scientific)
Aries Fluidized Bed System	Aries Clean Technologies (USA)	Industrial-scale	Biosolids, woody biomass	Advanced multi-stage control	Renewable energy + biochar	(Aries Clean Technologies)
Biogreen Gasifier	Biogreen Energy (France)	Modular/ industrial	Various biomass types	Multi-stage filters + condensers	Pyrolysis + gasification for multi-product recovery	(Biogreen Energy)
Carbon Lock Gasifier	Carbon Lock Technologies (Canada)	Medium-scale	Forest/agricultural residues	Designed for carbon removal	Biochar for C-sequestration + soil	(Carbon Lock Technologies)
Frontline BioEnergy Gasifier	Frontline BioEnergy (Ames, IA)	Large-scale; industrial applications	Diverse biomass; designed for fuel flexibility	Advanced gas cleaning technologies; tar-free syngas	Large-scale gasification system for industrial biochar and biofuel production.	(Frontline BioEnergy)
GEK TOTTI Gasifier	All Power Labs (USA)	Modular; research to small-scale	Lignocellulosic biomass; size 1–4 cm; moisture <30 %	Integrated emissions control; suitable for research and commercial use	Open-source gasifier for research and commercial use.	(All Power Labs)
Integrated Biomass Gasification System (IBGS)	Community Power Corporation (Littleton, CO)	Small-scale; community-based	Agricultural residues, wood chips	Includes air pollution control systems; suitable for small-scale applications	Small-scale gasifier for community-based biochar projects.	(Community Power Corporation)
Meva Energy Gasifier	Meva Energy (Sweden)	Industrial-scale; >1 MW	Pellets, sawdust, bark, straw, rice husks	Advanced gas cleaning; suitable for lean burn engines	Industrial-scale gasification system for clean energy and biochar.	(Meva Energy)
Phoenix Energy Biochar Gasifier	Phoenix Energy (California)	Farm-scale; 500 kW systems	Woody biomass; agricultural waste	Bioenergy with Carbon Capture and Storage (BECCS) integration	Farm-scale biomass gasifier with biochar recovery.	(Phoenix Energy)
Spanner Re^2 Biomass Gasifier	Spanner Re^2 GmbH (Germany)	Modular; 30–45 kW units	Natural wood chips, forest residues, shredded pallets	Integrated gas cleaning systems; low emissions	Modular biomass gasifier with biochar recovery.	(Spanner Re2 GmbH)
Taylor Biomass Energy Gasifier	Taylor Biomass Energy (Montgomery, NY)	Commercial-scale; waste-to-energy	Municipal solid waste, biomass	Designed for waste-to-energy conversion; emission controls integrated	Commercial-scale gasification system for waste-to-energy conversion.	(Taylor Biomass Energy)
TIGER Gasifier	Indian Institute of Science (India)	Research-scale	Various biomass types; moisture <20 %	Basic emission controls; suitable for research applications	Research-grade downdraft gasifier for biochar and energy production.	(Indian Institute of Science)

Table 4
Comparative Overview of Commercial and Laboratory-Scale Hydrothermal Carbonization (HTC) Reactors, summarizing key specifications of selected HTC reactor systems used globally, highlighting their scalability, feedstock compatibility, emission controls, and primary applications in biochar and hydrochar production.

Reactor Name	Company/ Manufacturer	Scalability	Feedstock Compatibility	Emission Controls	Description	References
HTCycle HTC System	HTCycle GmbH (Germany)	Industrial-scale	Organic waste, wet waste, agricultural residues	Integrated emission control systems; complies with EU regulations	Industrial-scale HTC system for organic waste to hydrochar conversion.	(HTCycle)
Parr Instrument Hydrothermal Reactor	Parr Instrument Company (USA)	Laboratory-scale	Aqueous mixtures; suitable for nanoparticle and zeolite synthesis	Encapsulated PTFE environment; designed for safe laboratory operations	Laboratory-scale HTC reactor for biochar research.	(Parr Instrument Co)
SunCoal HTC Reactor	SunCoal Industries (Germany)	Industrial-scale	Wet biomass, organic residues	High-pressure system with integrated emission controls	High-pressure HTC system for carbonizing wet biomass.	Suncoal. com
TerraNova Ultra HTC Plant	TerraNova Energy GmbH (Germany)	Large-scale	Municipal sludge, organic waste	Phosphorus recovery; low emissions through controlled process	Large-scale HTC system for municipal sludge processing.	(TerraNova. co,)

industrial systems such as HTCycle, TerraNova Ultra, and SunCoal designed for municipal sludge and organic waste processing.

4. The key reactor selection criteria, including technical, economic, and environmental dimensions

The best-suited form of pyrolysis reactor for a given application of biochar is determined by its function and co-benefits (biochar

Table 5
Comparison of properties of biochar and hydrochar.

Parameter	Biochar	Hydrochar	References
Production Temperature (°C)	300–700	180–250	Libra et al. (2011)
Carbon Content (w/w, %)	65–90 %	45–70 %	Kambo & Dutta (2015), Libra et al. (2011); Malghani et al. (2013)
Hydrogen Content (w/w, %)	0.5–3.0	4–6	Liu et al. (2023); Jiang et al. (2025)
Oxygen Content (w/w, %)	10–25	20–45	Liu et al. (2023); Jiang et al. (2025)
H/C Ratio	0.2–0.6	1.0–1.5	Kambo & Dutta (2015)
O/C Ratio	0.2–0.4	0.3–0.8	Libra et al. (2011)
Surface Area (m^2/g)	200–800	10–150	Jiang et al. (2025); Sun et al. (2014); Takaya et al. (2016)
pH	8–11 (alkaline)	4–7 (acidic–neutral)	Liu et al. (2023); Jiang et al. (2025)
Cation Exchange Capacity (cmol/kg)	5–60	10–120	Liu et al. (2023); Sun et al. (2014)
Carbon Stability			
Mineralization	0.5–8.9 % over 5 years	13–16 % over 8 weeks	Singh et al. (2012); Bamminger et al. (2014)
Carbon recovery	46 % (mostly aromatic)	57 % (~50 % aromatic)	Fuertes et al. (2010)
Long-term sequestration	Superior	Less suitable	Busch et al. (2015)
Additional advantage	Highly stable carbon	Better nutrient delivery	Busch et al. (2015)

production, energy generation, or waste management), availability and form of biomass, and end use of the biochar. It must be integrated into existing forest restoration, agricultural, and waste management activities and demands. In small-scale systems, socio-economic factors like traditional cooking practices, availability of local labor, and ease of maintenance needs attention in technology selection and implementation. Smaller low-cost units with less complex technology and low training requirements can be more appropriate for distributed-scale applications in forestry and agriculture in rural communities. For industrial-scale waste management demands, the larger automated systems are able to provide economies of scale, regulatory compliance, and high throughput.

Greenhouse gas (GHG) emissions from machine operation and a full life cycle assessment (LCA) of biochar versus a baseline fate of the biomass feedstock must be taken into consideration in determining the environmental footprint of biochar production systems (Amonette et al., 2021). For example, the conversion of forest residues into biochar rather than leaving them to decompose or be burned in piles for disposal has significant environmental advantages. Life cycle assessments from the Waste to Wisdom initiative revealed that biochar systems reduce net greenhouse gas emissions by avoiding methane and nitrous oxide release from decomposition and by stabilizing carbon in the form of recalcitrant biochar (Han et al., 2018; Amonette et al., 2021). This benefit can be monetized through carbon offsets within some carbon registries, such as the U.S. and Canada Biochar Protocol of the Climate Action Reserve. Besides climate mitigation, the application of biochar in the soil has been proven to improve the water holding capacity, nutrient supply, and microbial activities, particularly in dry or degraded soils. These benefits are particularly relevant in western U.S. conditions, where water conservation and post-disturbance recovery are important and are close to forest management sources of woody biomass.

LCA studies reveal that net greenhouse gas (GHG) reductions vary significantly depending on reactor type, feedstock, and system boundaries. For example, auger-reactor pyrolysis of switchgrass achieved high GHG reductions (2231–2772 kg CO_2-eq per tonne), largely due to high carbon yield and energy substitution benefits (Brassard et al., 2018). In contrast, gasification systems achieved 0.6–1.4 t CO_2-eq per tonne of feedstock, while fast pyrolysis reported 0.07–1.25 t CO_2-eq per tonne of feedstock (Carvalho et al., 2022; Ibarrola et al., 2012). Slow pyrolysis generally provides greater carbon abatement than fast pyrolysis or gasification because of higher biochar yields and greater carbon permanence (Lehmann and Joseph, 2015). System-level analyses also highlight differences among mobile units: Biochar Solutions Inc. (BSI) reactors exhibit a global warming potential (GWP) of 306–444 kg CO_2-eq per tonne of biochar, compared to 750–1016 kg CO_2-eq per tonne for CharBoss (Bergman et al., 2022; Puettmann et al., 2020). Portable systems such as the Oregon Kiln and CharBoss often yield lower global warming potential (GWP) values than more complex systems, primarily due to minimal feedstock preprocessing (Puettmann et al., 2020). The CharBoss system demonstrated a carbon dioxide removal potential of −2.70 t CO_2-eq per tonne of biochar produced, generating approximately 2403.81 t CO_2-eq annually (Johannesson et al., 2024). By converting forest biomass generated by restoration thinning into biochar, CharBoss presents a viable approach for producing marketable carbon dioxide removal (CDR) credits while promoting sustainable forest management. Overall, reactor configuration, feedstock source, and system boundary assumptions are critical determinants of net GHG reduction potential, underscoring the importance of harmonized LCA methodologies for consistent comparison across technologies.

4.1. Purpose of the reactor

The intended purpose of a reactor is the primary consideration in its selection and design, as it directly influences the technological configuration and operational parameters. For example, if the primary objective of the reactor is biochar production for soil amendment, carbon sequestration, or environmental remediation, slow pyrolysis-based reactors are most appropriate due to their ability to maximize recalcitrant carbon yield (Ghosh and Maiti, 2020). Alternatively, if energy production in the form of syngas, bio-oil, or heat is the priority, fast pyrolysis or gasification technologies are more suitable as the priority is the production of syngas and bio-oils compared to solid residues (Ippolito et al., 2020). If safe handling and disposal of biomass residues (e.g., forest residues, agricultural residues, or municipal organic refuse) are the key concerns, mobile pyrolysis units (e.g., CharBoss) or hydrothermal carbonization (HTC) reactors for wet biomass present viable solutions with minimal environmental pollution impact and a consistent carbon-recalcitrant product (Oyier et al., 2024; Rajput et al., 2024). In other cases, integrated systems may be selected that offer, simultaneous biochar production, energy generation, and residue management; however, these systems typically require greater operational complexity, greater initial capital investment, as well as greater technical know-how (Su et al., 2023). Hence, identifying the reactor's primary objective of biochar production, energy recovery, waste management, or an integrated approach is critical for guiding technology selection, maximizing operational efficiency, and ensuring the long-term viability and alignment of the system with project goals. Also, even with identical feedstocks, slow-pyrolysis systems can yield biochars with different properties and market values, reflecting tradeoffs in capital costs, feedstock preparation, residence time, and other operating conditions.

4.2. Amount and type of feedstock available

The type of feedstock utilized influences the characteristics of the resultant biochar significantly. Biochar derived from wood generally has a high specific surface area and porosity and is thus suitable for immobilization and adsorption of contaminants; whereas, biochar derived from herbaceous crop residues has better cation exchange capacity (CEC), an attribute that is beneficial for nutrient retention and soil fertility (Ippolito et al., 2020; Tomczyk et al., 2020). Manure and sludge-based biochar contains more nutrients and ash, but has less structural stability, necessitating careful reactor control to limit contaminant load (Mishra et al., 2023; Hassan et al., 2020).

Physical and chemical properties of the feedstocks, such as particle size, water content, and lignocellulosic content also impacts the selection of biochar production technology. For instance, dry and uniform small biomasses like ground crop residues, wood chips and sawdust can be efficiently processed in fixed-bed, fluidized bed reactors or gasification reactors (Hansen et al., 2015; Situmorang et al., 2020; Brassard et al., 2017 In contrast, heterogeneous and large pieces, like those common in forestry, requires box kilns, air curtain burners and batch kilns (Page-Dumroese et al., 2024; Wilson et al., 2024; Pierson et al., 2024). Rotary kilns or fluidized bed reactors are feedstock flexible and favored at large scales due to their ability to manage continuous feeding and higher throughput, but require feedstocks with relatively homogenous characteristics to facilitate automated feedstock handling (Moser et al., 2023; Situmorang et al., 2020; Li et al., 2019). High-moisture feedstocks are better suited for hydrothermal carbonization (HTC), which bypasses the energy-intensive drying phase (Libra et al., 2011; Lucian and Fiori, 2017). Thus, matching the reactor configuration with the specific feedstock properties ensures optimized biochar yield and quality for target applications.

Apart from the type, the amount of feedstock available plays a pivotal role in determining the appropriate reactor type and system design for biochar production. Where intermittent or batch volumes of biomass exist, e.g., on smallholder farms or seasonal harvesting; batch kilns and fixed-bed pyrolysis units are more appropriate since they have low capital outlays, are comparatively easy to manage, and can be easily designed to handle changing input streams (Tripathi et al., 2016). Conversely, in the case of large, continuous feedstock sources such as agro-industrial complexes, forest harvesting operations, municipal collection schemes for biomass, or central cooperative deals; continuously operating reactors such as rotary kilns, fluidized beds, or auger systems are preferred because they can handle high throughput and have high thermal performance (Li et al., 2019).

Biochar yield and quality are highly dependent on the feedstock quality; apart from that, studies show that sorted forest residues, particularly processed stem wood that has been debarked, offer superior characteristics such as lower ash content, higher bulk density, and more uniform particle size compared to unsorted slash or whole-tree residues (Bisson and Han, 2016). The study reported that the ash content in processed conifer stem wood was as low as 0.27 %, while mixed slash material exceeded 1.5 %, potentially reducing the agronomic value and stability of the resulting biochar. Kizha and Han (2016) also reported that sorting forest residues can reduce contamination and improve feedstock homogeneity, essential for consistent biochar production. Importantly, mismatches between reactor capacity and feedstock volume can lead to inefficiencies, underutilization, and elevated per-unit production costs. A careful assessment of feedstock quantity, consistency, and logistics is therefore essential to ensure technical compatibility, economic viability, and environmental performance of the biochar system.

Use of forest residues through sorting and grinding impacts feedstock quality as well as operations and economics. Although additional sorting adds field cost by roughly USD 1150 per hectare, it is usually offset by cost reduction on subsequent site preparation (up to USD 1100 per hectare) and carbon footprint reduction due to open burning (Kizha and Han, 2016). In northern California where the research was undertaken, timber harvest forest residues were generally open-burned to make the harvested area ready for reforestation, an activity known as site preparation. This cost-benefit tradeoff underlies the integration of residue sorting into biochar feedstock strategies.

4.3. Current forestry, agriculture, and waste management practices

A knowledge of local waste management, forestry, and agricultural practices is necessary to ensure that the selected bioreactor can be effectively integrated into local systems. In forestry operations, where significant quantities of woody residues are generated by timber harvesting, forestry operations, and restoration tinning; mobile pyrolysis units such as CharBoss are viable for in-field processing without hauling raw materials to long distances (>100 km) (Oyier et al., 2024; Page-Dumroese et al., 2024; Sarauer et al., 2019; Wilson et al., 2024). At primary wood processors, such as sawmills that can produce hundreds of tons of woody biomass residues per day, a larger, centralized system with energy capture is better matched to the scale of production and demand for processing heat and power. In agriculture, the type of crop residue management, such as open pile burning, leaving on site, or composting, determines whether stationary batch pyrolysis reactors or continuous kilns would be suitable (Tomczyk et al., 2020). Similarly, where wet organic wastes are concentrated but not effectively valorized, hydrothermal carbonization (HTC) offers an environmentally sound avenue to convert such wastes into carbon-rich products (Rajput et al., 2024). Selecting a bioreactor that aligns with or enhances existing practices promotes smoother integration, increases user adoption, minimizes operational disruptions, and optimizes both environmental and economic outcomes.

4.4. Alignment with socio-economic context

Effective application of biochar technology, particularly mobile and small-scale pyrolysis plants, is critically dependent on their local socio-economic compatibility, i.e., availability of labor and capital. In situations where the labor is readily available compared to the capital; low-capital, labor-intensive reactors such as Kon-Tiki kilns, TLUD (Top-Lit UpDraft) stoves, Hawaiian Luau pit, trench, or small batch kilns are suitable alternatives (Ghosh and Maiti, 2020). These systems are valued for being low-tech, low-cost, and easy to accept compared to the existing farming practices, i.e., on-farm composting and residue management. There are minimal technical inputs required, and they can be operated using locally obtained feedstocks like crop residues or manure. Socio-cultural factors also contribute to affecting acceptability: systems replicating conventional charcoal production or cooking activities have lower resistance from villages. On the other hand, highly automated high-technology systems are less optimal in low-capital settings unless augmented with training and long-term maintenance assistance. Additionally, spare part supportability, local maintenance and fabrication capability, and compatibility with government rural energy or soil health initiatives can play a significant role in long-term sustainability and scale-up potential.

4.5. Economic and regulatory environment, technical requirements, and operational considerations

4.5.1. Economic and regulatory considerations

While selecting a biochar reactor, the understanding of the economic and regulatory framework is of utmost importance (Ahmed et al., 2025). Most essential aspects include the total cost, which includes the fixed cost of equipment purchase (equipment installation, purchase, and axillary systems) along with the operating fixed and variable cost of the system, such as labor, feedstock processing, transport, and maintenance (Oyier et al., 2024). Financial viability may be improved if local markets for biochar exist or if government incentives such as subsidies, carbon credits, or grants are available. However, regulatory requirements, including emissions standards, feedstock limitations, and biochar certification criteria, can vary geographically and may influence reactor selection and production capacity. Thus, economic feasibility depends on factors such as the output of preprocessing equipment, fuel costs, labor availability, and overall logistics, which collectively integrate all parameters into an optimal process. Detailed economic analysis of specific systems is beyond the scope of this review, but technoeconomic analysis has proven to be an effective tool in predicting the financial performance of specific biochar projects, including projects with and without government incentives (Campbell et al., 2018).

4.5.1.1. Air pollutant emissions and mitigation. Air pollutant emissions from biochar production units are mostly due to incomplete combustion, including carbon monoxide (CO), volatile organic compounds (VOC), tars, nitrogen oxides, and particulate matter (Li, 2024). These emissions vary with respect to the reactor design, process temperature, and presence or absence of the control system. For example, traditional pit or open furnaces release more CO, methane, and aerosol due to incomplete combustion (Nsamba et al., 2015; Cornelissen et al., 2024). In contrast, rotary kilns and fluidized bed systems have enclosed chambers and thermal oxidizers that enable near-complete oxidation of volatiles, reducing VOC and particulate emissions significantly (Moser et al., 2023). Fixed-bed and auger reactors with afterburner or second-stage combustion zone fixed-bed can lower CO and VOC emissions up to 90 % compared to traditional kilns (Ronsse et al., 2013). Field-portable systems like CharBoss utilize forced-air curtains to enhance combustion further and minimize smoke and particulate emissions when burning in-woods (Page-Dumroese et al., 2024; Oyier et al., 2024; Pierson et al., 2024). Existing dual-auger systems have been shown to release as little as 160 g/h CO, 51 g/h NO_x, and 380 g/h particulate matter (Severy et al., 2018), and after-combustion systems have even been shown to release as little as 7 g/kg biochar (Sørmo et al., 2020). HTC reactors, operating in sealed, aqueous environments, generate minimal airborne emissions but require proper management of process liquids to prevent secondary contamination (Libra et al., 2011). Also, biochar itself is capable of acting as sorbents for airborne pollutants, e.g., metal vapors and organics, which can contribute to overall emission minimization.

Sophisticated control units such as cyclones, electrostatic precipitators, biofilters, and thermal oxidizers are being integrated into commercial reactors (e.g., Pyreg GmbH, ARTi, Aries Clean Technologies) to meet regulation standards. Incorporation of heat recovery and recirculation systems for flue gases also minimizes fuel consumption and pollutant emissions. Overall emission control by improved design, catalytic control, and constant monitoring is primarily needed to achieve cleaner production of biochar and European Biochar Certificate (EBC) and International Biochar Initiative (IBI) approvals.

4.5.1.2. Typical costs of biochar production reactors. Setup and running expenses of a biochar production facility vary widely based on reactor design, plant scale, and degree of technology. Capital costs include reactor purchase, installation, and ancillary equipment (e.g., heat recovery systems, emission controls), while operating costs consist of energy, labor, maintenance, and compliance. Representative cost ranges for standard reactors are given below based on recent literature and industry statistics and compilation thereof, tabulated in Table 6.

4.5.1.2.1. Stationary reactors.

- **Fixed Bed Reactors**: For fixed bed reactors processing 0.5–2 tons of biomass per hour, capital costs range from USD 50,000 to USD 250,000, reflecting their simple, low-automation design ideal for small-scale pyrolysis systems, sometimes with added emission control (Joseph et al., 2024; Osman et al., 2025). Operational costs range between USD 230 and USD 346 per ton of biochar, based on labor and energy consumption in low-automated systems. Total cost of production of small systems, covering capital amortization, biomass cost, and transport, ranges between USD 449 and USD 1847 per ton, with a 90 % probability interval of USD 571–USD 1455 per ton, depending on the production level and field conditions (Nematian et al., 2021).

- **Auger Reactors**: Designed for continuous operation in medium-scale systems (1–5 tons/hour), auger reactors have capital costs of USD 200,000–600,000. The cost of operation is less, USD 65–200 per ton, due to increased efficiency and automation, although impacted by energy needs and preprocessing biomass (Campbell et al., 2018; Tang et al., 2024; Sahoo et al., 2019; Brassard et al., 2017). Companies like ARTi (USA) and ABRI-Tech's auger system (Canada) offer modular systems that optimize costs for local biomass.

- **Rotary Kiln Reactors**: Suitable for larger-scale operations (5–20 tons/hour), these reactors have capital costs of USD 500,000–2,000,000. Operational costs range from USD 250–500 per ton, with the benefits of high throughput capacities and heat recovery equipment capable of optimizing energy costs up to 20 % (Jerzak et al., 2024). Pyreg GmbH (Germany) is one such company which optimize operating efficiency through combined heat recovery.

- **Fluidized Bed Gasifiers**: Designed for high-capacity processing (10–50 tons/hour), these systems have capital costs of USD 1,000,000–5,000,000. The cost of production ranges from USD 300–500 per ton, which is high energy input even though syngas use

Table 6
Comparison of capital and production costs for various reactor technologies for biochar production.

Category	Reactor	Capital Cost (USD)	Biochar Production Cost (USD/ton)	References
Stationary Reactors	Fixed Bed	50,000–250,000	230–346	Joseph et al. (2024); Osman et al. (2025);
	Hydrothermal Carbonization	300,000–1,500,000	150-230 (hydrochar)	Lucian and Fiori (2017)
	Rotary Kiln	500,000–2,000,000	250–500	Shackley et al. (2011)
	Auger Reactors	200,000–600,000	65–200	Campbell et al. (2018); Tang et al. (2024); Sahoo et al. (2019); Brassard et al. (2017);
	Fluidized Bed Gasifier	1,000,000–5,000,000	300–500	Nam et al. (2016); Campion et al. (2023)
	Downdraft Gasifier	112,500 (for 60 kW)	200–800 (~$0.196/kWh)	Indrawan et al. (2020), Situmorang et al. (2020)
Mobile/Field-Deployed	CharBoss	~150,000	300–400	Oyier et al. (2024), Air Burner Power Series (2025)
	Charm Industrial Pyrolyzer	500,000–2,000,000	100–200	(Charm Industrial), Isometric (2024)
	Big Box Biochar	100,000–300,000	200–350	United States Biochar Initiative (2023)
	Tigercat 6040 Carbonizer	>700,000	250–400	(Tigercat)
Portable Micro-Units	TLUDs	100–1000	50–150	Planboo (2023)
	Kon-Tiki kilns	1000–2000	50–100	Planboo (2023), Cornelissen et al. (2016)
	Hawaiian Luau pits	50–500	100–200	Hue (2020)

compensates for the cost (Nam et al., 2016; Campion et al., 2023). Companies like Aries Clean Technologies (USA) function with improved efficiency through syngas recycling.

- **Hydrothermal Carbonization (HTC) Reactors**: Optimized for wet biomass (2–10 tons/hour), HTC reactors have capital costs ranging from USD 300,000–1,500,000. The cost of operation ranges from USD 150–230 per ton, compensating for the advantage of nutrient recovery in units like TerraNova Ultra (Germany) (Lucian and Fiori, 2017).

- **Downdraft Gasifiers**: For smaller-scale applications (e.g., 60 kW systems), these reactors have a capital cost of approximately USD 112,500. Operating costs are USD 200–800 per ton, or USD 0.196 per kWh approximately, based on system efficiency and biomass feedstock (Indrawan et al., 2020; Situmorang et al., 2020).

4.5.1.2.2. Mobile/field-deployed.

- **CharBoss**: A mobile air curtain burner processing 1–2 tons of biomass per hour, the CharBoss has an estimated capital cost of approximately USD 150,000. Towability and automatic biochar extraction make it possible for in-woods production with fewer environmental impacts than open burning (Air Burner Power Series, 2025; Oyier et al., 2024). Operating costs range from a low of USD 300–USD 400 per ton of biochar, plus fuel (4.2 L/h diesel) and labor (Oyier et al., 2024; Air Burner Power Series, 2025). Total production costs are within the broader range of USD 449–1847 per ton for mini-scale systems (Nematian et al., 2021)

- **Charm Industrial Pyrolyzer**: Designed for mobile pyrolysis, these units process biomass into biochar and bio-oil, with capital costs ranging from USD 500,000 to USD 2,000,000, comparable to rotary kiln or auger systems. Operating costs operate in the range of USD 100–200 per ton, with optimum waste biomass utilization and carbon credit integration (Charm Industrial; Isometric, 2024).

- **Big Box Biochar**: These mobile systems, suitable for small to medium-scale field deployment (1–3 tons/hour), have estimated capital costs of USD 100,000–300,000. Operating costs range from USD 200–350 per ton, accepting efficiencies similar to auger reactors for portability (McAvoy, 2024).

- **Tigercat 6040 Carbonizer**: A mobile, high-throughput carbonizer for onsite wood debris conversion, with capital costs of over USD 700,000. Operational costs range from USD 250–400 per ton, with greater efficiency and fewer emissions from improved models (Tigercat).

4.5.1.2.3. Portable micro-units.

- **TLUDs (Top-Lit Up-Draft)**: These portable micro-units, suitable for smallholder use (50–500 L), have capital costs of USD 100–1000. It has a low operating costs of USD 50–150 per ton because of low energy inputs and use of local feedstocks, though labor-intensive (Planboo, 2023).

- **Kon-Tiki Kilns**: Designed for small-scale, efficient flame-curtain pyrolysis (1500 L), these kilns have capital costs of USD 1000–2000. Low operating costs of USD 50–100 per ton through low-cost feedstocks consumption and low operation (Planboo, 2023; Cornelissen et al., 2016).

- **Hawaiian Luau Pits**: Traditional, low-tech pit methods with capital costs of USD 50–500, requiring minimal materials. High operating costs of USD 100–200 per ton, although more so because of inefficiency and labor (Hue, 2020).

To reduce the biochar production cost, producers can invest in efficient reactors with heat recovery systems to reduce the utility bills, situate plants near the biomass sources to lower transportation fees (10–20 % of the operating cost), and access carbon credit markets, where biochar credits traded USD 100–200 per ton CO_2 equivalent in the USA and EUR 110–165 (1 USD ≈ 1.1 EUR) in Europe in 2023 to offset the production cost.

In brief, batch pyrolysis systems are the lowest in capital cost to some extent but are less efficient and costlier on a per-unit basis. Large continuous and gasifier-based facilities, though more capital-intensive, achieve greater operating efficiency, economies of scale, and per-unit costs.

4.6. Skills and operational requirements

The complexity of a system determines the level of technical expertise required to operate a bioreactor. For example, basic small-scale manual kilns or batch reactors require basic skills and familiarity with feedstock handling. However, for more advanced or automated systems, it demand technical knowledge in pyrolysis processes, instrumentation, engineering and quality control. Maintenance skills such as the ability to manage blockages, leaks, or software diagnostics are critical for long-term operational continuity of these systems. If the biochar is intended for agricultural use, familiarity with soil amendment practices and biochar-soil interactions can enhance production processes to meet downstream needs. Skill training is one of the biggest problems faced by the forestry sector, as the level of skill sets often defines the working capability of the production units, and in turn, the biochar properties, because skilled operators tend to produce better biochar in many cases. Hence, a skilled workforce is the driving force for a successful operation.

4.6.1. Feedstock reliability and system control

A reliable supply of suitable biomass feedstock is the key to the long-term sustainability of biochar manufacturing unit. Seasonal fluctuation, competition for other uses (e.g., animal feedstock or bioenergy), and transportation and collection logistics are important aspects of production logistics. Sustainability is also crucial: feedstocks must be harvested in a way that will not harm ecosystems or deplete resources. In addition, certification programs for biochar, along with the promotion of carbon offset initiatives that utilize biochar projects, emphasize the use of renewable resource-based feedstocks. The choice of manual versus automatic control systems influences logistic needs such as labor needs, quality biochar consistency, and scalability. For context, manual systems will suffice in small-scale agriculture or decentralized utilization, while automated units are best used in industrial applications requiring greater control, precision, and throughput.

4.7. Location and size of markets for products

The choice of biochar production machines for sustainable soil restoration should align with the location and scale of biochar markets. In places where the biochar market is developing and has future potential, e.g., in some areas of North America, Western Europe, and parts of Asia, there is generally a market for high-quality certified biochar for commercial farming, reclamation of soil, and environmental use (International Biochar Initiative, 2012). In such a scenario, commercially scaled reactors like fluidized bed systems or rotary kilns can be useful based on their capacity to attain high-demand levels and produce standardized quality biochar. The systems are economically justified by market scale and typically funded by carbon credit schemes or policy incentives. For example, Pacific Biochar (USA) works in partnership with forest management agencies to produce biochar from California wildfire prevention residues (Pacific Biochar). They possess Puro.earth certified biochar credits and long-term offtake contracts with corporations like Shopify and Microsoft (CarbonCredits.com, 2023).

Alternatively, where demand is localized and dependent on regionally based feedstocks and agrarian consumption, such as in rural or developing economies, particularly Sub-Saharan Africa, South Asia, or Latin America, mobile, batch, or small-scale pyrolysis units are more suitable due to low capital expenditure, operational flexibility, and agrarian integration simplifications (Nsamba et al., 2015) . Such countries are beginning to apply small-scale biochar systems for land reclamation and waste treatment and opening up scope for local-scale production systems according to the needs of the community. Distance to the market also affects the transport economics and therefore distributed, local production is more viable in low-infrastructure communities. In this case, it is useful to make a distinction between biochar production and use within an immediate agroecosystem or agroforestry system and biochar manufacture and application as a factory process producing a commodity product for several markets. It is critical to understand whether the market demands large-scale centralized or decentralized community-based use in order to select the appropriate reactor type.

4.8. Sustainable circular economy considerations

Integrating biochar production within a circular bioeconomy framework requires balancing renewable feedstock utilization with ecosystem integrity (Ghosh et al., 2025; Wang et al., 2020). While forestry residues represent valuable and low-cost feedstock for

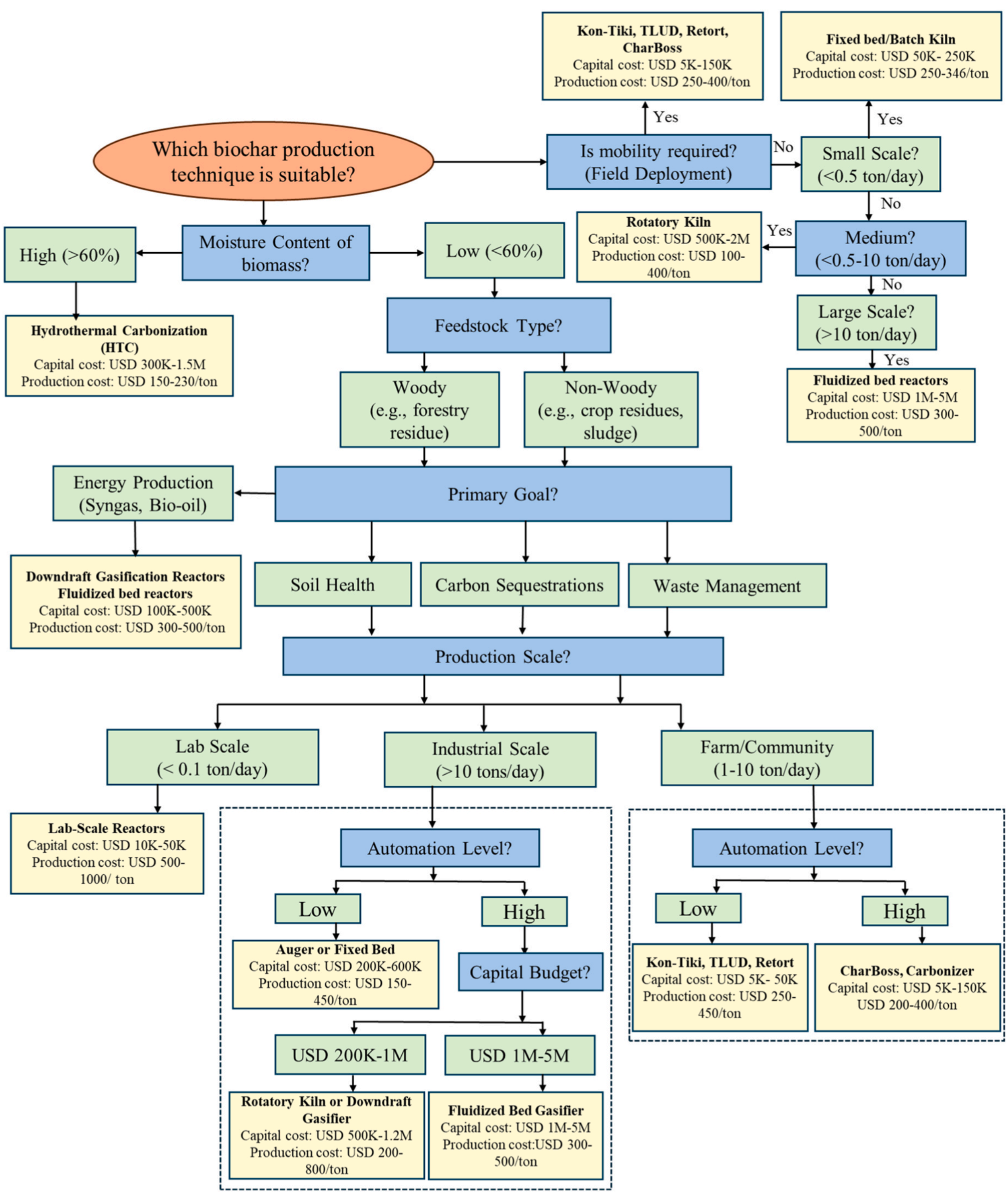

Fig. 1. Decision framework for selecting suitable biochar production techniques based on feedstock characteristics, production scale, and operational goals. Capital and production cost ranges are also indicated for various reactor types.

large-scale biochar production, excessive extraction can compromise soil fertility, biodiversity, and carbon cycling, particularly in climate-sensitive regions and on nutrient-poor soils. Biochar production from forest residues could supply up to 10 % of the carbon dioxide removal needed for 1.5 °C pathways (Tisserant and Cherubini, 2019), but sustainable extraction is critical. Low-value woody biomass must be managed carefully to avoid depleting soil carbon and harming forest productivity (Ghosh et al., 2025), particularly in climate-sensitive regions where soil health and carbon cycling are vulnerable. Sustainable residue removal thresholds typically retain coarse woody debris and nutrient-rich fine residues, especially foliage, and are essential to preserve forest resilience and regeneration potential under warming conditions (Thiffault et al., 2016; Bessaad et al., 2021; Stutz and Lang, 2017). These and other site-specific silvicultural practices and management strategies are used widely in sustainable forestry to reduce negative environmental impacts and protect forest carbon pools during biomass harvesting (Ameray et al., 2021; Thiffault et al., 2016). The circular economy benefits from converting forestry residues to biochar are enhanced when the baseline fate of residues is open pile burning for disposal, which is a common forestry practice in many areas. Incorporating life cycle assessment (LCA) and regional biomass availability modeling into reactor deployment strategies ensures that biochar production supports, rather than undermines, forest ecosystem services. Ultimately, positioning biochar systems within a circular economy should prioritize on waste valorization, carbon sequestration, and soil restoration while ensuring that forested landscapes are not pushed beyond their ecological carrying capacity.

Based on the established selection criteria, a comprehensive decision framework has been developed to facilitate the identification of suitable biochar production technologies (Fig. 1). This framework integrates crucial parameters such as feedstock, moisture content, operational scale, and primary application objectives including soil amendment, carbon sequestration, and energy recovery to ensure that technology choices reflect both technical suitability and economic viability. By systematically evaluating these factors, the framework enables stakeholders to select among a spectrum of reactor configurations, from small-scale, low-cost kilns to large-scale, fully automated gasification or fluidized-bed systems, thereby optimizing both process efficiency and project outcomes.

5. Challenges in biochar application

Biochar production, currently limited to around 1 million tons annually, is energy-intensive and costly ($500–$2000 per ton), with transportation and application adding expenses that deter small-scale farmers (Nematian et al., 2021; Market Research Report, 2023). Also, uniform soil incorporation is challenging, requiring specialized equipment, and feedstock supply varies regionally, competing with uses like bioenergy or composting. Scaling up is constrained by logistical issues and the need for sustainable biomass sourcing to avoid depleting resources.

Biochar application techniques and scaling their associated technologies are critical for leveraging benefits like carbon sequestration and soil fertility enhancement, but face logistical and economic challenges. Common biochar application methods include broadcast-and-disk, which spreads biochar with a lime spreader and shallowly disks it to reduce erosion, costing $29–$300/acre for 2.5–50 tons/acre (Williams and Arnott, 2010; Nyambo et al., 2021). The more labor-intensive trench-and-fill method uses 30–60 cm trenches filled with biochar, providing stable storage at $34–$512/acre for 5–75 tons/acre (Williams and Arnott, 2010). Blending biochar with compost or fertilizers enhances nutrient availability, while wetting mitigates dust risks during handling (Ghosh and Maiti, 2020). Scaling these technologies is hindered by high production costs ($500–$2000/ton), inconsistent biochar quality, and the need for sustainable feedstock sourcing to prevent overharvesting. Innovations like mobile pyrolysis units for on-farm production and precision application equipment (e.g., no-till drills, drone-assisted spreaders) can improve efficiency for large-scale fields. Machine learning for optimizing application rates and bioeconomy models linking biochar to biomass waste further has the potential to address scalability.

6. Conclusion

Biochar production technologies have evolved to optimize quality, efficiency, and environmental performance through reactor design tailored to feedstock, scale, and application. The review concluded that the type of reactor (for example, pyrolysis, gasification, or hydrothermal carbonization) has a direct impact on the carbon stability, surface area, porosity, and contaminant concentration of biochar. This, in turn, determines its suitability for applications such as soil amendment, long-term carbon sequestration, or targeted pollution control. Fixed-bed and slow pyrolysis reactors offer high-carbon yield for long-term storage, and HTC and gasification offer high-surface-area biochar to be used for remediation and nutrient retention. Selection of reactors also depends on socio-economic factors such as feedstock availability, capacity, cost, and regulation, where small-scale TLUDs and Kon-Tiki kilns are appropriate for decentralized use, and rotary kilns, fluid beds, and HTC reactors allow for larger industrial systems. Emerging mobile units like ABI CharBoss and Tigercat Carbonizer demonstrate in-situ biochar production potential for emission reduction and forest resilience. Future deployment of biochar will depend on adaptive reactor architecture design, integrating automation and emissions control, and integrating lifecycle studies and certification to guarantee that engineering innovations align with climate-resilient, circular bioeconomy objectives.

CRediT authorship contribution statement

Dipita Ghosh: Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Data curation, Conceptualization. **Nathaniel Anderson:** Writing – review & editing, Validation, Supervision, Project administration. **Han-Sup Han:** Writing – review & editing, Validation, Supervision, Funding acquisition.

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Data availability

Data will be made available on request.

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