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Engineering Thermochemistry and Process Technologies to Enable Gigaton-Scale Sustainable Biochar Production

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ABSTRACT

Biochar is a sustainable carbon material whose production represents one of the few recognized carbon dioxide removal (CDR) pathways capable of delivering gigaton (Gt)-scale atmospheric carbon sequestration. Developing industrial-scale technologies for sustainable biochar production is pivotal for enabling global deployment and realizes its full potential. Although the fundamentals and applications of biochar have been extensively reviewed, reviews dedicated to large-scale production technologies and process engineering remain limited. This work comprehensively evaluates thermochemical conversion technologies, pyrolysis reactors, demonstrated successful processes, scale-up challenges, and opportunities for industrial biochar production. This review first outlines thermochemical conversion techniques, pyrolysis mechanisms, and key parameters governing biochar formation. It then critically discusses major reactor configurations, highlighting their respective strengths and limitations. It also novelly maps the global implementations of biochar technologies and showcases commercially validated pyrolysis processes. Major scale-up challenges and pathways toward sustainable deployment, including heat and energy management, environmental impacts, application and market dynamics, and CDR benefits, are assessed. Finally, future research directions and engineering strategies required to advance next-generation pyrolysis technologies and sustainable biochar production are identified. This review aims to provide an integrated framework to guide process innovation and accelerate the global deployment of biochar as a Gt-scale CDR solution for climate change mitigation.

1 | Introduction

The extensive reliance on fossil fuels has driven modern economic development but has simultaneously accelerated environmental degradation and global climate change, creating urgent challenges for sustainable development [1]. Rapid population growth, socioeconomic expansion, and the depletion of finite energy resources have further intensified

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Abbreviations: AC, activated carbon; BECCS, bioenergy with carbon capture and storage; BFB, bubbling fluidized bed; CAGR, compound annual growth rate; CDR, carbon dioxide removal; CFB, circulating fluidized bed; DACCS, direct air carbon capture and storage; EBI, European Biochar Industry; ETC, engineering thermochemistry; GHG, greenhouse gas; Gt, gigaton; HTC, hydrothermal treatment; HTT, highest treatment temperature; IBI, International Biochar Initiative; LCA, life cycle assessment; Mt, million tons; PTB, pneumatic transport bed; USBI, US Biochar Initiative.

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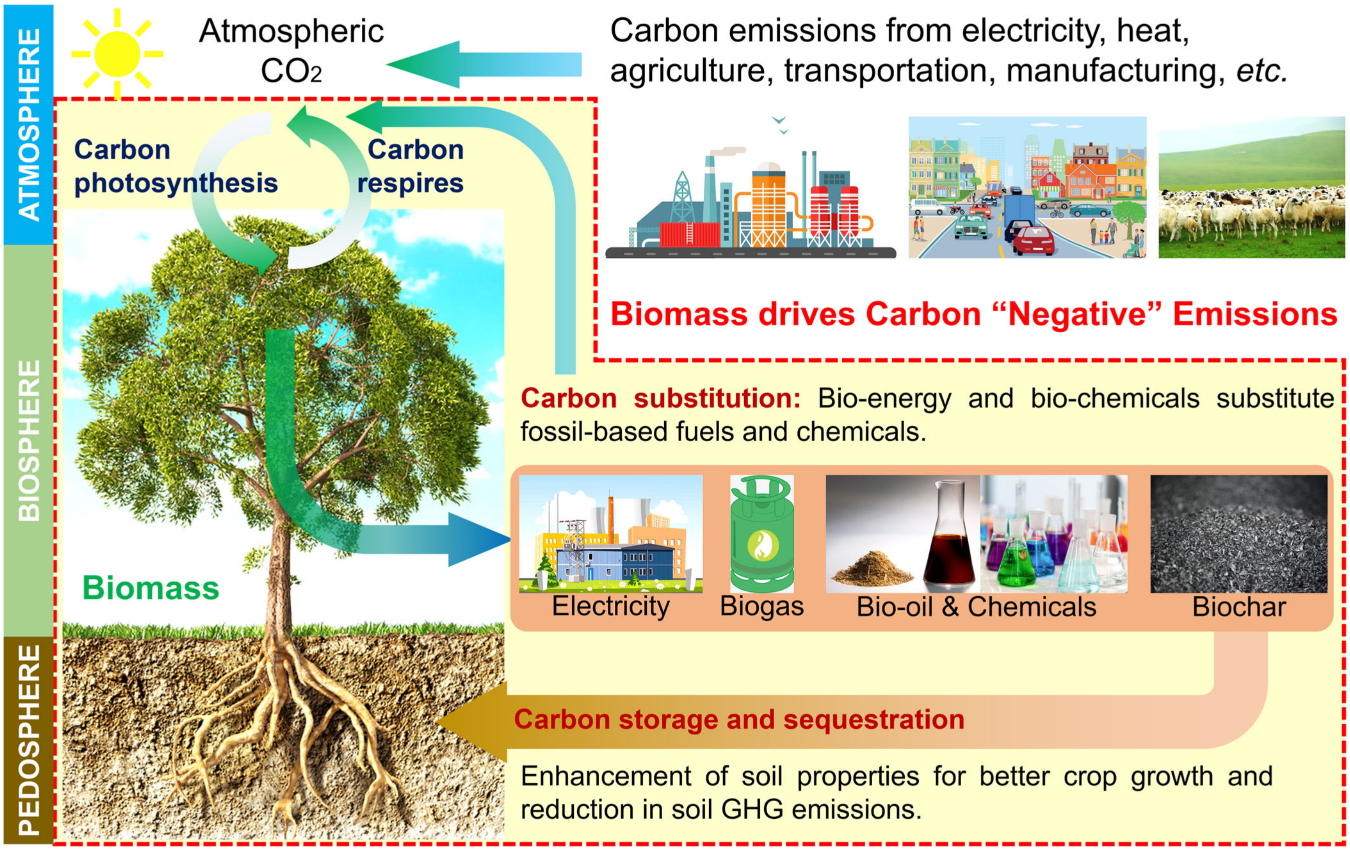


FIGURE 1 | Schematic representation of renewable biomass enabling a sustainable carbon cycle and biochar-mediated carbon sequestration. GHG, greenhouse gas.

the global energy crisis. Limiting global warming to well below 1.5°C, as outlined in the Paris Agreement, requires not only rapid decarbonization of energy systems but also large-scale deployment of carbon dioxide removal (CDR) technologies capable of permanently removing atmospheric CO_2 [2, 3]. Achieving carbon neutrality by mid-century therefore demands transformative advances in both renewable energy utilization and negative-emission technologies [4].

Among renewable resources, biomass represents the only sustainable carbon-containing feedstock capable of simultaneously supporting energy production, material synthesis, and carbon removal [5, 6]. As illustrated in Figure 1, thermochemical conversion enables biomass to be transformed into fuels, chemicals, and biochar, thereby establishing a sustainable carbon cycle that substitutes fossil resources while stabilizing atmospheric carbon. Biochar, a carbon-rich solid produced under oxygen-limited thermal conditions, is particularly attractive because it enables long-term carbon sequestration while co-producing renewable energy carriers. Its ability to retain carbon in stable solid form for centuries to millennia positions biochar as an effective CDR technology [7, 8]. When applied to soils, biochar further acts as a durable carbon sink by converting atmospheric CO_2 into stabilized soil carbon [9, 10]. Consequently, biochar has emerged as one of the most immediately deployable and scalable CDR pathways [11].

The growing scientific and industrial interest in biochar is reflected in rapidly increasing research output (Figure 2) and expanding applications, including environmental remediation [12, 13], agricultural engineering [14–19], carbon capture and storage [6, 20–23], catalysts [24–26], and electrochemical energy storage [27–30]. Numerous review articles have summarized biochar properties, modification strategies, and application-specific performances [31–33]. However, most existing reviews emphasize material characteristics or end-use applications, whereas production technologies are typically discussed only through brief comparisons of preparation methods. Moreover, current discussions largely remain confined to laboratory-scale synthesis

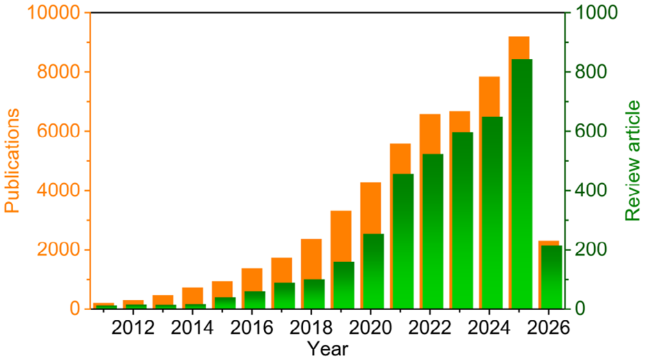


FIGURE 2 | Annual number of research and review publications retrieved from the Web of Science database using the keyword "biochar" between 2011 and 2026 (data accessed in April 2026).

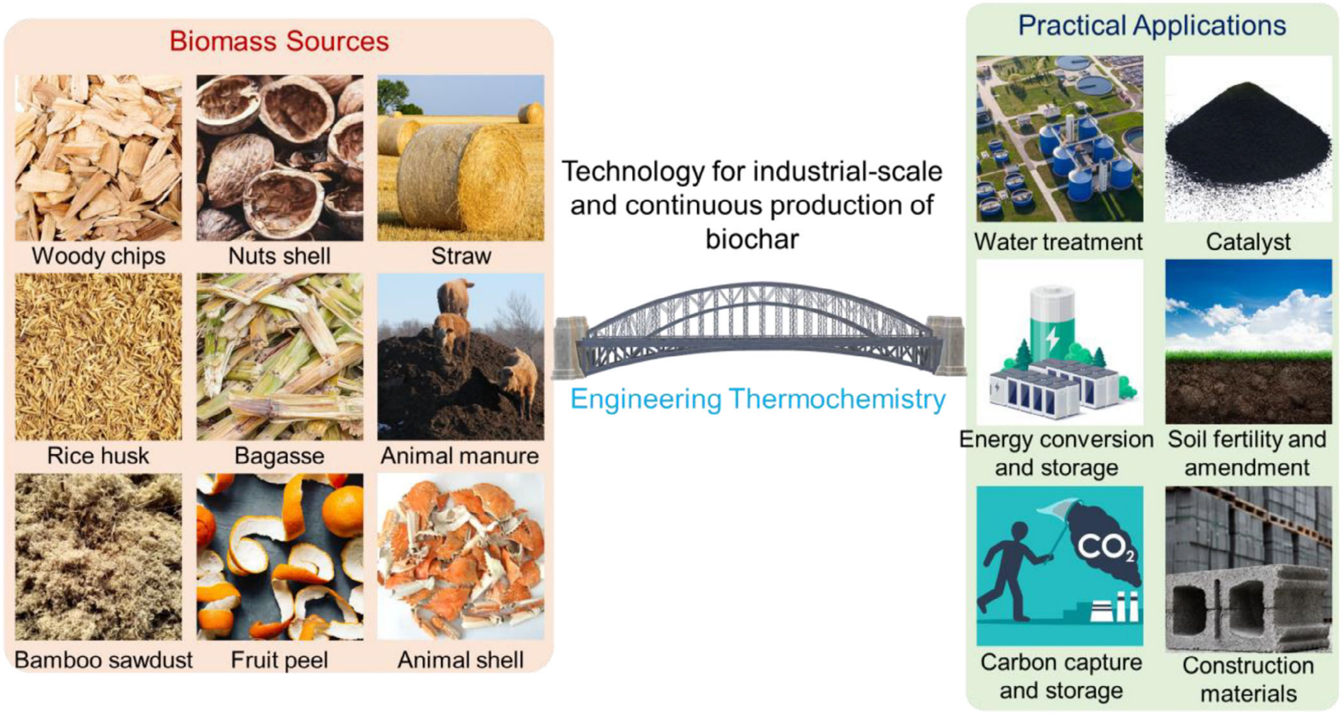


FIGURE 3 | Engineering thermochemistry bridges biomass resources and real-world applications by enabling scaled, continuous industrial biochar production.

using limited feedstock quantities. Critical aspects required for industrial deployment, such as reactor engineering, thermochemical process integration, continuous large-scale operation, CDR benefits, and market opportunities, remain insufficiently addressed.

Achieving gigaton (Gt)-scale carbon removal through biochar requires transitioning from laboratory-scale preparation to engineered thermochemical systems capable of continuous, efficient, and scalable operation [34]. Pyrolysis technologies must therefore be understood not merely as chemical conversion processes but as integrated engineering systems governed by reaction thermodynamics, heat and mass transfer, reactor design, and process optimization. This systems-oriented perspective is increasingly framed within the emerging concept of engineering thermochemistry (ETC), which integrates heat-driven chemical reactions with reactor and process engineering to enable scalable thermochemical conversion technologies [4, 35]. ETC provides a unifying framework linking biomass resources, thermochemical conversion, and industrial implementation (Figure 3). By coordinating reaction chemistry with energy supply and process design, ETC enables three complementary climate strategies: carbon reduction through bioenergy, carbon substitution through biofuels and chemicals, and carbon removal via stable biochar formation [4]. Consequently, ETC serves as a critical bridge between biomass conversion science and the large-scale deployment of biochar as a practical CDR solution.

Despite rapid advances in biomass conversion research, a comprehensive synthesis focused on thermochemical engineering principles, reactor technologies, industrial processes, and scale-up challenges for biochar production remains lacking. Addressing this gap is essential for translating laboratory knowledge into deployable industrial systems. In this context, this review critically examines large-scale biochar production from an ETC perspective. It introduces thermochemical conversion pathways and the mechanisms governing biochar formation, followed by a systematic evaluation of pyrolysis reactors and their engineering performance. Global deployment trends and commercially demonstrated processes are then analyzed to identify technological maturity and industrial best practices. Major challenges associated with scale-up and sustainable deployment, including heat and energy management, environmental performance, techno-economic feasibility, applications and markets, and CDR potential, are subsequently discussed. Finally, future research directions are proposed to advance next-generation pyrolysis technologies and accelerate scalable biochar production for climate mitigation and sustainable development.

2 | ETC for Large-Scale Biochar Production

2.1 | Thermochemical Conversion Techniques

Biomass is broadly categorized as plant- and animal-derived sources; this review focuses on lignocellulosic biomass, which accounts for approximately 86% of global annual biomass production. Biochar preparation relies on thermochemical conversion techniques, which involve heating biomass in the absence or limited presence of oxygen. Central to these processes are heat-induced and heat-driven thermochemical reactions that decompose complex organic compounds into simpler molecules, release volatiles (condensable oils and non-condensable gases), and maximize retention of solid carbon as biochar [36]. The primary thermochemical pathways for biomass include torrefaction, hydrothermal carbonization (HTC), pyrolysis, and partial

TABLE 1 | Comparison of thermochemical conversion technologies for biochar production.

Production technology	Torrefaction	Hydrothermal carbonization	Slow pyrolysis	Fast pyrolysis	Gasification
Temperature (°C)	200–300	180–260	>350	500–900	750–1000
Biochar yield (wt%)	60–90	50–80	20–35	12–35	5–12
Biochar carbon yield (wt%)	70–85	60–70	50–60	20–25	<15
Heating rate (°C/min)	10–100	1–10	0.5–100	>1000	1000
Residence time	10–60 min	Minutes to hours	Minutes to days	0.5–10 s	10–20 s
Major product	Torrefied biomass	Hydrochar	Biochar	Bio-oil	Syngas

gasification [37]. Table 1 summarizes key processing parameters and products, including temperature, heating rate, residence time, and biochar yield across these technologies. Although theoretical distinctions between techniques are well-defined, practical implementations often blur these boundaries. For instance, processes may combine high heating rates with extended volatile residence times, challenging conventional classifications. These pathways differ in processing temperatures and carbonization intensity, ranging from low to high severity. Biochar yield follows a distinct inverse relationship with processing temperature across techniques: torrefaction > HTC > pyrolysis > gasification. Notably, pyrolysis constitutes the fundamental reaction mechanism underlying all these processes.

Torrefaction operates at lower temperatures and consumes less energy compared to other thermochemical conversion techniques. However, its applications remain primarily confined to energy uses for torrefied biomass, unlike pyrolysis-derived biochar, which offers broader utility [38]. HTC effectively processes high-moisture biomass feedstocks without pre-drying. Despite this advantage, HTC requires high operating pressures and additional separation and drying steps for final hydrochar production, increasing manufacturing complexity and costs. This process also generates residual wastewater, known as processing water, which contains high concentrations of organic compounds (e.g., organic acids, sugars, furans, and phenols) and toxic components, necessitating specialized treatment for safe disposal [39–43]. Similarly, hydrochar often contains residual toxic organic compounds that require further treatment before it can be used as a soil fertilizer or conditioner [44, 45]. Gasification demonstrates the capability to process diverse feedstocks but requires biomass pulverization, such as in fluidized-bed gasifier, for enhanced efficiency and process reliability [46]. Feedstock moisture must typically remain below 30 wt% [25, 46], and improper operation risks emissions of particulate matter and volatile organic compounds [47].

In contrast, pyrolysis, particularly slow pyrolysis, exhibits high operational tolerance and exceptional feedstock flexibility, accommodating varied biomass sizes, moisture levels, and physical properties [48]. Although pretreatment, such as pre-drying, may improve efficiency in some cases, the process remains generally adaptable. Conditions are readily adjustable to optimize outputs: Slow pyrolysis maximizes biochar yield, whereas fast pyrolysis prioritizes bio-oil production. Pyrolysis effectively converts waste biomass into value-added products (e.g., bio-oil, biogas, and biochar) with superior quality compared to other thermochemical routes. Although the initial cost of pyrolysis plants can be significant, large-scale facilities often offset this through cost efficiency, leveraging high efficiency and production of valuable coproducts [49]. Moreover, pyrolysis is more environmentally friendly compared to gasification and HTC, due to its lower gas volume generation and minimal emissions of harmful gases and wastewater [50].

When examining the limitations of each thermochemical conversion technique, gasification faces operational challenges, particularly due to tar formation, which can cause blockages in downstream processes and reduce production efficiency [51, 52]. Additionally, gasification primarily produces syngas with limited biochar output and poses inherent risks of fire and explosion due to high operating pressures and temperatures involved [53]. HTC operates under subcritical water conditions and is susceptible to corrosion from salt precipitation [41, 54, 55]. Its batch-mode operation further limits the ability to produce hydrochar continuously and at scale. Given these limitations, pyrolysis emerges as the preferred biochar production technology, with demonstrated scalability and feedstock adaptability [56]. Critically, pyrolysis-based biochar production represents a major CDR technology warranting extensive global R&D for climate mitigation and pollution control. This review consequently focuses on pyrolysis technology advancements and applications.

2.2 | ETC in Biomass Pyrolysis Systems

It is essential to note that the advancement of biomass pyrolysis technology is closely linked to the novel concept of ETC, which deals with heat-induced or heat-driven thermochemical reactions and associated engineering challenges [4, 35]. Pyrolysis, as a representative thermochemical conversion process, exemplifies the application of ETC from fundamental studies to industrial implementation. ETC covers all aspects of biomass pyrolysis technology and engineering, including pyrolysis chemistry, reaction kinetics, reactor design and multiphase hydrodynamics, and process engineering. The development of innovative biomass pyrolysis technology follows a systematic progression across different scales from the molecular to industrial level, as shown in Figure 4. It begins with understanding thermochemical reaction mechanisms at the molecular scale, which involves elementary reactions and free radical reactions [57]. At the particle and reactor scales, the focus shifts to studying primary factors and secondary reactions, developing methods to control reaction pathways, and applying heat-mass transfer and flow-matching

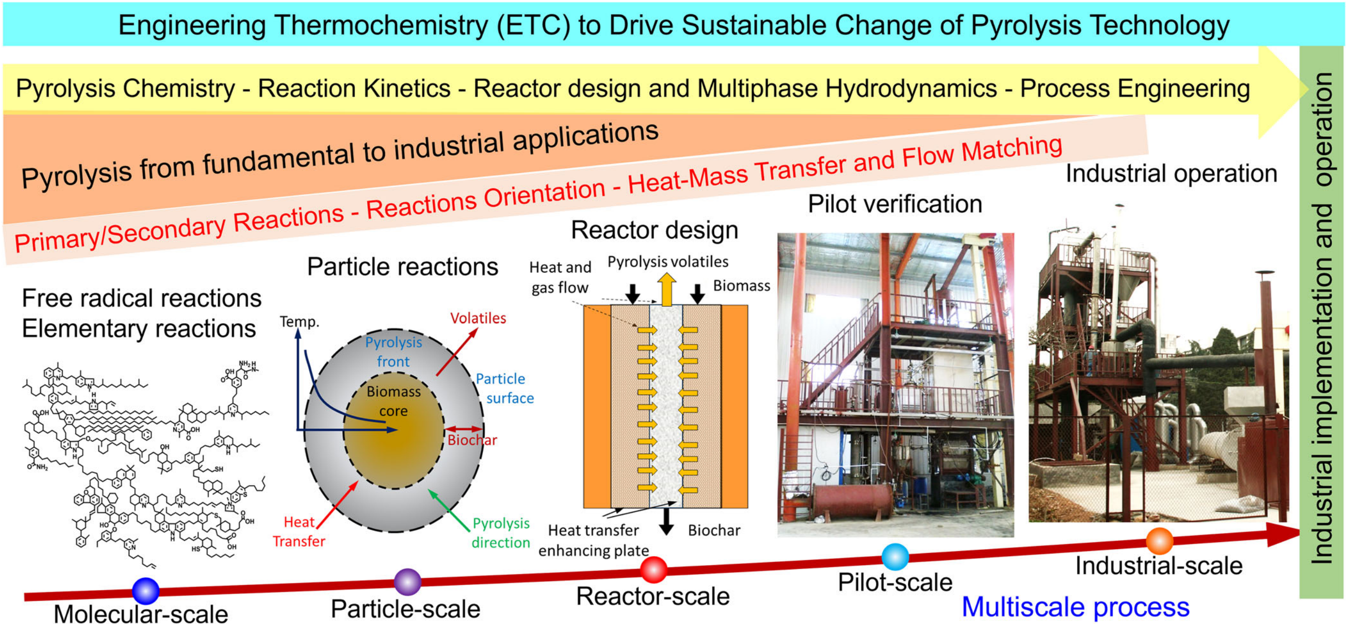


FIGURE 4 | Engineering thermochemistry to drive the development of biomass pyrolysis technology.

strategies. This stage is crucial for the novel design of reactors and processes, aiming to improve the efficiency and output of pyrolysis systems. Subsequently, reactor and process modeling enable the engineering of pyrolysis system toward industrial-scale deployment. Establishing a pilot-scale plant is necessary to demonstrate the feasibility of the technology, bridging the gap to commercialization. During industrial operation, critical challenges may arise that require revisiting earlier stages of development for refinement, creating a closed-loop innovation cycle in ETC. This systematic approach ensures that biomass pyrolysis technology advances along a well-defined path, leveraging ETC principles to enable efficient, scalable solutions for biochar production and sustainable development.

The power of ETC to advance next-generation pyrolysis technologies is exemplified by the development of a moving bed reactor with internals (see Figure 11C for details). A representative case arises from pyrolysis processes in the fossil fuel industry, particularly coal coking, where longstanding challenges, including low oil yield, poor oil quality characterized by high heavy-oil and dust contents, and inferior char quality, were addressed through ETC-guided innovation [58]. By elucidating the role of uncontrolled secondary reactions of pyrolysis volatiles and identifying the mismatch among heat transfer, mass transfer, and flow behavior, researchers designed a moving bed reactor with internal structures, notably a central volatile-collection channel (illustrated at the reactor scale in Figure 4). This configuration reversed the flow pathway of pyrolysis volatiles, enabling controlled thermal and catalytic cracking of heavy oil components while simultaneously facilitating in situ dust removal by regulating the volatiles go through the moving particle bed. Subsequently, reactor and process modeling, together with multi-scale simulations, were conducted to support reactor engineering and scale-up, guided by a mechanistic understanding of coupled heat-mass transfer and flow dynamics in larger systems [59–62]. The technology was successfully scaled from laboratory scale (10 kg batch capacity) to pilot scale (1000 t/year, shown in Figure 4 at the pilot scale), and is currently progressing toward commercial deployment with an anticipated processing capacity of up to 400 000 t year [63].

This case demonstrates the potential of ETC to drive transformative and sustainable advancements in pyrolysis technology. By systematically addressing process complexities across multiple scales, from molecular mechanisms to industrial implementation, ETC provides an integrated framework for innovation in pyrolysis systems, enabling simultaneous improvements in product yield, quality, and process efficiency. In the following section, guided by the ETC concept, biomass pyrolysis technology is deconstructed into its key engineering components, including pyrolysis fundamentals, reactor design and scale-up strategies, and process- and system-level considerations.

3 | Fundamentals of Biochar Formation

3.1 | Pyrolysis Chemistry and Mechanisms of Biochar Formation

Understanding biochar formation mechanism is crucial for controlling and tailoring final product properties. Pyrolysis has a long history spanning over centuries and is widely employed to convert carbonaceous resources and solid wastes into energy fuels and carbon-rich residues, such as biomass, coal, oil shale, and scrap tires [58, 64, 65]. This intricate process involves a series of complex reactions, primarily driven by heat-induced, endothermic thermochemical decomposition [4]. Biomass pyrolysis typically progresses through distinct stages: drying, biomolecular decomposition, bio-oil production, and biochar formation [66]. During pyrolysis, biomass is heated to high temperatures in the absence of oxygen or with limited oxygen, which promotes the cleavage of volatile biomolecules. This condition allows biomass to be heated beyond its thermal stability limit, unlike combustion in

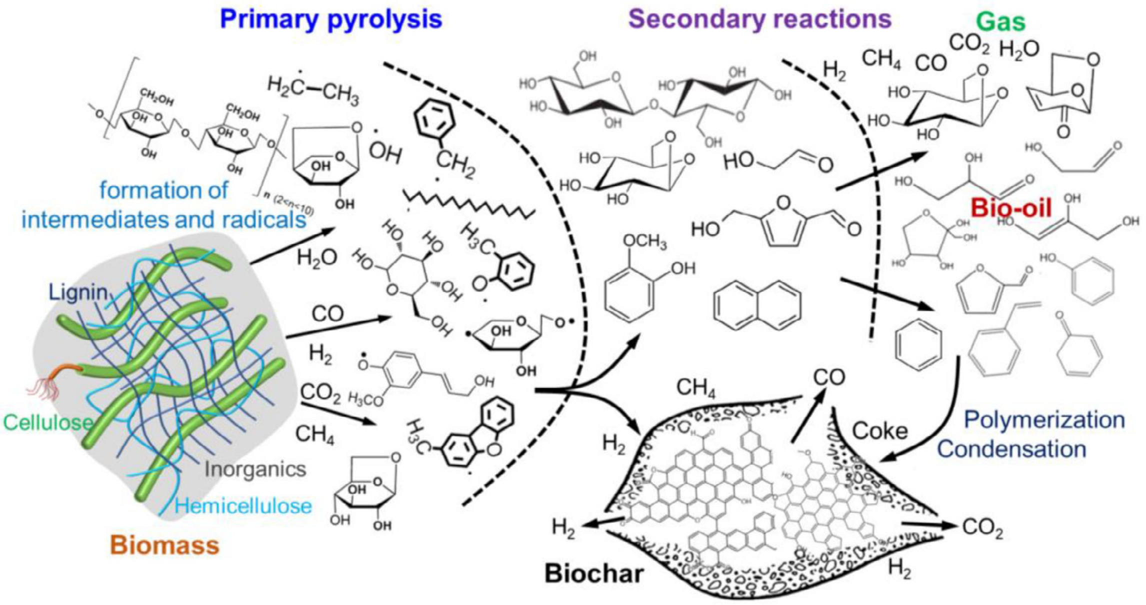


FIGURE 5 | Schematic illustration of primary pyrolysis and secondary reactions for lignocellulosic biomass pyrolysis.

an oxygen-rich atmosphere, leading to the breakdown of complex molecules into smaller ones, such as condensable bio-oil and noncondensable gases. Simultaneously, the carbon framework undergoes aromatization, polymerization, and condensation reactions, leading to the formation of biochar. Overall, pyrolysis reactions can be viewed as a type of "disproportionation" reaction, where biomass is simultaneously transformed into hydrogen-rich oil and gas and carbon-rich biochar.

Macroscopically, pyrolysis occurs in two stages: primary pyrolysis and secondary reactions, as illustrated in Figure 5 [67, 68]. During the primary pyrolysis stage, biomass undergoes initial cleavage and devolatilization at a limited extent, breaking down into macromolecular, heavy components featured volatiles, and solid biochar [66]. This stage involves processes such as dehydration, decarboxylation, and dehydrogenation, which generate carbonyl, carboxyl, and hydroxyl groups [69]. Following primary pyrolysis, secondary reactions take place, where primary volatiles undergo further cracking, polymerization, and condensation reactions. These secondary reactions result in the formation of low molecular weight compounds, light oils, secondary solid carbon/biochar, and gaseous products. The secondary reactions occur between volatiles and solid biochar during the release of volatiles from biomass particles and bed particles into free space, as well as between gaseous phase volatiles and between volatiles and the reactor walls [70, 71].

Pyrolysis products can be categorized into three main groups of gas species, liquid products (bio-oil and water), and biochar. The gas products include H_2, CH_4, CO, CO_2, and small quantities of C2–C3 gases, whereas the liquid products include a mixture of different types of compounds, such as anhydrosugars, furans, alcohols, aliphatic, aromatic, and polyaromatic hydrocarbons, and water [72]. The biochar yield corresponds to the solid carbonaceous material remaining after pyrolysis, comprising carbon-rich organics and ash. The composition of biochar depends mainly on the final pyrolysis temperature and the biomass feedstock. The carbon content of biochar increases at higher pyrolysis temperatures, showing average oxygen and hydrogen contents of 10.0 and 1.5 wt%, respectively, at 700°C on a dry ash-free basis [73]. The ash content of biochar is primarily influenced by the initial inorganic composition of the biomass, with major oxide compounds being SiO_2, CaO, K_2O, Al_2O_3, MgO, Fe_2O_3, and so forth [74]. Notably, biochar formation occurs during both the primary pyrolysis and secondary reaction stages.

From a microscopic perspective, biochar formation during lignocellulosic biomass pyrolysis is elucidated through thermal decomposition mechanisms of its primary components: cellulose, hemicellulose, and lignin [75]. These constituents typically comprise 30–50 wt% for cellulose, 20–40 wt% for hemicellulose, and 10–40 wt% for lignin in lignocellulosic biomass [76, 77]. Representative compositions include olive wood (31.5 wt% cellulose, 23.7 wt% lignin) [78], rice husk (36.8 wt% cellulose, 20.6 wt% hemicellulose, 14.9 wt% lignin) [79], and bamboo (41.0 wt% cellulose, 26.5 wt% hemicellulose, 25.3 wt% lignin) [80]. Each compound undergoes distinct thermochemical reactions through divergent kinetic and mechanistic pathways, collectively contributing to the formation of biochar, bio-oils, and gases. Decomposition kinetics and conversion extents are primarily governed by process parameters including pyrolysis temperature, particle size, and heating rate [81]. Characteristic decomposition initiates at 200–260°C for hemicellulose, 240–350°C for cellulose, and 280–500°C for lignin [75, 77, 82]. These temperature ranges represent critical points at which the respective biomass components undergo significant transformations, releasing volatile compounds and leaving behind the carbon-rich biochar product. Furthermore, the decomposition of biomass, which is a mixture of cellulose, hemicellulose, lignin, and inorganic components, starts at lower temperatures, around 200–250°C, and continues through 500–600°C, depending on the specific composition of the biomass. The decomposition of these components is influenced by the presence of inorganic components, interactions with each other, and the occurrence of secondary reactions. The intricate interplay of these components and their reactions govern the composition and properties of the resulting biochar, making pyrolysis a complex but controllable process for tailoring biochar characteristics based on the intended application.

Beyond cellulose, hemicellulose, and lignin, inorganic species present in biomass significantly influence biochar formation during pyrolysis. Biomass pyrolysis exhibits autocatalytic behavior, with inherent inorganic constituents, particularly alkali and alkaline earth metals, playing a crucial catalytic role in this process [83]. For example, potassium (K) and sodium (Na) demonstrate strong catalytic activity in biomass pyrolysis. These metals facilitate catalytic bio-oil reforming reactions, leading to the formation of lower molecular weight cellulose and lignin-derived products with improved quality [84]. Concurrently, they alter product distribution by reducing the carbon yield of desirable aromatic hydrocarbons and olefins while accelerating pathways favoring increased yields of thermally derived char and non-condensable gases (e.g., CO, H_2, CH_4, C_2H_4, and CO_2). In general, inherent inorganic elements affect the initiation of decomposition reactions, including the maximum devolatilization rate temperature and decomposition pathways. This leads to enhanced production of low-molecular-weight condensable species and non-condensable gases, ultimately contributing to higher biochar yields [85]. The catalytic effects of these inorganic constituents are therefore pivotal in determining the outcomes of biomass pyrolysis and subsequent biochar formation.

3.2 | Key Parameters Influencing Pyrolysis Behavior

Biochar quality and yield are profoundly influenced by pyrolysis techniques and operational parameters. The critical factors governing biochar production encompass (1) biomass feedstock properties (chemical composition, moisture content, and particle size); (2) reaction conditions (pyrolysis temperature, residence time, heating rate, and pressure); (3) the surrounding environment (carrier gas type and flow rate); and (4) additional factors such as catalyst use [48, 86]. These operating parameters collectively govern not only yield and quality of biochar but also the characteristics and quantity of coproducts. Thus, understanding the influence of pyrolysis parameters on product outcomes is essential for process optimization through strategic manipulation of key variables.

3.2.1 | Pyrolysis Temperature

Among the parameters governing biochar production, pyrolysis temperature, specifically the highest treatment temperature (HTT), represents the most critical factor, exerting a greater influence on biochar characteristics and yield than residence time, heating rate, or particle size [87]. For lignocellulosic biomass, hemicellulose and lignin exhibit lower thermal degradation temperatures and rates compared to cellulose [77, 82]. Hemicellulose decomposes at approximately 220°C, followed by cellulose at higher temperatures around 300°C, whereas lignin decomposes over a broader temperature range from 160–180°C to beyond 500°C due to its complex structure [88, 89]. These ranges are approximate and subject to variation based on biomass type, heating rate, and experimental conditions. Biochar yield typically decreases significantly with increasing HTT up to 500°C, beyond which the decline moderates. For example, pyrolysis of cottonseed hulls between 200°C and 800°C showed a rapid yield decrease from 83.4 to 28.9 wt% as HTT rose from 200°C to 500°C, followed by a modest reduction to 24.2 wt% at 800°C [90]. Figure 6A illustrates this temperature dependence across diverse feedstocks (wood, bamboo, straws, algae, and sewage sludge). Despite variations in biomass compositions, heating rates, and residence times, a consistent trend emerges. Biochar yield declines sharply until 400–500°C, then plateaus gradually. This pattern arises because most biomass components decompose below 500°C. Notably, biochar yields at similar HTT, such as at 500°C, tend to converge within 30–40 wt% for most feedstocks. Sewage sludge constitutes a significant exception, where high ash content sustains yields >50 wt% even at 700°C [91].

Correspondingly, elevated HTT reduces hydrogen (H) and oxygen (O) content while increasing carbon (C) content in biochar, leading to lower atomic H/C and O/C ratios. These shifts signify enhanced aromaticity and reduced polarity of biochar [91]. A van Krevelen diagram (Figure 7), constructed using various biochars, clearly demonstrates this progressive decline in atomic H/C and O/C ratios with increasing HTT for plant-based biomass. It should be noted that these data originate from varied experimental conditions encompassing different feedstocks, reactor types, heating rates, and residence times. This well-established trend arises because lignocellulosic biomass undergoes dehydration and depolymerization into smaller lignin- and cellulose-derived fragments as pyrolysis temperatures increase [91]. In contrast, biochars produced from poultry manure and sewage sludge, materials lacking lignocellulosic compounds, do not experience this depolymerization pathway.

The morphology and surface structure of biochar are also markedly influenced by HTT. Surface area typically increases with rising pyrolysis temperatures until a threshold is reached, beyond which it declines [119]. This trend is attributed to the decomposition of aliphatic alkyl and ester groups at elevated HTT, which exposes the aromatic lignin core and develops porosity [97]. Concurrently, increasing HTT reduces nitrogen content (via volatilization of N-compounds), cation exchange capacity, functional groups, and available phosphorus (P). Conversely, it enhances aromatization, pH in solution (due to basic functional groups), calorific value, ash content, and electrical conductivity [94, 120, 121]. Higher HTT also promotes the formation of recalcitrant carbon fractions and crystalline structures [94, 122]. The optimal HTT is biomass feedstock dependent, representing a compromise between maximizing biochar yield and optimizing its stability and physicochemical properties [86, 87].

3.2.2 | Heating Rate

Heating rate plays a significant role in biomass pyrolysis by affecting heat and mass transfer, which, in turn, influences the composition and characteristics of the final products. Generally, a low heating rate (slow pyrolysis) favors the formation of more biochar and less bio-oil [123], whereas a high heating rate (fast pyrolysis) leads to greater fragmentation and cracking of biomass, resulting in more gases and liquids [124]. High heating rates accelerate biomass depolymerization through rapid bond

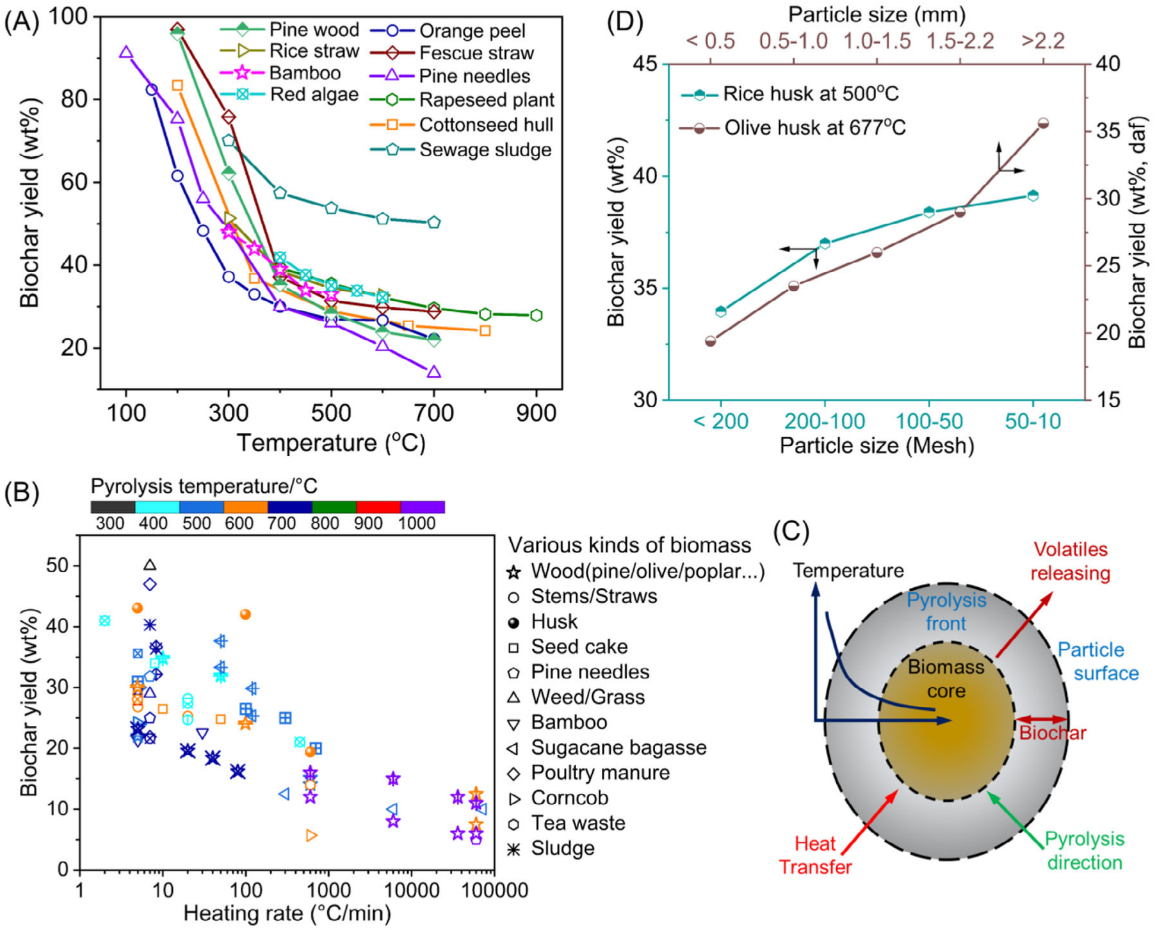


FIGURE 6 | Influence of pyrolysis conditions on biochar yield. (A) Effect of pyrolysis temperature on biochar yield for diverse biomass types across different reactors, heating rates, and residence times. Data sources: cottonseed hull [92], pine wood and fescue straw [93], rice straw [94], bamboo [95], red algae [96], orange peel [97], pine needles [98], rapeseed plant [99], and sewage sludge [91]. (B) Variation of biochar yield with heating rate for various feedstocks under different pyrolysis temperatures. Data sources: wood [100–102] stems/straws [99, 103–105], husk [86], seed cake [106, 107], pine needles [98], weed/grass [91], bamboo [108], sugarcane bagasse [109], poultry manure [91], corncob and tea waste [110], and sludge [91]. (C) Schematic of internal heat transfer, volatile release, and temperature gradients within a biomass particle during pyrolysis. (D) Effect of particle size on biochar yield. Data sources: olive husk [110] and rice husk [111].

cleavage, causing increased internal pressure, rapid volatiles release, and ultimately lower biochar yields [124]. Higher biochar yields at low heating rates are due to the longer residence time of volatiles, which allows secondary reactions with the solid phase, such as bio-oil cracking into lighter compounds and secondary char formation [125].

Figure 6B shows how biochar yield varies with heating rates across different biomass types and pyrolysis temperatures. Although pyrolysis temperature and biomass composition (e.g., ash and chemical contents) strongly affect biochar yield, a clear trend remains that biochar yield decreases as heating rate increases, spanning heating rates from 5°C/min to 1200°C/s. However, with a narrow range (e.g., 5–100°C/min), differences in biochar yield are not as noticeable [86, 100]. Even at very high heating rates (e.g., 5–1200°C/s), the effect plateaus beyond 100–600°C/s, with further increases in heating rate having little impact on product yields [109, 126, 127]. The influence of heating rate is also more pronounced at lower pyrolysis temperatures [128]. Additionally, heating rate can affect biochar stability, with low heating rates favoring more stability [129]. Longer heating durations allow pyrolysis temperature to better control stability, especially at higher temperatures [130], and enhance aromaticity compared to faster heating [131].

3.2.3 | Particle Size

Particle size also plays an important role in biomass pyrolysis, particularly in relation to heating rate and pyrolysis temperature. Generally, larger particles impede heat transfer from the surface to the core [132]. This creates a significant temperature gradient within the particle, favoring volatile cracking and biochar formation, as depicted in Figure 6C [133]. As particle size increases, volatiles must travel longer distances through the hot biochar layer, leading to more intensive intraparticle reactions before escaping [110, 134]. Larger particles thus show more pronounced temperature gradients and secondary reactions, leading to higher biochar yields and lower bio-oil yields [132]. For instance, as shown in Figure 6D, biochar yield from olive husk increased from 19.4 to 35.6 wt% at 677°C when particle size increased from 0.5 to 2.2 mm [110]. Similarly, for rice husk, biochar yield rose

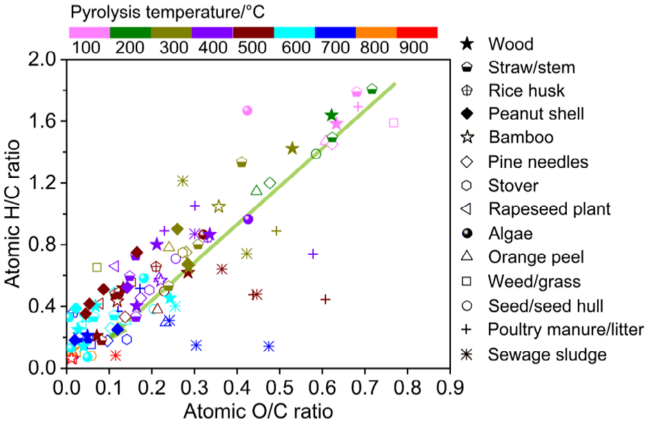


FIGURE 7 | A van Krevelen diagram illustrates atomic H/C versus O/C ratios for biochars derived from diverse biomass sources across pyrolysis temperatures. Data sources: wood [24, 91, 112], straw/stem [93, 94, 112, 113], rice husk [86], peanut shell [104], bamboo [114], pine needles [98], stover [104, 115, 116], rapeseed plant [99], algae [96, 117], orange peel [97], weed/grass [91], seed/seed hull [92], poultry manure/litter [118], and sewage sludge [91].

from 33.96 wt% (<200 mesh) to 39.14 wt% (50–10 mesh) at 500°C [111]. As biomass is a poor heat conductor, larger particles require much longer pyrolysis durations, which explain why traditional charcoal kilns using wood logs (several to tens of centimeters in size) need residence times of several days [132]. Moreover, higher pyrolysis temperatures intensify the temperature gradient, causing volatiles escaping from the cooler core to encounter hotter zones, which enhances secondary reactions and increases biochar formation [135]. However, this effect diminishes at extremely high heating rates (fast pyrolysis) and very high temperatures (1000–1400°C) [136], where particle size has less influence [137].

3.2.4 | Biomass Feedstocks

Beyond variations in cellulose, hemicellulose, and lignin content, biomass feedstocks exhibit distinct inherent properties, including pH, moisture content, and ash composition, that critically govern biochar yield and characteristics. As illustrated in Figure 8 using globally abundant biomass examples, feedstock properties directly determine biochar attributes and application potential. Cellulose- and lignin-rich feedstocks (e.g., wood and bamboo) yield biochars with elevated carbon content, suitable for charcoal and activated carbon (AC) production. Notably, a higher lignin content in the feedstock generally leads to a greater biochar yield, as cellulose and hemicellulose primarily decompose into volatile compounds, whereas lignin predominantly contributes to the solid biochar fraction [138–140]. Biomass with excellent mechanical strength, such as coconut shells, is advantageous for producing biochar with high hardness, which is ideal for applications including AC and electrode materials. Generally, feedstocks with higher ash contents, such as sewage sludge, tend to produce more biochar because, at typical pyrolysis temperatures, most mineral components in the ash fraction remain in the biochar, with only a small portion undergoing decomposition [141]. This retention preserves essential plant nutrients like K and P within the biochar during pyrolysis, although their forms and bioavailability to plants may change [142]. Feedstocks inherently rich in nutrients, such as livestock manure, also have the potential to yield nutrient-enriched biochar [143, 144]. However, nitrogen represents an exception, as most nitrogen in biomass is lost from the biochar due to devolatilization, particularly at temperatures above 400°C [145–147]. It is crucial to inspect feedstocks, especially those derived from industrial or landfill wastes, before their use in biochar production to ensure they do not contain elevated levels of heavy metals, which could contaminate the final biochar [148].

Additionally, the oxygen content of biomass affects its reactivity during pyrolysis, with studies indicating that higher oxygen levels generally enhance reactivity [149]. The moisture content also influences biochar production as well. Biomass with lower moisture content produces more biochar due to diminished steam-induced devolatilization and steam reforming reactions [150]. Furthermore, lower moisture content reduces the heat energy required for pyrolysis and shortens process duration, increasing the economic feasibility compared to high-moisture biomass [48]. Therefore, special dehydration or drying pretreatments are often necessary to reduce moisture content and ensure stable pyrolysis operations. More importantly, in large-scale or commercial biochar production, a consistent supply of homogeneous biomass feedstock is crucial for producing biochar with uniform properties. However, agricultural waste is often seasonal, whereas others, such as organic food waste, leaf litter, and grass from urban areas, are often landfilled or used for anaerobic digestion. The heterogeneity and limited availability of suitable feedstocks remain major challenges to the feasibility of large-scale biochar production. To reduce processing costs and avoid competition with other biomass applications, pyrolysis technologies should prioritize waste biomass or environmentally sustainable feedstocks that are abundant and rapidly renewable, such as bamboo residues and wood processing by-products.

3.2.5 | Secondary Reactions

Biomass pyrolysis process can be broadly divided into primary pyrolysis and secondary reactions, as illustrated in Figure 5. Typically, due to convective flow of volatiles released during biomass heating and transport in the reactor, these volatiles inevitably pass through high-temperature zones and hot biochar, making secondary reactions unavoidable [151]. These secondary reactions include thermal cracking of volatiles and interactions between volatiles and biochar, both within particles and in the particle bed as volatiles move toward final collection, as depicted in Figure 9. These reactions significantly impact biochar yield and properties, and they are closely linked to factors such as heating rate, particle size, and pyrolysis temperature, as discussed above [152]. Secondary reactions between volatiles and biochar lead to further decomposition of volatile compounds, resulting in secondary char formation, increased biochar yield, lighter oil compounds, and more gaseous products [153]. Secondary char forms through a series of reactions, including cyclization of hydrocarbon chains, dehydrogenation, aromatization, polymerization and condensation of aromatics, and coking [154, 155].

Moreover, secondary reactions among volatile compounds also contribute to secondary charring [156]. Additionally, these reactions can promote the carbonization of remaining organic compounds in the biomass, producing biochar with higher carbon

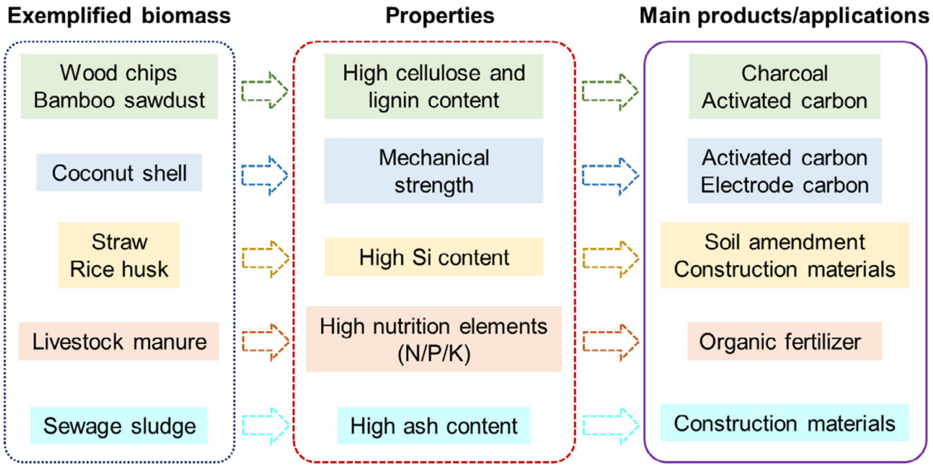


FIGURE 8 | Relationships between the properties of representative globally abundant biomass feedstocks, their corresponding biochar characteristics, and primary applications.

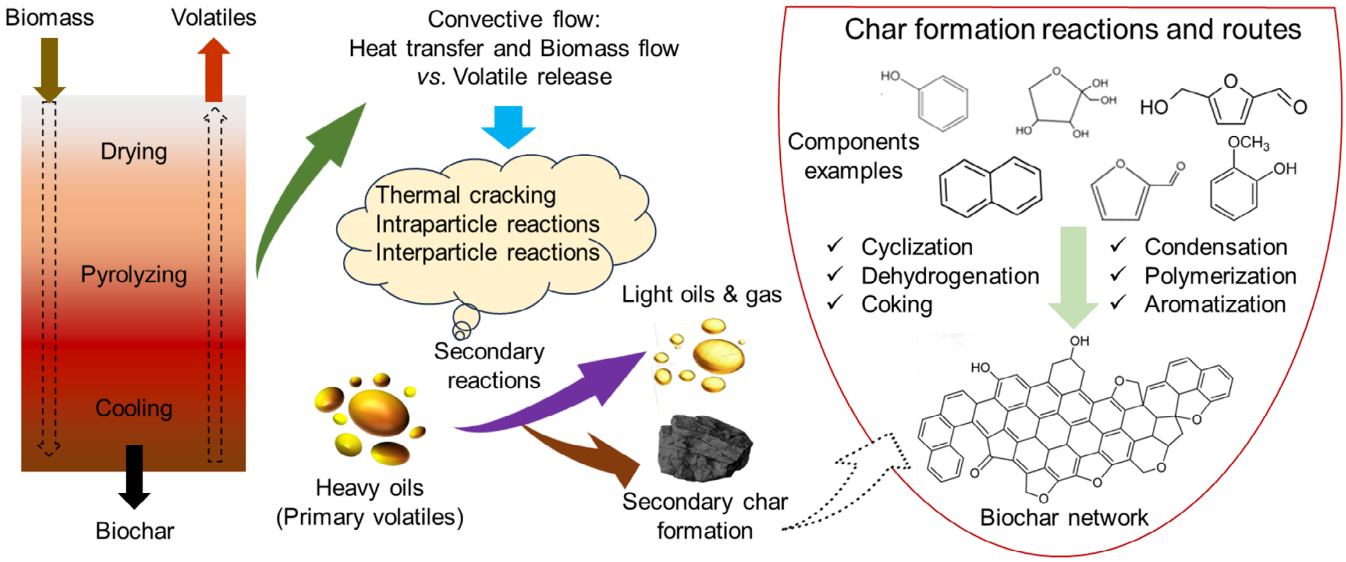


FIGURE 9 | Effect of secondary reactions on the yield and quality of biochar and liquid oils.

content [151, 157]. A notable reduction in biochar reactivity is often observed due to secondary reactions, primarily due to secondary char formation rather than loss of oxygen-containing functional groups or pore blockage, especially in micropores [158]. On the other hand, secondary reactions can be used to tailor biochar's physical and chemical properties, including surface area, porosity, functional groups, reactivity, and adsorption capacity [159]. Understanding and controlling these secondary reactions are important for optimizing biochar production and tailoring biochar and liquid oil properties for specific applications. This knowledge is essential for reactor design and selection for biochar production [160–163], particularly for novel pyrolysis reactor development, which will be discussed in the following sections [164, 165].

4 | Pyrolysis Reactors for Biochar Production

The production of high-quality biochar through safe and efficient manufacturing begins with the design of well-engineered facilities. Biomass pyrolysis equipment typically comprises a feeder, reactor, condensation section, and solid collector [166]. The pyrolysis process is commonly categorized based on the type of reactor used, as the reactor serves as the core and most crucial component. Although numerous reactors have been developed for biomass pyrolysis, it is impractical to review all of them within the scope of this article. Therefore, this review focuses on the most widely employed and adaptive reactors specifically designed for biochar production. In this section, pyrolysis reactors are classified into fixed-bed and movable-bed reactors, depending on the movement of the biomass feedstocks within the reactor and the method used to facilitate this movement. The main adaptive reactors for biomass pyrolysis include fixed-bed reactors, gravity-driven moving bed reactors, pneumatic fluidized bed reactors, and mechanically driven reactors such as rotary kilns and screw (auger) reactors. Pyrolysis reactors can also be classified according to other criteria such as heating rate (slow, intermediate, and fast), target product (biochar, bio-oil, and gas), heating method (direct heating, indirect heating,

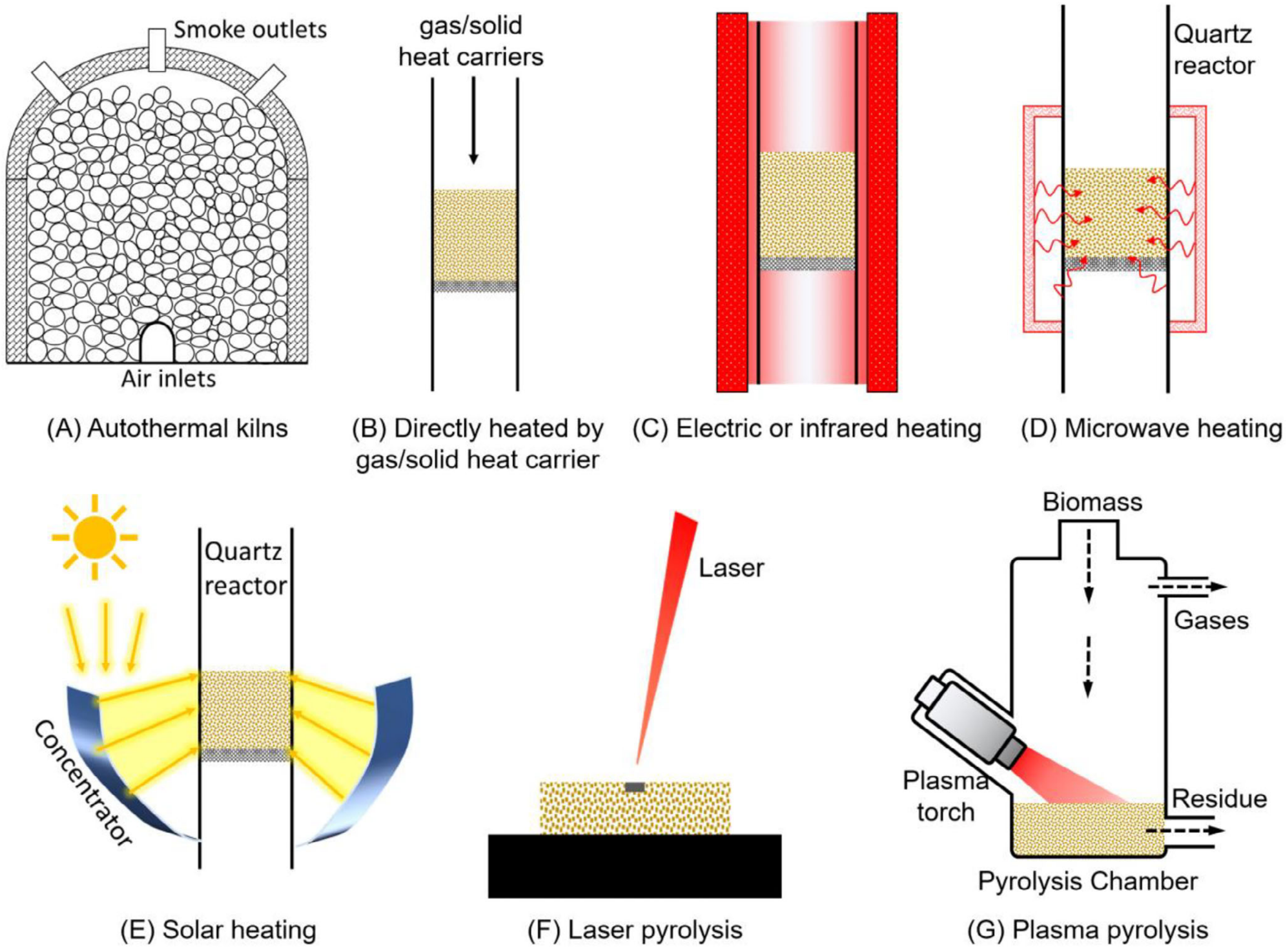


FIGURE 10 | Schematic representation of fixed-bed reactors using various heating approaches, including (A) autothermal kilns, (B) direct heating by gas or solid heat carriers, (C) electrical or infrared heating, (D) microwave heating, (E) solar heating, (F) laser pyrolysis, and (G) plasma pyrolysis.

microwave, solar heating, autothermal, etc.), operating pressure (atmospheric, vacuum, pressurized), and heat source (electric, gas heater, biomass combustion, solid heat carriers) [49]. Table 2 provides an overview of key adaptive reactors used in biomass pyrolysis.

4.1 | Fixed-Bed Reactors and Heat Supply Strategies

A fixed-bed reactor is characterized by stationary feedstocks within the reactor, making it one of the simplest types of reactors to operate and control. The practice of carbonizing wood to produce biochar, akin to the use of a fixed-bed reactor, dates back thousands of years, resembling a traditional campfire [49]. Kilns, as shown in Figure 10A, represent a well-known category of fixed-bed reactor that is extensively used for charcoal production [166]. These kilns are designed to achieve self-sustaining temperatures during the biochar formation process, a method known as autothermal pyrolysis [193]. Over the centuries, the fundamental design of kiln reactors has remained largely unchanged, with modifications primarily involving the shape and construction materials, such as earth, brick, concrete, and steel, to protect against oxygen ingress. These subtle adaptations have led to the development of various kiln types, which continue to be widely used and commercially favored, especially in underdeveloped regions [49]. Additionally, some simple kiln designs have been developed for small-scale portable biochar production in home gardens, farms, and communities by companies like Best Biochar Garden Kiln [194] and Biochar Now [195] in the United States. Kilns are highly valued for their simplicity, cost-effectiveness, and ability to produce biochar efficiently with minimal technological input.

Kiln reactors offer flexibility in terms of capacity and are particularly well-suited for processing woody logs and cordwood, primarily for fuel charcoal production. Traditionally, kilns are used exclusively for charcoal making from wood logs. Despite their enduring use and adaptability, these systems are associated with significant environmental concerns, as pyrolysis or combustion vapors are often released directly into the atmosphere, and the condensation of oils in soils poses additional environmental risks and health hazards. Moreover, kilns require manual labor for both loading and discharging, making the process labor-intensive and inefficient in biochar production. Due to the slow heating rates, kiln operations are time-consuming, often

TABLE 2 | The advantages and disadvantages of different reactors for biomass pyrolysis.

Reactor	Advantages	Disadvantages	Complexity[a]	Requirements[b]	Scale-up	Status	Capacity[c]	Ref.
Fixed-bed reactor/kilns	Simple equipment Easy and flexible operation Low cost Wide feedstock applicability	Insufficient heat transfer Low efficiency Difficulty in continuous operation High labor demand	Low	Low	Easy	Commercial	80 t/U (about 80 h for batch) [167]	[165, 167–177]
Moving bed reactor	Simplicity in reactor structure Ease of process control Low cost of feedstock transport	Feedstocks sensitivity Risk of plugging in reactor Insufficient heat transfer	Medium	Medium	Medium	Commercial	7–10 tons per hour (t/h)	[58, 64, 114, 178, 179]
Fluidized bed reactor	Continuous operation Sufficient mixing and heat-transfer Accuracy in temperature control Adequacy of scaling up	Easy blocking in feeding process Expensive pretreatment Wearing of reactor Large amount of carrier gas Sophisticated equipment Difficulty in biochar separation	High	High	Easy	Commercial	20 t/h	[49, 180–183]
Rotary kiln	Excellent feedstock adaptability Easy adjustability of residence time Well-mixing of substances Good heat transfer	High investment cost Startup wood required Abrasion of reactor	Low	Medium	Easy	Commercial	12 t/h	[184–187]
Auger reactor	Excellent control of flow and time Wide feedstock applicability Compact structure Suitable for mobile applications Simple to design and maintain	Longer residence time Easy to wear and plugging risk Poor particle mixing at radial direction Potential for insufficient heat transfer Difficulty in scaling-up	Medium	Medium	Medium	Commercial/ Demonstration	2–3 t/h	[49, 188–192]

[a] Reactor structure and process control.

[b] Feedstocks treatment and equipment.

[c] Highest unit capacity achieved currently for biomass processing.

taking several days to complete. Additionally, kilns are most effective for large-sized biomass like wood logs or log-like bulks, and encounter challenges when carbonizing small-sized biomass waste [167]. As the energy from the feedstock is solely responsible for heating the process, fixed-bed reactors relying on autothermal heating are also ineffective for the pyrolysis of residues with low heating values, such as sewage sludge, thereby limiting their applicability. Furthermore, this method of autothermal heating, which involves combustion within the reactor, offers limited control over the pyrolysis process and carbonization quality, such as biochar yield and quality.

In addition to autothermal kilns, fixed-bed reactors with external heating are most commonly used in laboratory-scale investigations and can be oriented either vertically or horizontally. They are versatile enough to be configured for two-stage catalytic pyrolysis research [154] or adapted into semicontinuous roll-away bed kilns [177]. Typically constructed from quartz glass or stainless-steel tubes, these reactors may feature beds composed of a mixture of sand and biomass particles, though they often consist solely of raw materials. The pyrolysis process can be conducted with or without the presence of an inert gas. In essence, fixed-bed reactors offer several advantages, including straightforward equipment setup, operational simplicity, cost-effectiveness, and flexibility in accommodating various biomass feedstocks. However, they also have limitations, such as restricted heat transfer efficiency, challenges in scaling up unit capacity, and difficulties in achieving continuous operation. Despite these drawbacks, fixed-bed reactors have been successfully adapted for commercial use, including in semicontinuous wagon retorts and Carbo twin retorts [49].

Apart from autothermal heating method, fixed-bed reactors offer great flexibility in selecting alternative heating approaches. Thermal energy can be supplied through various techniques, including direct heating with high-temperature gas or solid heat carriers [168, 196], indirect heating via electrical coils and hot flue gas [169, 170], as well as more innovative methods such as infrared [165, 197], solar [171–173, 198], microwave [174, 199, 200], laser [175, 176, 201–205], and plasma [206–209] heating, as illustrated in Figure 10B–G. In conventional electrical heating or indirectly heating through reactor walls, heat transfer occurs via conduction and convection, starting from the coil to the reactor and then from the surface to the interior of the biomass feedstocks. Direct heating with gas or solid heat carriers enables fast pyrolysis with more efficient heat transfer than conventional methods, resulting in higher bio-oil yields and lower biochar yields [210]. Microwave heating works by penetrating the target biomass with microwave radiation, inducing molecular dipole reorientation and friction, leading to internal heat generation throughout the sample's volume. Compared to conventional heating, microwave heating offers advantages such as volumetric and selective heating, instantaneous control, shorter processing times, and higher energy efficiency [211]. However, it also has limitations, including higher power requirements for poor microwave-absorbing materials, uneven heating that creates hot and cold spots, and the need for more complex reactor design. Although microwave pyrolysis achieves a higher heating rate than conventional pyrolysis, the differences in product yields are not substantial at similar pyrolysis temperatures [212, 213].

Infrared and solar heating also provide higher heating rates through radiation heat transfer. For example, the fast pyrolysis of pine sawdust in an infrared-heated fixed-bed reactor resulted in a biochar yield of 17.6 wt% at a heating rate of 100°C/s and a temperature of 500°C [214]. Laser heating, which can rapidly generate extremely high temperatures, has been used to produce porous laser-induced graphene from various biomass sources, including paper, pinewood, coconut, cork, muslin cloth, potato, and bread [202–204]. Moreover, plasma pyrolysis is an extremely fast process (taking less than 1 s) that involves the high-temperature dissociation of biomass into gases and slag/biochar in a near-oxygen-free environment, with plasma temperatures ranging from approximately 2000°C to 1 000 000°C [27]. This offers advantages of environment-safe processing, production of high-quality syngas/hydrogen, reduced space requirements, and minimal harmful emissions, though it also demands high energy and maintenance costs [206–209]. In general, heating methods such as gas or solid heat carriers, infrared radiation, solar energy, microwave, laser, and plasma are characteristic of fast and flash pyrolysis. Conversely, indirect heating through reactor walls using electrical coils or hot flue gas induces a slow pyrolysis process. These heating methods are suitable for the pyrolysis reactors discussed below. For continuous and large-scale biochar production, methods, like electrical, indirect flue gas, gas heat carriers, and microwave heating, are preferred and have been developed for process engineering.

4.2 | Moving Bed Reactors

Establishing a continuous pyrolysis process with a fixed-bed reactor poses certain challenges, whereas continuous production offers notable advantages such as increased productivity, consistent product quality, reduced labor demands, and lower energy consumption compared to batch-type production. Continuous pyrolysis necessitates a steady input of raw biomass feedstocks and the uninterrupted discharge of pyrolysis products such as biochar, bio-oil, and gas. Additionally, both the substrates and products must undergo continuous movement within the pyrolyzer. Gravity can serve as a simple and cost-effective method to facilitate this continuous motion. Figure 11 illustrates typical types and structures of moving bed reactors. One prominent example is the Herreshoff or multiple-hearth furnace, as shown in Figure 11A. This furnace has been developed as a large-scale technology for the continuous pyrolysis of small-sized biomass. It comprises 4–10 circular hearths or plates arranged vertically inside a refractory-lined steel shell. A central vertical rotating shaft with radial arms at a vertical rotating rate of 1–2 rpm moves the feedstocks from the top of each hearth to the bottom, utilizing a spiral of teeth across each hearth. Specifically designed to convert biomass such as sawdust, bark, husk, or milled wood into biochar, this reactor can operate under vacuum conditions, with its capacity developed up to 4 t/h/U [49]. This system is typically heated to temperatures of 500–600°C using external gas or oil burners and introduced into the reactor at the bottom of carbonization zone, resulting in a biochar yield around 25–30 wt%. One notable advantage of the Herreshoff furnace is its excellent efficiency and flexibility in processing fine-grained feedstocks that typically have little economic value.

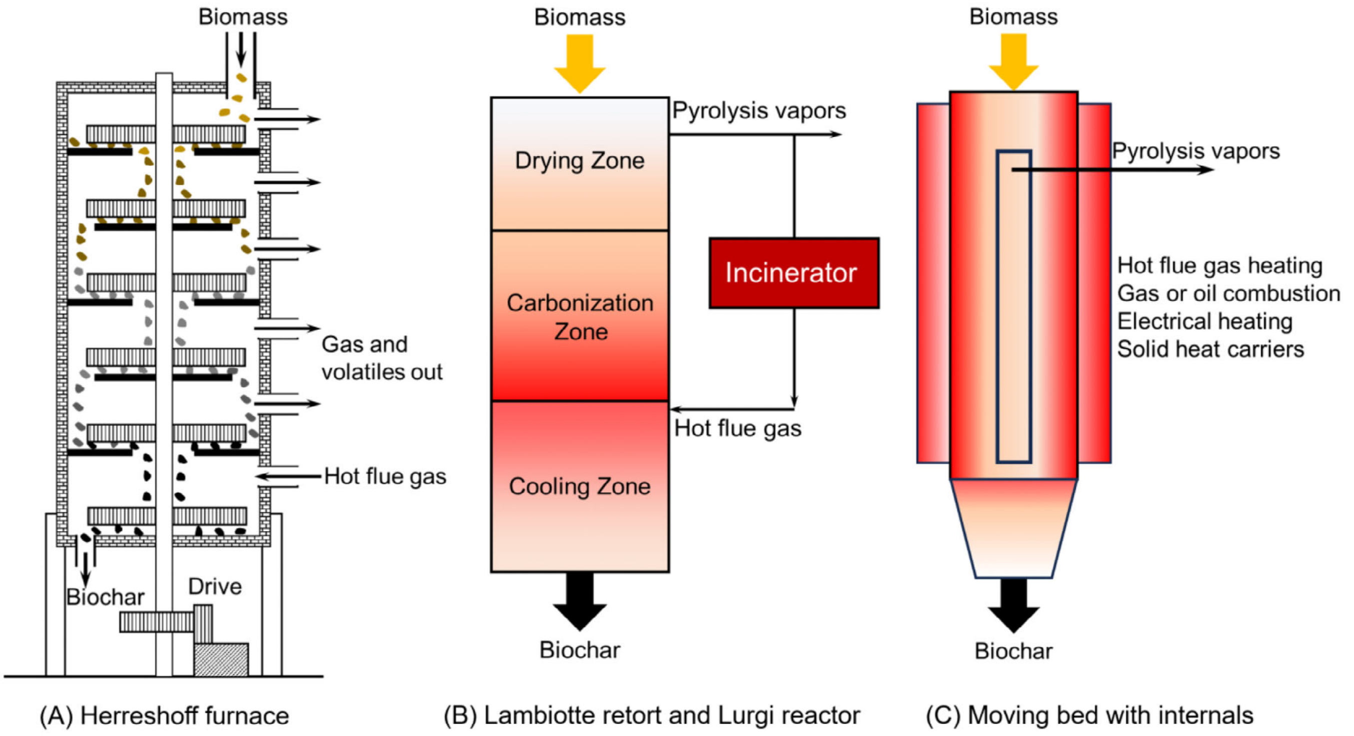


FIGURE 11 | Schematic showing of typical moving bed reactors for biomass pyrolysis: (A) Herreshoff furnace; (B) Lambiotte retort and Lurgi reactor; (C) moving bed with internals.

In addition to the Herreshoff furnace, there are other types of moving bed reactors, such as the Lambiotte retort and Lurgi reactor [178], depicted in Figure 11B by their schematic structure drawing. These reactors also operate on the principle of gravity, with feedstocks entering from the top and descending vertically through the reactor. This design ensures a constant feedstock level to prevent gas leakage. Typically, these reactors consist of an upper drying zone, a middle carbonization zone, and a lower cooling zone. During the carbonization process in the middle section, biomass feedstock decomposes, yielding biochar, vapors, and gases. Carbonization typically occurs within a temperature range of 550–600°C, and a biochar yield of approximately 30–35 wt% can be obtained. Gases produced in this section are drawn upward using a fan. The energy required for carbonization is supplied by hot flue gas generated from the combustion of a portion of pyrolysis vapors in an external incinerator. These reactors can be scaled up to a high capacity of up to 7–10 t/h/U [49]. To maintain bed permeability and prevent blockage, biomass with a wide size range (i.e., 5–50 mm wood blocks) is preferred over powders alone. Noteworthy advantages of these reactors include high automation, elevated biochar yields, superior product quality, and potential cogeneration using produced vapors. However, these reactors are sensitive to the moisture content of biomass. High moisture content can reduce the reactor capacity, potentially requiring auxiliary fuels. Additionally, the vertical movement of feedstocks in the reactor may cause attrition and the production of fines.

Moving bed reactors offer ease of construction and control, primarily by regulating the timing and quantity of biochar discharge at the bottom, ensuring the complete release of pyrolysis volatiles. As biomass descends from the top to the bottom of the reactor under gravity, it undergoes heating and pyrolysis along its vertical movement. Special attention should be given to the particle size and moving state of substrates in the moving bed to prevent plugging. In a demonstration project, bamboo chips with a particle size of less than 5 mm were first dried in a torrefaction furnace and then pyrolyzed in a vertical moving bed reactor at 600°C [114]. The dealing capacity of this moving bed for biomass was 7 t/h and 21 wt% of biochar yield was obtained through this system. Throughout the torrefaction and pyrolysis process, heat was supplied by high-temperature flue gas generated from the combustion of biomass and pyrolysis volatiles. Some modifications to moving bed reactors involve integrating gas combustion directly into the reactor by introducing a controlled amount of oxygen at the bottom. This creates a partial oxidation zone (combustion or gasification), enabling heat supply through an autothermal pathway, which is similar to pyrolytic gasification. Some modified moving bed reactors have been developed and deployed, including the pyrolysis of sewage sludge with a capacity of 34 000 t/a in Australia by the company Pyrocal [215], and the pyrolysis of forest residues with a capacity of 1–3 t/h in Canada by Pyrovac [216].

Recently, innovative moving bed reactors with internals (namely, a configuration of central volatiles collection channel) have been developed to optimize the pyrolysis of various carbonous resources, including coal [58, 164], oil shale [65, 217, 218], and waste tires [219], aiming to maximize both oil and gas yields while improving the quality of char, as illustrated in Figure 11C. Traditional moving bed reactors, such as industrial coking reactors for coal char/coke production, often encountered challenges where pyrolysis volatiles experienced severe secondary reactions (volatile cracking, aromatization, and condensation reactions) when flowing from the low-temperature region (center of the reactor, 500–600°C) to the high-temperature region (reactor wall, 1000–1200°C) [58]. This resulted in a very low oil yield with a high content of heavy oil components and significant dust content [58, 220]. By integrating specially designed internals, these modern reactors mitigate issues such as low oil yield, high ash/dust content (>10 wt%), and excessive heavy oil components in the pyrolytic oil, while also preventing blockages in the volatiles collection process [64, 221]. This is achieved by directing the majority of volatiles laterally through the low-temperature bed layer, moving from the high-temperature reactor wall to the cooler central zone. This approach facilitates controlled cracking or catalytic cracking of heavy oil compounds and enables dust removal in the volatile phase by using the moving bed as a filter. Consequently, reactors equipped with internals have demonstrated significantly increased oil yields (by 2 times), reduced heavy oil content (by >50%), decreased dust content (<0.1 wt%), and enhanced heat transfer efficiency (by 2–4 times) compared to the reactors without internals [58, 64, 217, 219]. These moving bed reactors can be heated through various methods, including electrical heating, hot flue gas from an external incinerator, direct burning of pyrolysis gas outside the reactor, or using solid heat carriers. For external heating methods, reactor wall temperatures can reach up to 1000°C to ensure efficient heat transfer and complete pyrolysis of the feedstocks [65, 218, 222]. These reactors demonstrate excellent adaptability to biomass, are easily scalable, and can handle processing capacities of up to 3 t/h/U [58, 164].

To conclude, moving bed reactors offer several advantages, including a simple reactor structure, easy process control, high labor efficiency, low energy cost for biomass transportation within the reactor, and high biochar yields. However, they are sensitive to the moisture content of feedstocks and require the particle size to be within a specific range to prevent potential plugging (i.e., chips/pellets/fine particles for Herreshoff furnace, blocks for Lurgi reactor, and chips/particles for moving bed reactor with internals). Additionally, if heat is supplied indirectly through the reactor wall, the heat transfer efficiency is reduced, impacting both capacity and overall process efficiency. Direct heating using gas or solid heat carriers poses challenges such as the generation of numerous diluted gas products and difficulties in separating biochar for mixed solids. In cases where internal combustion or gasification is used, controlling the oxidation process and heat supply can become complex, adding to the operational challenges.

4.3 | Fluidized Bed Reactors

In this type of reactor, bed materials, such as quartz sand or catalysts, are suspended in an inert gas atmosphere. When biomass is introduced, it comes into extensive contact with these heated bed materials, leading to rapid heating and initiating pyrolysis reactions [80, 182, 223, 224]. Fluidized bed reactors are characterized by several key features: (1) continuous operation: Feedstocks can be continuously fed into and removed from the reactor, allowing for uninterrupted processing; (2) sufficient heat transfer: The thorough mixing of biomass with bed material particles at high temperatures ensures a relatively uniform temperature distribution throughout the reactor; and (3) easy scale-up: These reactors are easily scalable, making them ideal for commercial applications in biomass utilization processes such as combustion, gasification, and pyrolysis [180]. A schematic diagram of fluidized bed reactors is depicted in Figure 12, which includes four main parts: a biomass feeding section, the reactor itself, a cyclone separator, and a condensation section [225]. Fluidized bed reactors can be categorized into three types based on gas flow rate and biomass particle behavior: bubbling fluidized bed (BFB, Figure 12A), circulating fluidized bed (CFB, Figure 12B) and pneumatic transport bed (PTB, Figure 12C) [226]. When the gas flow is slow, biomass particles remain stationary in the bed (fixed-bed pyrolysis). As the gas flow rate increases, the bed begins to swell, and once a certain threshold of velocity has been exceeded, a fluidized bed is generated. Initially, this is a BFB, but further acceleration of the gas flow rate transforms the process into a CFB. A yet faster gas speed gives rise to the pneumatic transport of solid substances. Generally, the heat for biomass pyrolysis in fluidized bed reactors is supplied by the bed materials and carrier gas, which come from the combustion of pyrolysis gases or external fuels.

The fluidized bed was originally invented by Fritz Winkler in 1921 and initially found application in the gasification of coal. However, it was not until the early 1960s that Douglas Elliot conceived the idea of using fluidized beds for coal combustion [180]. By the late 20th century, fluidized beds were increasingly used for biomass combustion, gasification, and pyrolysis. As a continuous process, fluidized bed pyrolysis became especially popular in commercial settings, with feeding rates reaching up to 20 t/h [49]. For instance, rice husk was pyrolyzed in a fluidized bed reactor at 450°C, yielding 30 wt% biochar and 50 wt% bio-oil [181]. A commercial-scale plant featuring a downdraft CFB reactor was developed for bio-oil production through rice husk pyrolysis [182, 183]. This technological process consists of a feeding unit, heat carrier unit, fluidized bed reactor, cyclone system, condensation unit, and carbon separating system. Operating at a feeding rate of 1–3 t/h, with a biomass reaction time of approximately 2 s, the plant achieved the highest bio-oil yield of 48.1 wt% at a pyrolysis temperature of 550°C, whereas char and non-condensable gas yields were 26.0 and 25.9 wt%, respectively. Fluidized bed reactors are renowned for their potential to produce high oil yields, up to 70 wt%, albeit at the expense of lower biochar yields [182, 227].

These reactors offer several advantages over other types of reactors, including excellent heat and mass transfer rates, which enable fast heating rates and maintain constant temperatures. They produce largely uniform products and lack moving parts in the hot region, simplifying maintenance and reducing the risk of mechanical failure. Additionally, they are easy to seal, effectively preventing air from entering the reactor. However, fluidized beds are primarily designed to maximize bio-oil production, making them less suitable for biochar production due to the low biochar yield and the complexity of separating bed materials like sand from the biochar. To achieve adequate gas–solid heat transfer, the biomass particles must be very small due to the poor thermal conductivity of biomass (typically around 0.1 W/(m K) along the grain and around 0.05 W/(m K) across the grain) [49]. Moreover, controlling residence times in fluidized bed reactors can be challenging, and bed material depletion is an ongoing concern as constant collisions between bed materials and biomass can lead to reactor wear and scuffing [228].

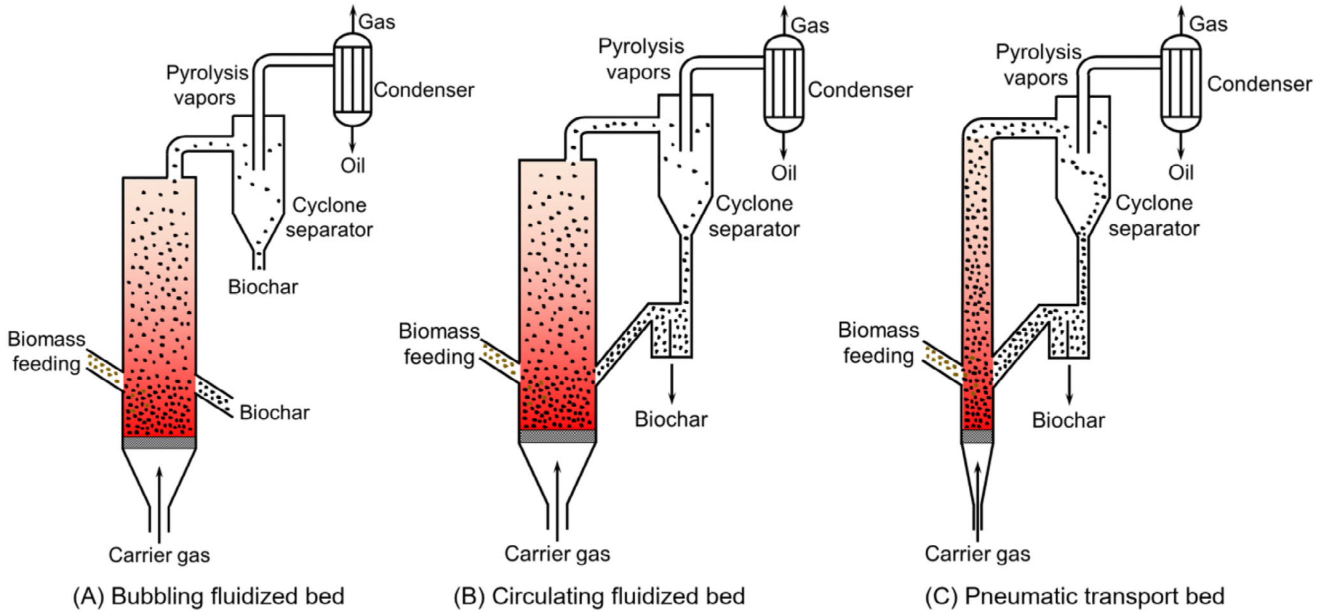


FIGURE 12 | Schematic representation of fluidized bed reactors: (A) bubbling fluidized bed, (B) circulating fluidized bed, and (C) pneumatic transport bed.

4.4 | Rotary Kiln Reactors

The rotary kiln reactor design is widely employed in the processing industry, proving to be a reliable system for biomass pyrolysis. The typical structure consists of a feeding section, a rotating reactor with a specially designed inclined angle (e.g., 3°–10°), a mechanical driver for rotating the reactor, an energy supply part, and a system for separating and collecting pyrolysis volatiles and biochar [229, 230]. The solid and gaseous products are discharged through fixed parts at the end of the rotary reactor. Figure 13 illustrates the two main types of rotary drum designs: directly heated and indirectly heated. In directly heated rotary kilns, biomass is heated by direct contact with hot gas or through self-heating (partial combustion) with oxygen. Alternatively, in indirectly heated rotary kilns, heat is supplied through the reactor walls by burning fuels (i.e., natural gas and biomass fuel particles) or hot gas (i.e., flue gas) outside the reactor, resulting in a low to medium heat transfer rate. A more popular method involves providing the necessary heat for pyrolysis by burning the generated pyrolysis volatiles. The residence time of biomass in these reactors is controlled by the angle of the kiln and the rotation rate, and the pyrolysis process can be regulated through temperature measurement within the reactor. Rotary kiln reactors are extensively used in both lab-scale studies and industrial-scale operations [231–234]. Table 3 summarizes the yields of liquid, biochar, and gas products from biomass pyrolysis using rotary kiln reactors, indicating a biochar yield range of 20–40 wt%. For instance, when olive stones were pyrolyzed in a rotary kiln at 900°C, the yields of biochar and liquid products were 26.5 and 38.1 wt%, respectively [235]. The pyrolysis of cattle manure in a continuous rotary kiln reactor yielded 39.1 wt% biochar and 26.4 wt% liquid product at 600°C [236]. Additionally, a pilot-scale externally heated rotary kiln reactor, with a handling capacity of about 800 kg/h of straw, produced approximately 32 wt% biochar at 600°C [186].

Rotary kiln pyrolyzers offer several advantages compared to other types of reactors. These reactors demonstrate excellent feedstock adaptability, accommodating a wide range of feedstocks with varying shapes, sizes (from fine particles to chips and granules), and calorific values [117, 241]. Additionally, rotary kilns provide easy adjustability of residence time for solids in the kiln chamber, allowing for optimal operation. They are less sensitive to the nature of the fuel and offer good mixing of materials, ensuring effective heat transfer during the slow rotation of the inclined kiln and thus contributing to the production of uniform pyrolytic products. Furthermore, rotary kiln reactors support continuous operation and can be scaled from small units (<0.1 t/h) to large operations handling over 10 t/h [184, 242]. The flow of biomass in the kiln can be optimized by using baffles, which enhance mixing and heat transfer, ensuring uniform residence time distribution and, consequently, consistent product quality [239]. Despite these advantages, rotary kilns also present some challenges, such as high initial investment and abrasion and wear of reactor by continuous mechanical rotation over time. Overall, the versatility, efficiency, and scalability of rotary kiln pyrolyzers make them a highly effective option for biomass pyrolysis, despite the associated costs and maintenance requirements.

4.5 | Auger or Screw Reactors

Auger or screw pyrolysis reactors are among the most popular and extensively studied reactor designs for biomass pyrolysis. Figure 14 illustrates the schematic of an auger reactor designed for this purpose. Auger reactors use a rotating screw or a set of screws to continually advance the feedstocks through the heating zone along the length of the reactor tube. The mechanical forces inherent in auger reactors could enhance particle mixing in axial direction and heat transfer, which are pivotal for the success of the pyrolysis process [188]. The rotation velocity

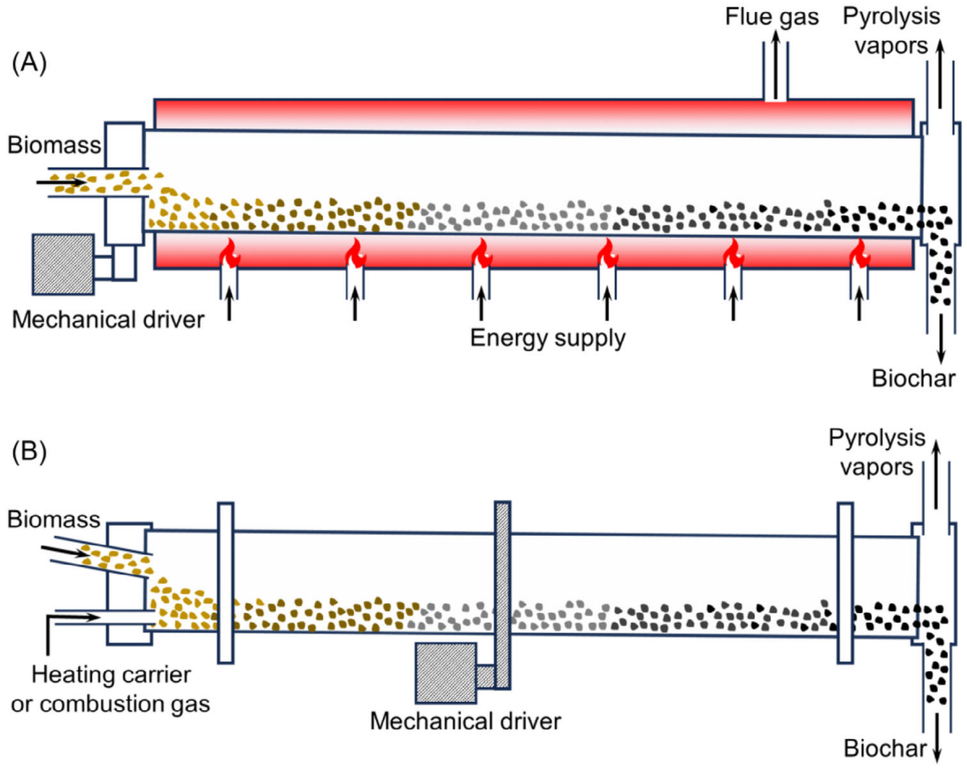


FIGURE 13 | Schematics of rotary kiln reactors processing biomass: (A) indirectly heated type and (B) directly heated type.

TABLE 3 | Yields of biochar, liquid, and gas products from biomass pyrolysis using rotary kiln reactors.

Biomass species	Capacity (kg/h)	Operation mode	Heating method	Temp. (°C)	Yield (wt%)			Ref.
					Biochar	**Liquid**	**Gas**	
Olive stones	0.1/each	Batch	External (electric)	900	26.5	38.1	35.4	[235]
Grass	0.075/each	Batch	External (electric)	500	27.91	52.99 (bio-oil)	19.10	[237]
Corn stover	0.175/each	Batch	External (electric)	800	29.73	45.29	24.98	[238]
Eupatorium adenophorum Spreng	0.45	Continuous	External (electric)	550	33.41	32.17	34.41	[239]
Tobacco stem	0.45	Continuous	External (electric)	500	33.28	41.26	25.46	[239]
Cattle manure	1.5	Continuous	External (electric)	600	39.1	26.4	34.5	[236]
Straw	800	Continuous	External (flue gas)	600	32	6 (bio-oil)	62	[186]
Wood chips	500	Continuous	External (flue gas)	600	29.8	4.4 (bio-oil)	/	[240]
Wood	6	Continuous	External (electric)	800	17.9	30.5	54.1	[230]

of the screw allows precise regulation of feedstock residence time. Due to the relatively lower rotational speed compared to the carrier gas velocity in alternative reactors like fluidized bed reactors, the solids experience a relatively longer residence time, typically ranging from minutes to tens of minutes. Beyond transport function, well-designed augers improve particle mixing and heat transfer between solid heat carriers and reactants, facilitating effective axial dispersion and ensuring uniform heating of feedstock particles within the reactor [243]. Additionally, auger reactors offer flexibility in achieving the energy required for pyrolysis through either indirect heating via the reactor walls or direct heating using heat carrier materials. Indirect heating can be accomplished using electrical furnaces in laboratory facilities or by burning the gas fraction released during the pyrolysis process along with auxiliary fuels such as natural gas or biomass, particularly in demonstration and industrial plants [118]. Direct heating, which is particularly well-suited for the production of bio-oil [244], leverages inert solid heat carriers (e.g., sand, ceramic balls, silicon carbide, and steel balls) to enhance heat transfer rates, bringing biomass particles into direct contact with a hot heat carrier to ensure rapid heat transfer essential for fast pyrolysis [190, 245, 246].

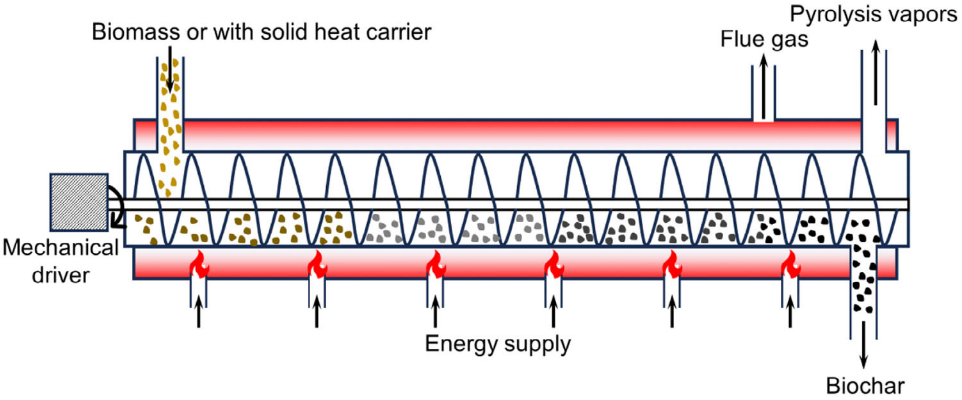


FIGURE 14 | This figure schematically illustrates the process of the auger reactor.

TABLE 4 | Yields of biochar, liquid, and gas products from biomass pyrolysis using auger reactors.

Biomass species	**Capacity (kg/h)**	**Heating method**	**Temp. (°C)**	**Yield (wt%)**			**Ref.**
				Biochar	**Liquid**	**Gas**	
Without solid heat carrier							
Corn stalk	0.12	External (electric)	600	27.0	47.0	26.0	[189]
Rice husk	0.12	External (electric)	600	31.0	46.0	23.0	[189]
Wood chips	1.5	External (electric)	500	30.0	58.0	12.0	[247]
Pinewood chips	6.9	External (electric)	500	25.8	58.7	15.5	[248]
Rice straw	6	External (electric)	500	44.9	25.7	13.2	[249]
Textile dyeing sludge	0.9	Microwave heating	750	63.9	10.0	26.1	[250]
With solid heat carrier							
Wheat straw	500	Hot sand	500	23.0	55.0	22.0	[251]
Hardwood	10	Stainless steel balls	500	18.5	66.5	15.0	[190]
Softwood	10	Stainless steel balls	500	14.9	69.1	16.0	[190]
Wheat straw	10	Stainless steel balls	500	24.5	51.4	24.1	[190]
Wheat bran	10	Stainless steel balls	500	18.2	60.0	21.8	[190]
Red oak wood	1	Steel shot	600	11.0	73.6	16.4	[245]
Red oak wood	1	Fine sand	515	22.5	63.7	13.9	[246]

The distribution of products, including liquid, gas, and biochar, is significantly influenced by the auger speed (determining feedstock residence time), carrier gas flow rate (regulating vapor residence time), and pyrolysis temperature. The product yields from biomass pyrolysis using auger reactors with or without solid heat carriers are presented in Table 4. Operational conditions in auger pyrolysis reactors typically yield 11–45 wt% biochar and 26–70 wt% bio-oil [49, 188]. Although comparisons can be challenging, it appears that higher bio-oil yields and lower biochar yields are generally obtained with solid heat carriers compared to those obtained without, especially for similar biomass compositions of wood and straw. For instance, the pyrolysis of rice husk and corn stalks in an externally electrically heated auger reactor at 600°C resulted in biochar yields of 31 and 27 wt%, with corresponding bio-oil yields of 46 and 51 wt%, respectively [189]. The pyrolysis of Douglas-fir wood in an auger reactor at 500°C achieved a bio-oil yield of 59 wt% and a char yield of 30 wt% [247]. A twin-screw type reactor, designed with a biomass capacity of 10 kg/h and utilizing stainless steel balls as a solid heat carrier, investigated the fast pyrolysis of hardwood, softwood, wheat straw, and wheat bran, yielding biochar in the range of 14.9–18.5 wt% and bio-oil from 39.2 to 47.6 wt% [190].

Auger reactors offer a multitude of advantages in the realm of biomass pyrolysis [229]. They exhibit versatility by accommodating various feedstock types in terms of shapes and sizes. The design of the auger facilitates precise control over mass flow rate and residence time, enabling meticulous regulation of the pyrolysis process [188]. Gravity facilitates easy separation of the solid fraction, simplifying the handling of output materials. The compact structure of auger reactors contributes to a smaller reactor size and reduced energy requirements for pyrolysis reactions, making the technology highly energy-efficient and minimizing capital costs associated with constructing a pyrolysis plant. Moreover, auger reactors demonstrate proficiency in handling granular and powdery materials, diminishing the need for extensive feedstock pretreatment and reducing overall energy consumption. Installation versatility is another notable feature, as auger reactors can be deployed in horizontal, inclined, or vertical configurations simply by altering the direction of the screw's rotation. They are relatively straightforward to design, operate stably when properly maintained, require minimal to no carrier gas, and boast low energy consumption. Auger technology is relatively scalable to demonstration or commercial capacities with ease; however, individual unit sizes are limited to approximately 2–3 t/h [188, 252]. Challenges also arise from the presence of a moving auger in high-temperature environments, leading to issues like wear, plugging, and clogging, particularly at elevated operating temperatures. This necessitates frequent maintenance and replacement of mechanical moving parts. The longer residence time of pyrolysis vapors in auger reactors can promote secondary reactions, potentially increasing biochar yield at the expense of bio-oil yield. Heat transfer complexities, especially at larger scales, and potential limitations in achieving uniform mixing in the radial direction may result in variations in the quality of produced biochar. Nevertheless, the ability to control process parameters and the robustness of the design make auger reactors a highly viable option for biomass pyrolysis applications.

4.6 | Integrated and Emerging Pyrolysis Reactor Designs

The application of specific pyrolysis reactors highlights the unique advantages they offer for biomass thermochemical conversion, yet each reactor type also presents inherent limitations. To address these challenges and leverage the strengths of different reactors, integrated reactor systems have been developed. These systems combine various reactor types to create a synergistic approach, enhancing feedstock flexibility, process efficiency, and technical feasibility. Notable innovations in this field include the integration of a rotary kiln reactor with a fluidized bed for biomass pyrolysis [253] as shown in Figure 15A, an auger reactor with a fluidized bed reactor for scrap tire pyrolysis [254] in Figure 15B, an auger reactor combined with a cyclonic reactor (similar to PTBs with cyclones) for biomass torrefaction and pyrolysis [255] in Figure 15C, and a screw reactor with a rotary kiln for pyrolysis gasification of sewage sludge [256] in Figure 15D.

One significant example of such innovation is an integrated reactor system that combines a rotary kiln and a fluidized bed to enable continuous biomass pyrolysis (as depicted in Figure 15A) and further incorporates a transport bed reactor for AC production [253]. In this system, the rotary kiln is used for energy recovery, feedstock drying, and pre-pyrolysis, the fluidized bed facilitates flash carbonization of the biomass, and the pneumatic riser (transport bed reactor) is employed for biochar activation. A practical application of this integrated reactor involved the treatment of distilled spirit lees (SL) from the brewing industry, which has a high moisture content of up to 60 wt%. The entire process of producing powder AC was completed in approximately 30 min, including the majority of time dedicated to drying, a short period (2–5 min) for carbonization, and about 10 s for activation. Under optimized conditions, SL pyrolysis yielded around 39.0 wt% (dry base) of biochar at 450°C for 5 min and approximately 20 wt% (dry base) of final AC product at 900°C for 10 s [257]. Heat balance calculations confirmed the autothermal nature of the process, demonstrating its self-sufficiency in energy.

This integrated reactor system has successfully progressed from lab-scale experiments to pilot-scale demonstrations. A pilot plant, with a capacity to process 2000 kg/h of granular feedstocks such as SL, sawdust, and rice husk, was designed and commissioned to operate in an autothermal and continuous manner. The integrated reactor exhibited high feedstock flexibility inherited from the rotary kiln, along with high processing efficiency and significantly reduced processing time, attributes of the fluidized bed. Moreover, the system achieved high energy efficiency through systematic energy recovery, eliminating the need for external heat input. The detailed pyrolysis process using this integrated reactor is further elaborated in Section 5.4. This innovative approach highlights the potential of integrated reactors to overcome the limitations of individual reactors, offering a more versatile, efficient, and scalable solution for biomass pyrolysis. For example, Airex Energy in Canada has developed an integrated reactor, which combines an auger reactor with a cyclonic reactor (Figure 15C). It achieves fast biomass pyrolysis in just 3 s, producing biochar with a high efficiency [255].

4.7 | Comparative Assessment of Reactor Performance

Selecting an appropriate reactor for biochar production requires careful consideration of multiple factors, including biomass properties, desired production scale, process stability, energy efficiency, and the potential for valorization of pyrolysis products. Figure 16 provides a comparative analysis of the strengths and weaknesses of the above-discussed pyrolysis reactors. The indices used in the comparison are defined as follows: Scalability refers to the ease with which the unit capacity of each reactor can be scaled up; continuous production reflects the ability and ease to operate the reactor continuously for biochar production; feedstock flexibility indicates the reactor's adaptability to various biomass feedstocks (i.e., shape and size); heat transfer measures the efficiency of heat distribution within the reactor; process controllability evaluates the ease of controlling the pyrolysis process and ensuring biochar quality; and biochar yield represents the relative biochar output across these reactors. Fast pyrolysis systems are designed to process small particles, prioritizing the maximization of bio-oil yield, whereas intermediate pyrolysis reactors offer balanced production of biochar and bio-oil on a large scale. Traditional carbonization kilns, representative of slow pyrolysis technology, are primarily used for producing charcoal from wood trunks or logs. More specifically, fixed-bed reactors are characterized by their ease of scale-up (but high land use), low structural complexity, and minimal processing requirements. Nonetheless, biochar production in fixed-bed reactors is typically batch-based, which limits continuous operation. Furthermore, slow heat transfer in large-scale fixed-bed reactors can lead to inefficiencies, challenges in process control, and variability in biochar quality. Additionally, fluidized bed reactors are more effective in producing high yields of bio-oil, though they are less

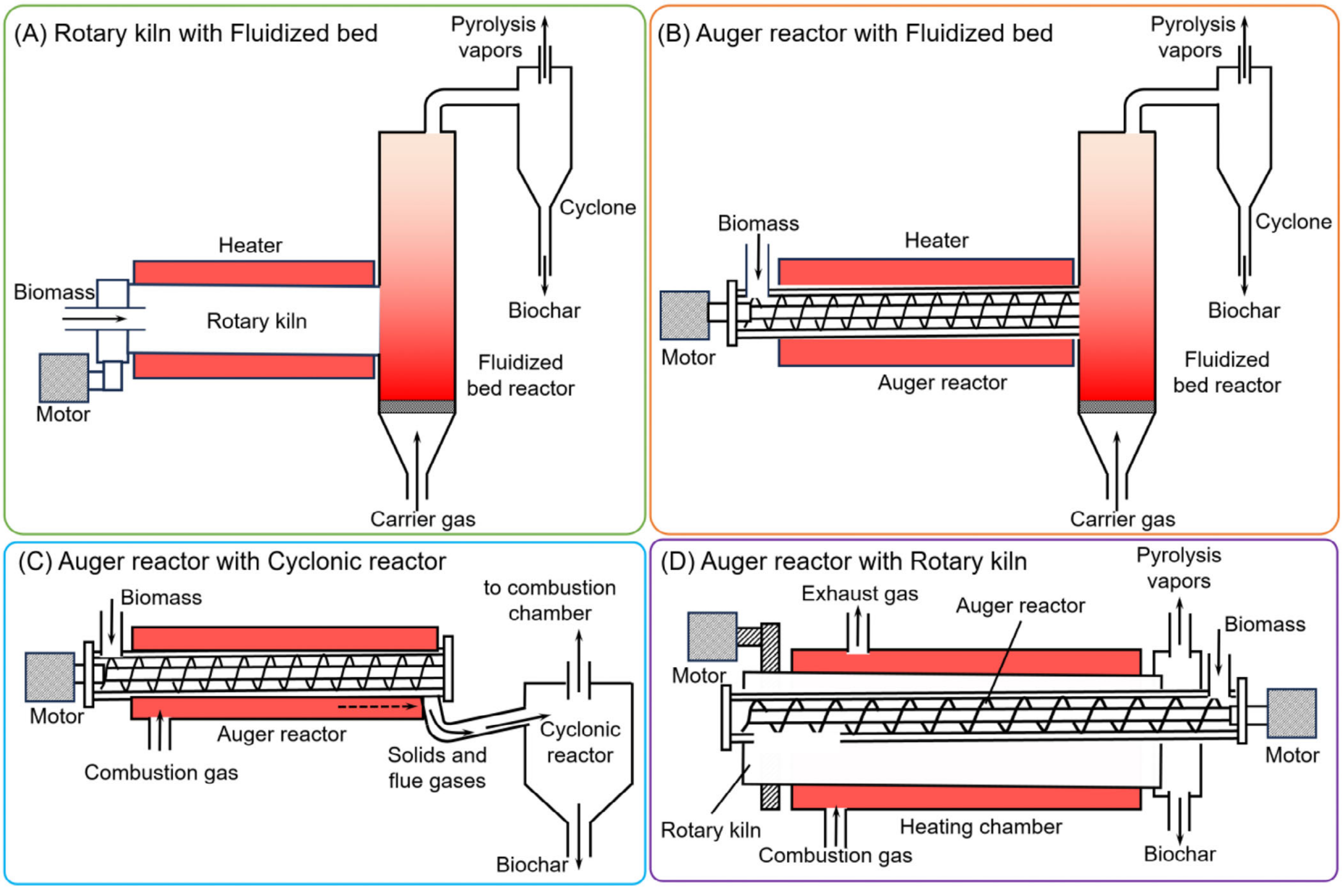


FIGURE 15 | Schematic illustration of different structures of integrated reactors: (A) rotary kiln with fluidized bed [253]; (B) auger reactor with fluidized bed [254]; (C) auger reactor with cyclonic reactor [255]; and (D) auger reactor with rotary kiln [256].

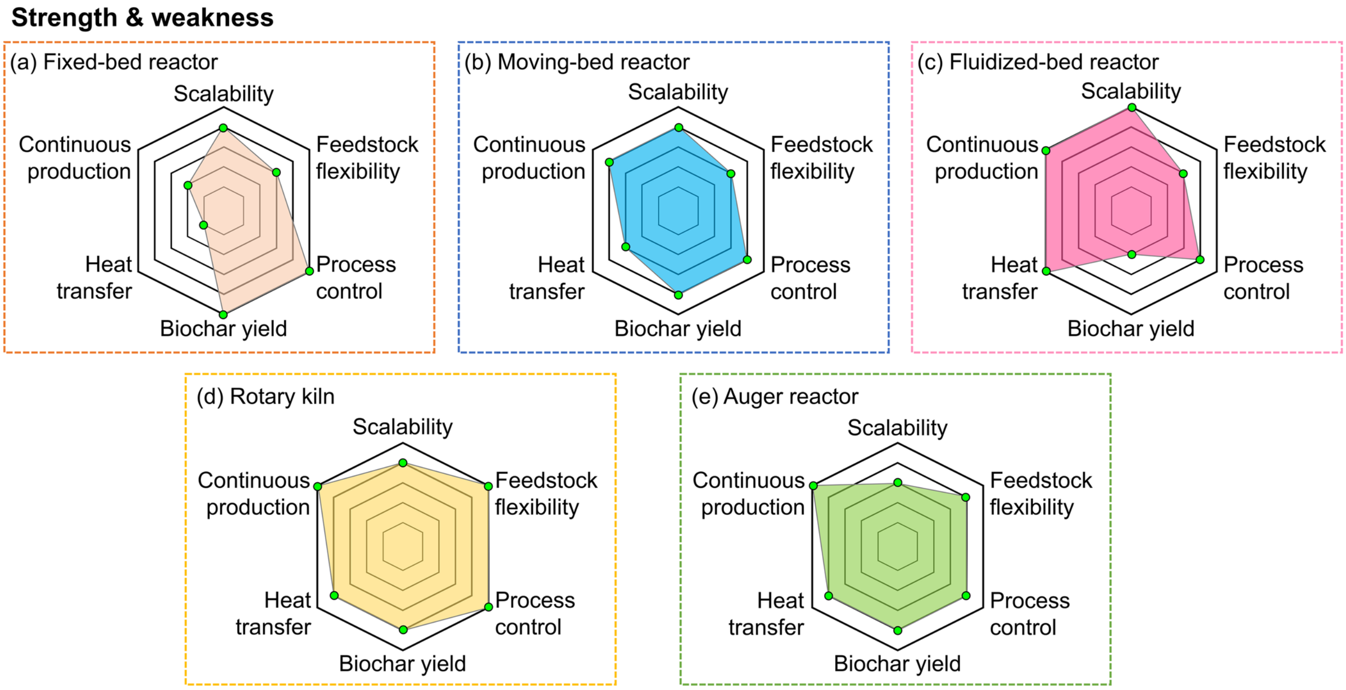


FIGURE 16 | Comparison of pyrolysis reactors and their suitability for industrial biochar production in terms of scalability, heat transfer, feedstock flexibility, biochar yield, and process controllability: (A) fixed-bed reactor; (B) moving-bed reactor; (C) fluidized-bed reactor; (D) rotary kiln; (E) auger reactor.

efficient for biochar production. The separation of biochar from bed materials or heat carriers in fluidized bed reactors presents a significant challenge, adding complexity to the process.

Rotary kilns, classified as intermediate pyrolysis reactors, offer excellent feedstock flexibility, easy operation adjustment, and ease of scaling up. Moving bed reactors have a simple structure, ease of process control, and good feedstock flexibility but low heat transfer efficiency in larger reactors when external heating is used. Auger reactors are advantageous due to their controlled residence time and wide adaptability to various feedstocks. However, their scalability is constrained, with a typical unit capacity limit of 2–3 t/h, and heat transfer challenges become more significant as the reactor size increases [188]. Reactors with moving mechanical components and high particle velocities throughout the reactor, such as fluidized bed, rotary kiln, and auger reactor configurations, are generally more compact in structure, requiring less space. However, the high velocities and temperatures in these systems can lead to increased wear, corrosion, and metal fatigue, potentially affecting long-term reliability. Considering key factors like scalability, continuous production ability, feedstock flexibility, heat transfer efficiency, process controllability, and the quality and yield of biochar, rotary kiln and auger reactors emerge as the most promising technologies for achieving Gt-scale biochar production [166, 229]. Moreover, integrated reactors, which combine the advantages of separate reactor technologies, also demonstrate intriguing potential for large-scale continuous biomass pyrolysis. The synergistic effects arising from the combination of reactor types contribute to enhanced performance and overall system efficiency.

To determine the most appropriate technology for biomass pyrolysis, a comprehensive assessment must consider technical, financial, and environmental criteria [167]. These include several key considerations: (1) technical aspects: suitability for various types of biomass, feedstock pretreatment requirements, energy efficiency and heat supply approaches, throughput capacity, portability, labor intensity, process controllability, reactor lifespan, conversion efficiency, and demonstrated use; (2) financial aspects: capital investment, operating costs, gas and oil recovery for heat utilization and downstream value-added applications; and (3) environmental and health aspects: emissions of pollutants, tar/bio-oil recovery, water requirement, and overall safety of the operation. Achieving a successful biochar production process requires careful consideration and balancing of all these aspects. Collaboration among academic researchers, industrial experts, and market analysts is essential in making informed decisions that align with sustainability and efficiency goals.

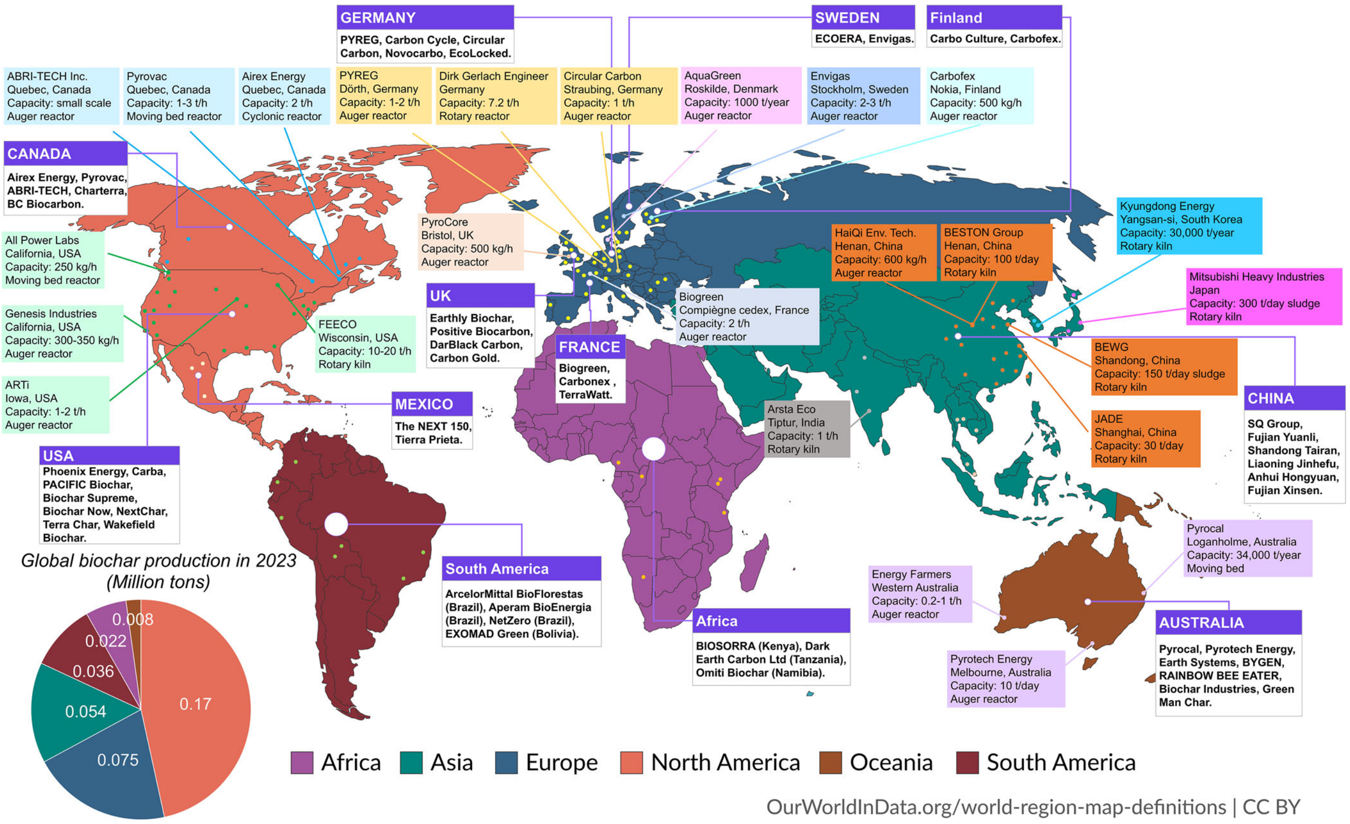
5 | Industrial Pyrolysis Processes and Technology Deployment

5.1 | Global Deployment of Biochar Technologies

Biomass pyrolysis has emerged as a critical process for converting biomass waste into energy and producing biochar, gaining significant attention since the 1970s due to the oil crisis, environmental concerns, and the shift toward sustainable energy solutions. The widespread and efficient applications of biochar in agriculture, environmental management, energy production, and industrial processes have driven continuous interest and advancement in biomass pyrolysis technologies, particularly for large-scale biochar production. Today, the urgent need to mitigate climate change and reduce carbon emissions has placed increasing pressure on both society and economic development. As a CDR technology, biochar production through pyrolysis is becoming increasingly vital. The burgeoning markets for biochar carbon credits and the rapid deployment of biochar technologies underscore the growing momentum toward achieving carbon neutrality and adhering to the Paris Agreement's goal of limiting global warming to well below 1.5°C. In line with these trends, the sustainable development and implementation of biochar production facilities, particularly those utilizing pyrolysis technologies, continue to flourish. Over the past few decades, significant efforts from academic institutions and industrial stakeholders, including biochar producers, distributors, value-added product manufacturers, and equipment suppliers, have converged to advance this field. This collaborative effort is pivotal in scaling up biochar production and enhancing technology's role in sustainable development and climate action.

Figure 17 provides a comprehensive overview of typical pyrolysis technologies and biochar production plants worldwide, highlighting key players in various countries and regions based on available data. These players include manufacturers of pyrolysis plants, systems, and machinery, as well as biochar producers and distributors. Additionally, Table 5 offers available examples of commercial pyrolysis plants and processes designed for large-scale biochar production. It is important to note that this list is not exhaustive, as the number of technology providers and biochar plant operators is rapidly increasing due to ongoing developments in this field. As depicted in Figure 17, biochar production technologies have been widely deployed across the globe, with the United States, Europe, and China being the most active countries and regions in establishing these plants. The development of biochar production systems varies based on several factors, including feedstock type, intended biochar use, production technology, local economics, and operational context. In developing economies, much of the biochar work tracked by the International Biochar Initiative (IBI) occurs at the microscale, such as biochar cookstoves, or at the village level, involving small-scale systems. However, large-scale systems are also in operation.

According to reports from the IBI and the US Biochar Initiative (USBI), more than 60% of global biochar production relies on auger reactors and rotary kilns, aligning with academic assessments of these technologies [258]. This alignment is further supported by the observation that major biochar production companies primarily utilize auger reactors and rotary kilns in Figure 17. Auger reactors typically have a unit capacity of up to 2–3 t/h, whereas rotary kilns offer a higher capacity, ranging from 10 to 20 t/h. These capacities are consistent with previous analyses and comparisons of these technologies, reinforcing their prominence in large-scale biochar production. When designing a pyrolysis plant, it is crucial to integrate variables thoughtfully, including pyrolysis reactor, feedstock characteristics and supply stability, specific operational conditions, heat supply, and environmental concerns. These considerations are vital for optimizing overall performance and ensuring the sustainability of the biochar production process. It is challenging to develop



OurWorldInData.org/world-region-map-definitions | CC BY

FIGURE 17 | World map highlights key countries and regions engaged in biochar production, major suppliers, example companies with their preferred technologies and unit scales, and global biochar production in 2023. Data sources from the IBI, USBI, EBI, and https://www.cdr.fyi/.

a one-size-fits-all design that is sustainable across all potential applications. In the following sections, we will delve into a detailed discussion of the three most widely used biochar production technologies: the rotary kiln, the auger reactor, and the integrated reactor.

As illustrated in the inset of Figure 17, data from the IBI, USBI, and European Biochar Industry Consortium (EBI) reports indicate that biochar is increasingly recognized as a leading solution for durable CDR. Global biochar production reached at least 365 000 t in 2023, reflecting a remarkable 91% compound annual growth rate (CAGR) from reported 2021 production levels [258]. The regional breakdown of biochar production in 2023 shows that North America leads with 170 000 t, followed by Europe with 75 000 t, Asia with 54 000 t, South America with 36 000 t, Africa with 27 000 t, and Oceania contributing 4100 t [258]. Overall, the investigations discussed above clearly demonstrate the rapid development and deployment of pyrolysis technologies for large-scale biochar production.

5.2 | Rotary Kiln-Based Pyrolysis Process

Rotary kilns are the preferred reactor design for the thermal conversion of particulate biomass solids due to their numerous unique advantages outlined in Section 4. The most significant advantage of rotary kilns is their exceptional flexibility, which allows them to accommodate a wide range of biomass feedstocks and processing requirements [242]. This adaptability has led to their widespread adoption across various scales, from lab-scale to full-scale industrial operations [253]. Rotary kilns are utilized for processing diverse biomass types, including wood chips and pellets [185, 187, 259], aquatic weed and grass [117, 237], crop residues [238, 260], sewage sludge [242], animal manure [236], waste biomass and solids [186, 233, 261, 262], and even waste tires [232, 241]. The longstanding history of rotary kiln technology in industries such as drying and cement production further demonstrates its commercial viability and reliability. Some of the largest rotary kilns are employed in cement manufacturing, showcasing the scalability and robustness of this technology [263]. Rotary kilns have also advanced to find significant applications in the production of biochar and AC, particularly using bamboo and coconut shells in China and Southeast Asia, as identified through the authors' investigations. This versatility can also be evidenced by the websites of companies manufacturing rotary kiln reactors in Table 5. Another key advantage of rotary kilns is their large freeboard, which allows for better contact between the solid material and any reactive gases (such as water vapor) used for the activation or functionalization of biochar. This feature makes rotary kilns particularly efficient when coupled with processes for producing AC, highlighting their widespread use and effectiveness in these applications.

A simplified process flow diagram for commercial-scale biomass pyrolysis using rotary kilns is presented in Figure 18, illustrating the key stages involved in transforming raw biomass into biochar and valuable by-products. The process begins with feedstock pretreatment, where the raw biomass is first dewatered and

TABLE 5 | Typical commercial biomass pyrolysis plants and processes around the world (not in any particular order).

Type of reactor	Feedstocks	Companies/Institutions	Website/Source
Traditional kilns	Logs, chips, pellets	Used by households, farmers, and small companies, Best Biochar Garden Kiln (USA), Biochar Now (USA)	[165, 167–176], https://bestbiocharkiln.com/, https://biocharnow.com/
Fixed-bed reactor		Carbon Compost Co. Ltd. (UK), CarbonZero (Switzerland), Carboculture (Finland)	www.carboncompost.co.uk, www.carbonzero.ch, https://carboculture.com/
Moving bed reactor	Chips and pellets	CSE Hankin (USA), All Power Labs (USA), Tianyuan Machinery (China), Pyrovac (Canada), Pyrocal (Australia), Green Power (Bulgaria)	http://hankines.com, www.allpowerlabs.com/, http://en.tyjx.cc/, https://pyrovac.com/, https://www.pyrocal.com.au/, https://greenpower.equipment/
Auger reactor		ARTi (USA), Applied Gaia Corporation (USA), BIOGREEN-Spirajoule (France), Genesis Industries (USA), Circular Carbon GmbH (Germany), AquaGreen (Denmark), PyroCore Ltd (UK), PYREG GmbH (Germany), ABRI-TECH Inc. (Canada), HaiQi Env. Tech. (China), Envigas (Sweden), Carbofex (Finland), Energy Farmers (Australia), Pyrotech Energy (Australia), WAI (Norway)	https://www.arti.com/, http://appliedgaia.com, www.biogreen-energy.com, http://egenindustries.com, https://circular-carbon.com/en/, https://aquagreen.dk/, http://pyrocore.com, www.pyreg.de/, https://abritechinc.com/, https://www.haiqienvtech.com/, https://www.envigas.com/, https://carbofex.fi/, https://www.energyfarmers.com.au/, https://www.energyfarmers.com.au/, https://pyrotechenergy.com/, https://waies.no/
Rotary kiln		FEECO (USA), Mitsubishi Heavy Industries (Japan), Ansac Anergy Ltd. (Australia), BESTON Group (China), Baoyuan (China), MINGJIE (China), BEWG (China), JADE (China), 3R-Systems (Germany), Dirk Gerlach Engineer (Germany), Kyungdong Energy (South Korea), Arsta Eco (India), Advanced Resilient Biocarbon (UAS)	https://feeco.com/, www.mhi.com/jp/group/mhiec/, www.ansac.com.au/, https://www.bestongroup.com/, www.baoyuanjx.com/, www.mingjiegroup.com/, www.bewg.net/en/, https://en.jade-cn.com/, www.3r-systems.de/, https://dgengineering.de/Index-E.html, http://www.kd-energy.com/en/main/main.asp, https://arstaeco.com/, https://advancedresilientbiocarbon.com/
Fluidized bed reactor	Fine particles	Anellotech (USA), Avello Bioenergy (USA), Nettenergy BV (the Netherlands)	http://anellotech.com, www.avellobioenergy.com, www.nettenergy.com/index.php/en/
Integrated reactor	Chips and pellets	Airex Energy (Canada), SYUCT (China), Chosun University (South Korea)	https://airex-energy.com/, https://www.rcmlab.net/ [256]

dried to a moisture content below 25 wt%, ideally utilizing residual heat from the pyrolysis process itself. The dried biomass is then shredded into smaller particles, typically up to several tens of millimeters, to ensure efficient processing within the reactor [168, 250]. This prepared feedstock is stored in appropriate storage facilities and then transported via a screw conveyor from the biomass bin to the rotary kiln reactor. The rotary kiln pyrolysis reactor is the core of this system, and it consists of a cylindrical chamber indirectly heated within a rectangular insulated chamber. These commercial rotary kilns usually range from 1.5 to 2.0 m in diameter and 12 to 15 m in length. The reactor is inclined, with the entrance elevated above the outlet, at an

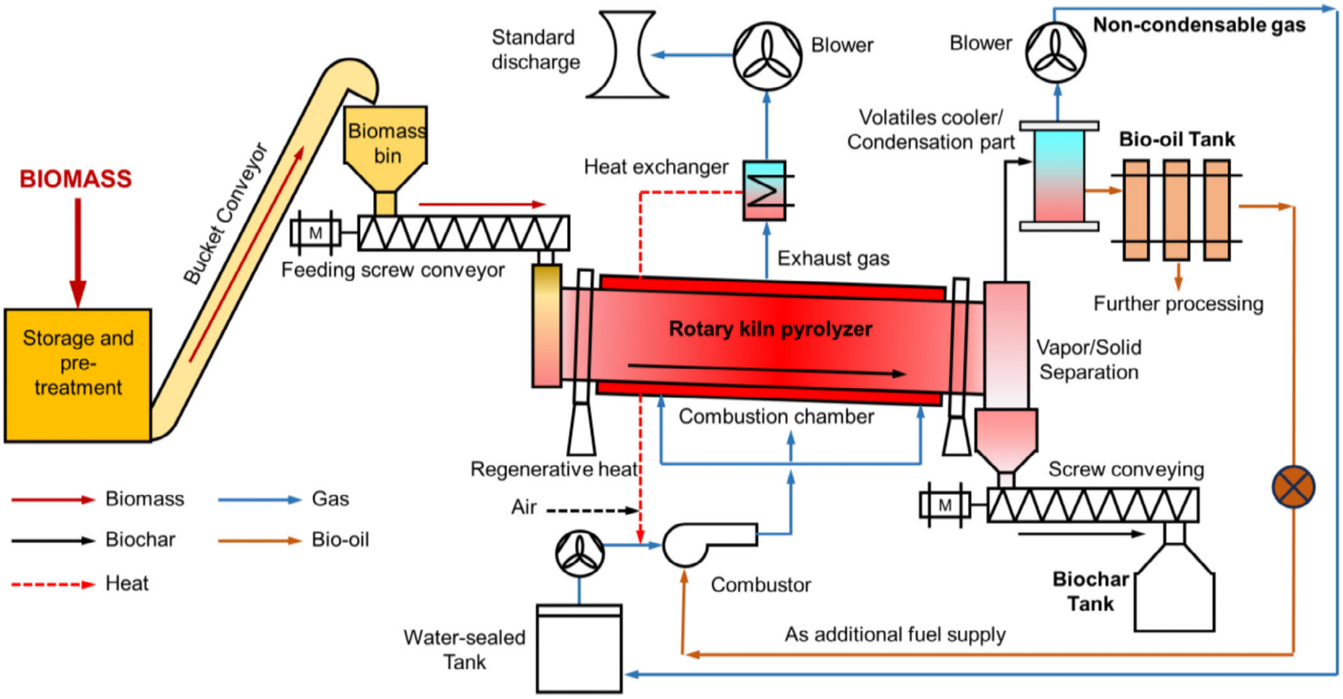


FIGURE 18 | Commercial-scale biochar production process using rotary kiln reactor.

adjustable angle between 0° and 15°. This inclination facilitates the gradual movement of biomass through the chamber as it undergoes pyrolysis. To ensure process safety and efficiency, seals are placed at both ends of the rotary cylinder to minimize air ingress and prevent the leakage of volatile process gases.

Heating the reactor is primarily achieved by burning gases generated during the pyrolysis process in an adjacent combustion chamber. After pyrolysis, the residue exiting the reactor contains both biochar and pyrolysis volatiles. These components are automatically separated at the reactor outlet: The biochar falls by gravity, whereas the pyrolysis volatiles rise for further cooling and collection. The biochar product is then cooled and transported to a storage hopper. Gas and bio-oil separation is achieved through a condensation process, which may involve direct cooling using spray condensation and indirect condensation via row tube heat exchanger. The separated gas is recycled and burned to provide heat for the pyrolysis process, whereas the final exhaust gas undergoes desulfurization and denitrification treatment before standard discharge. The obtained bio-oil can be stored for further processing or used for additional heat supply. Waste heat recovery within the system is needed to increase energy efficiency. It's important to note that actual commercial-scale projects might differ from this simplified concept. The process can be more complex when involving additional equipment and processes or simplified by avoiding the bio-oil separation step with combustion of condensable and non-condensable gases together.

The establishment of commercial-scale biomass pyrolysis plants using rotary kilns presents several significant challenges: (1) condensation part blockage: A primary challenge is the potential blockage of the condensation unit due to the presence of dust and fine biochar powders in the pyrolysis vapors. This can be avoided by avoiding condensation at all and combustion of all by-products. (2) Stable heat supply and recovery: Ensuring a stable and reliable heat supply for pyrolysis, typically achieved through gas and oil combustion, is critical for commercial-scale operations. Additionally, maximizing heat recovery and utilization within the system is necessary to improve overall energy efficiency. (3) Enhanced heat transfer: Improving heat transfer within the rotary kiln reactor is another key challenge. Enhancing heat transfer measures, such as internal heating and partial combustion, can optimize the pyrolysis process and increase its efficiency. Despite these challenges, several commercial-scale plants utilizing rotary kiln technology have been successfully established, as indicated in Table 5. Notable examples include biomass pyrolysis with a capacity of 170 tons per day (t/day) by Dirk Gerlach Engineer in Germany [264]; woody waste with a capacity of 100 t/day by BESTON (China) [265]; swedge sludge with a capacity of 150 t/day by Beijing Enterprises Water Group Limited (BEWG, China) [266]; sludge with a capacity of 300 t/day by Mitsubishi Heavy Industries (MHI, Japan) [267]; and wood chips with a capacity of 30 000 t/year by Kyungdong Development (KD Energy, South Korea) [268]. These commercial-scale operations serve as valuable examples of how these challenges can be addressed and demonstrate the feasibility of large-scale biochar production using rotary kilns.

5.3 | Auger Reactor-Based Pyrolysis Process

Auger reactors are characterized by their long, hollow, tubular-shaped reactor chambers, which contain a rotating screw mechanism designed to transport biomass through the reactor. Unlike rotary kilns, where the outer shell rotates, the auger reactor features a stationary outer shell with a rotating internal auger. This technology has a long-standing history, with one of its earliest applications dating back to a semicommercial plant in 1927 [269]. The use of augers for conveying and processing solid materials is prevalent across numerous industries. In addition, auger reactors have attracted significant attention from academic institutions and research organizations worldwide, leading to the design and development of systems capable of processing almost all types of lignocellulosic biomass. Academic contributions have been crucial in advancing research on biomass pyrolysis using auger reactors to produce various value-added products. Notable contributors to this field include Mississippi State University (with a unit capacity of 7 kg/h) [270, 271] and Iowa State University (2 kg/h) [272] in the United States, University of Leeds (0.24 kg/h) [273] and University of Edinburgh (50 kg/h) [243] in the United Kingdom, Laval University [274] in Canada (1 kg/h), Dalian University of Technology (1.5 kg/h) [275, 276] and Guangzhou Institute of Energy Conversion (20 kg/h) [277] in China, Instituto de Carboquímica (ICB-CSIC, 15 kg/h) [248] in Spain, Institute of Catalysis Research and Technology (IKFT, a twin-auger reactor with a capacity of 10 kg/h) [190, 278] and Institute for Technical Chemistry (ITC, 15 kg/h) [279] in Germany, Istanbul Technical University (1–10 kg/h) in Türkiye [280], University of Seoul (0.3 kg/h) in South Korea [254], among others. In addition to academic research, auger reactors are among the most widely explored technologies for commercial-scale biomass pyrolysis. Several companies and research centers have successfully implemented auger reactor systems for commercial applications. Examples include ABRI-TECH Inc. (with the highest unit capacity of 50 t/day) in Canada; PYREG GmbH (13 000 t/year) in Germany; BIOGREEN-Spirajoule (2 t/h) in France; PyroCore Ltd. (500 kg/h) in the United Kingdom, HaiQi Env. Tech. (600 kg/h) in China; Carbofex (500 kg/h) in Finland; and Envigas (2–3 t/h) in Sweden, as indicated in Figure 19 and Table 5 [188, 281].

Numerous types of auger reactors have been designed and implemented for commercial-scale applications, sharing a common process flow, as illustrated in Figure 19. Biomass feedstocks undergo similar pretreatment as in the case of rotary kiln units, resulting in biomass with particle sizes typically less than 70 mm, free of metal objects, and with a moisture content below 30 wt% [282]. The prepared feedstock is transported from the storage hopper to the biomass bin and subsequently fed into the auger reactor. Inside the reactor, the rotating screw continuously transports the biomass from the inlet to the biochar outlet, between which pyrolysis occurs. External heating, often provided by hot combustion gases, supplies the necessary thermal energy for pyrolysis, as depicted in the simplified process diagram in Figure 19. Preliminary energy balance calculations (inset of Figure 19) for the pyrolysis of cocoa, coffee, and nut shells suggest that the system can operate in an autothermal mode. More detailed methods of heat supply will be discussed in the following section. In certain cases, multistage auger reactors are preferred to facilitate process control and mitigate potential risks associated with long auger reactors, such as mechanical deformation of the screw, especially at high temperatures [188]. The inclination of these auger reactors helps save installation space. At the reactor's exit, biochar collection, pyrolysis volatile condensation, and separation processes closely resemble those of rotary kiln reactors. This shared common process flow demonstrates the versatility and practicality of auger reactors for biomass pyrolysis in commercial settings.

Auger reactors have undergone extensive development and have successfully scaled up to commercial capacities of up to 50 t/day. However, it is important to recognize that auger reactors have a practical upper unit capacity limit, which is significantly lower than that of rotary kilns, capable of handling up to 10–20 t/h [231, 283]. This limitation arises primarily from challenges in reactor design, including issues related to poor mixing in the radial direction and difficulties in achieving efficient heat transfer within the reactor, and the weight of the screw, which limits its further scaling up. For industrial-scale applications requiring very high capacities (e.g., >100 t/day), rotary kilns are typically the preferred technology. Additionally, auger reactors are space-efficient, often operating at higher load factors and requiring less volume for the same feedstock throughput. Nevertheless, establishing commercial-scale biomass pyrolysis using auger reactors comes with its own set of challenges and difficulties, some of which are similar to those encountered with rotary kilns. These include potential blockages in the volatile condensation part, ensuring a stable heat supply and recovery, and enhancing heat transfer efficiency. Moreover, concerns related to plugging risks and mechanical wear and tear, especially at high temperatures, should be considered [229]. To mitigate these challenges, a twin-screw configuration is recommended for auger reactors. This design minimizes the risk of clogging and adhesion of feedstocks, as the intermeshed screws continuously scrape the space between each other's flights [188, 251]. This action prevents material buildup, promotes mixing, and improves heat transfer due to the self-cleaning properties of the twin screws [190].

Several successful commercial pyrolysis plants employing auger reactors have been developed for biochar production. For example, ABRI-TECH Inc. has developed a single-auger reactor for fast pyrolysis using a high temperature, high-density steel shot heat carrier, focusing on modular small- and medium-sized heated auger pyrolyzers. These systems range in capacity from 20 kg/day (lab-scale) to 50 t/day [188]. In addition, PYREG has developed a continuous slow pyrolysis process utilizing an indirectly heated twin-auger reactor operating at temperatures between 500°C and 750°C [284]. The gas products are combusted in a flameless oxidation burner (FLOX) at temperatures around 1000°C, providing heat for the pyrolysis process and additional energy for household use. The first full-scale plant began operations in Switzerland in 2009, followed by installations in Australia (2011) and Germany (2018). The company offers pyrolysis systems for biomass treatment with capacities ranging from 1100 to 13 000 t/year, and for sewage sludge treatment with capacities between 1100 and 3100 t/year. These systems can generate excess heat energy with an output of 1.4–10 million kWh and carbon removal potential of 700–8400 t CO_2/a. The success of these commercial-scale biomass pyrolysis plants demonstrates the adaptability and flexibility of auger reactor technology for biochar production and highlights its potential for a wide range of applications [285].

5.4 | Integrated Reactor-Based Pyrolysis Process

On the basis of the available data, biomass pyrolysis utilizing an integrated reactor is demonstrated through a successful pilot-scale case study conducted by Prof. Xu's research group at Shenyang University of Chemical Technology (SYUCT) and Institute of Process Engineering, Chinese Academy of Sciences

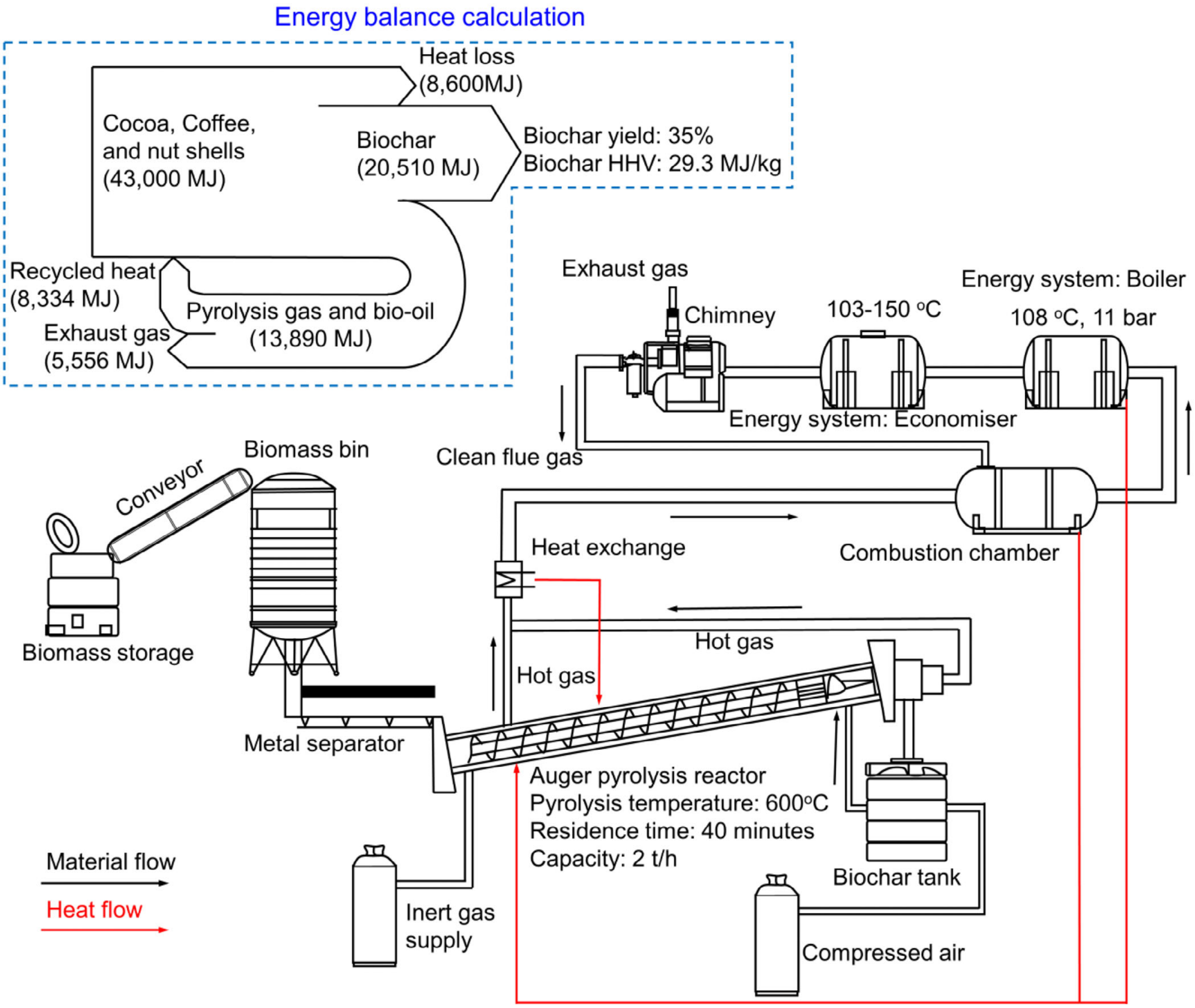


FIGURE 19 | Commercial-scale biochar production using an auger reactor with a throughput of 2 t/h.

(IPE-CAS) [63, 253]. Figure 20 illustrates the schematic diagram of this continuous biochar production process, which employs integrated rotary kiln and fluidized bed reactors. In this process, SL with a high moisture content of 60 wt% are continuously fed into the rotary kiln dryer, where they are dried using hot flue gas generated in firebox 1. The dried SL is then split into two streams: One is combusted in firebox 2 to produce high-temperature flue gas, which, mixed with unburned carbon, is delivered into the pyrolyzer to carbonize the remaining portion of the dried SL. Simultaneously, the resultant biochar and volatiles (including bio-oil and non-condensable gas) are separated in the cyclone. The volatiles are directed to firebox 1 as fuel, where their combustion generates high-temperature flue gas used for drying. The generated biochar is collected in a hopper beneath the cyclone for prolonged volatile release and is continuously fed into a pneumatic riser activator. Air, serving as both a fluidizing medium and a combustion agent, is introduced at the bottom of the riser reactor. This setup allows for the combustion of a small part of biochar and the combustible gas generated during activation, maintaining the required high temperature (about 1000°C) for biochar activation. Steam is introduced laterally into the pneumatic riser to facilitate activation, whereas the high-temperature activation products, including AC and gas, undergo heat recovery and cooling. The final AC is then collected through cyclones. This integrated system demonstrates an efficient and continuous biochar production process with effective resource utilization and energy recovery.

Notably, all process stages, including drying, pyrolysis, activation, and the integrated combustion and heat exchange, occur sequentially and continuously within a single system without requiring external heat input. The combustion of pyrolysis volatiles provides the necessary heat for drying, whereas pyrolysis is initiated by burning a portion of the dried raw material. The activation process utilizes steam generated during the cooling of activation products. The adaptability of this pyrolysis process is highlighted by its adjustable conditions and parameters. Drying time can be controlled by varying the rotation speed of the rotary kiln reactor. Long conveying tubes downstream of the rotary kiln dryer allow hot gas from the kiln to continue drying the material

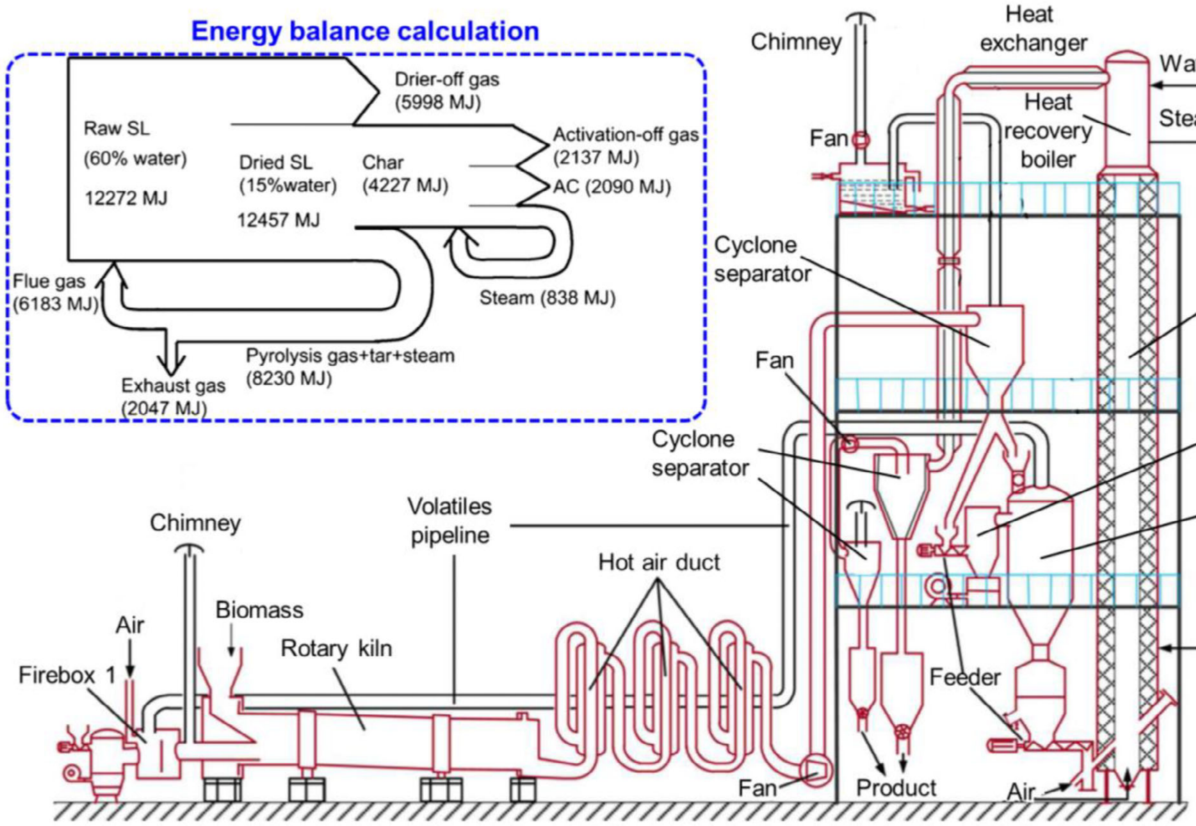


FIGURE 20 | Schematic process diagram of the pilot plant for continuous biochar production using an integrated reactor with a capacity of 2 t/h wet spirit lees, and the inset is the energy footprint of this process evaluated with the balance calculation (*E* is the input or output energy per hour). SL, spirit lees. Adapted with permission [253]; Copyright 2013, American Chemical Society.

during transport, reducing the moisture content of the SL to below 20 wt%. Additionally, the pyrolysis temperature can be regulated by adjusting the proportion of dried SL directed toward combustion versus pyrolysis. These adjustments ensure process flexibility, enabling optimization based on specific feedstock characteristics and operational requirements.

Figure 20 presents the energy balance data for this pilot-scale pyrolysis process, which has a capacity of 2 t/h wet SL, producing 250 kg/h of biochar. The input energy of 12 457 MJ is distributed across four major streams: produced AC (2090 MJ), effluent gas from the dryer (6183 MJ), effluent gas from the activator (2137 MJ), and directly exhausted gas from the combustor (2047 MJ). The energy from the off-gas of the dryer is derived from the combustion of carbonization gases. Additionally, the steam required for activation is obtained by utilizing the high-temperature sensible heat from the exhausted gas of the activator. Mass and heat balance calculations clarify that for SL feedstock with a moisture content of about 60 wt%, the developed production process for AC can operate in an autothermal mode without external heat input. This highlights the efficiency and sustainability of the process, as the energy generated within the system is sufficient to sustain all stages.

This pilot-scale pyrolysis process, with a capacity of 2 t/h wet SL, exhibits adjustable conditions and parameters for effective control. Successfully commissioned for continuous operation in 2011 for SL pyrolysis and activation in Nanyang City, Henan Province, China, it has proven to be highly adaptable for process modifications. A variant of the process, excluding the activation stage, has been consecutively applied to various biomass feedstocks for biochar production, including forestry waste (with a capacity of 10 000 t/a in Yichun City, Heilongjiang Province, China) and *Eupatorium adenophorum* Spreng (with a capacity of 3000 t/a in Panzhihua City, Sichuan Province, China). Currently, a commercial plant with a capacity of 20 000 t/a is under construction by Prof. Xu's group [63, 286]. Moreover, for other successful integrated reactors for commercial biomass pyrolysis, a large-scale system developed by Airex Energy using a cyclonic reactor with a capacity of 15 000 t/year further demonstrates the scalability of this technology employing integrated reactors [255].

6 | Key Challenges in Scaling Up Biochar Production

Scaling up technologies from small lab-scale experiments to pilot, demonstration, or industrial plants is inherently complex. Processes effective at laboratory scale may not translate seamlessly to larger operations. Scaling up, a central focus in ETC, requires a thorough understanding of how each process stage evolves from laboratory experiments to mathematical modeling, pilot-scale design, and finally, commercial operation. In biomass pyrolysis, there is a significant gap in the engineering criteria for designing and operating industrial plants. Existing literature offers few clear guidelines for scaling well-performing pyrolysis reactors, forcing companies to rely heavily on empirical experience rather than standardized scientific principles when building commercial facilities. Developing flexible pyrolysis designs capable of producing gas, bio-oil, and biochar in industrially relevant quantities remains a major technological challenge for the thermochemical community. Key considerations in scaling biomass pyrolysis to commercial levels include ensuring process efficiency, managing feedstock variability, integrating energy requirements, and maintaining economic feasibility. Overcoming these challenges is essential for advancing biomass pyrolysis technologies and enabling their widespread adoption.

6.1 | Process Efficiency and Heat Management

Achieving high process efficiency in large-scale pyrolysis technology poses significant challenges, with efficient heat transfer to the reactor and feedstocks being one of the most critical factors. This challenge arises due to the poor thermal conductivity of biomass. Ensuring uniform heat distribution throughout the biomass is essential to maintain consistent pyrolysis conditions and produce uniform biochar quality. However, as the reactor size increases, maintaining uniform temperature profiles, optimizing conditions, and minimizing heat loss become increasingly complex, often creating bottlenecks in the pyrolysis process. Pyrolysis is primarily an endothermic reaction, requiring substantial heat input to raise the biomass from ambient temperature to the necessary reaction temperature (e.g., >400°C for rice husk or stalks, >450°C for woody biomass, >550°C for sewage sludge) [188], although the heat required for the reaction itself is relatively modest [287]. Therefore, scaling up necessitates more powerful and efficient heating systems to ensure consistent temperature distribution across larger reactors. As has been described above, the primary methods for providing the required heat are outlined in the following three ways shown in Figure 21A:

- External heating through heat transfer surfaces located in suitable positions in the reactor.
- Direct heating using gas or solid heat carriers, such as heating the purge gas or bed materials. However, excessively high heat carrier temperatures or flow rates may be needed, leading to potential issues of local overheating.
- Autothermal heating by adding air or oxygen-containing agents to drive partial oxidation and combustion, though this may create hot spots in the reactor.

Different approaches can be employed to provide heat, including combustion of pyrolysis products (gases, liquids, biochar), raw biomass, natural gas, or oil. This aspect of pyrolysis reactor design and optimization becomes increasingly critical as plants scale-up. Beyond technical considerations, economic factors, the availability of heat sources, and the desired end products often dictate the choice of heat supply. For example, some processes may opt to burn raw biomass instead of biochar, particularly where there is a lucrative market for biochar. Alternatively, fossil fuels may be used if they are inexpensive and do not interfere with process or product constraints (e.g., continuous fossil fuel use is currently prohibited for carbon removal certificates in the voluntary carbon market), especially if the by-products are of sufficiently high value. In the context of biochar production, the combustion of gaseous and liquid pyrolysis coproducts may be necessary, particularly in cases where wet biomass is processed, due to the insufficient energy available when relying solely on pyrolysis gases [289].

The elimination of separate combustors and heat transfer equipment significantly signifies the pyrolysis system. Thereby, in most large-scale biochar production plants, fuels such as by-produced gases and bio-oils and raw biomass pellets are burned directly outside the reactor wall to provide the necessary heat for the pyrolysis process (see Figure 21A). In conventional pyrolysis with external heating, heat transfer typically scales with the reactor's diameter (reactor wall area), as it follows the surface area-induced heat transfer phenomenon [188]. As the reactor size increases, the surface area-to-volume ratio decreases, posing challenges for heat transfer in larger reactors and leading to decreased heat efficiency. Therefore, autothermal pyrolysis reactors, which utilize volumetric combustion for heat transfer, offer greater efficiency since heat transfer scales with the square of the reactor diameter [290]. Although more challenging to design, this approach provides substantial capital cost advantages when scaling up to commercial-sized reactors [291]. Autothermal pyrolysis has been successfully demonstrated in several reactor types, including fluidized bed reactors [292, 293] and conical spouted bed reactors [290], and efforts have been made to implement autothermal pyrolysis in rotary kilns [242, 294] and auger pyrolyzers [295]. Efficient feedstock mixing in these reactors is critical to prevent hot spots, which can lead to uneven heating and product quality issues [296]. The choice of heat supply and transfer method largely depends on the reactor design and specific technological requirements.

The heating rate of biomass particles is typically the rate-limiting step in pyrolysis. As reactors scale-up, ensuring uniform heating requires innovative designs that enhance particle movement within the reactor. Furthermore, scaling up may impact residence time due to altered heat transfer rates, potentially necessitating longer residence times to ensure complete pyrolysis. However, larger reactors generally experience lower heat losses per unit of throughput, benefiting from systematic energy recycling and utilization, which improves overall thermal efficiency. Adequate insulation and heat management systems are crucial to minimizing heat losses and maintaining high-temperature conditions. In summary, heat transfer in large-scale biomass pyrolysis plants is a critical factor for achieving efficient and consistent pyrolysis reactions. Proper reactor design, selection of heat supply and transfer methods, residence time control, and precise temperature monitoring are essential to overcoming heat transfer challenges at larger scales.

Interestingly, larger pyrolysis plants tend to employ external heating using hot gas, whereas smaller plants, primarily for research and technology development, often utilize electrical heating. Research-focused setups prioritize flexibility, the ease of use, and reliability of electric heating, where economic and energy efficiency concerns are secondary. Electric heaters, being simpler and more accessible, are widely used in these smaller systems. In contrast, larger plants prioritize cost efficiency, making direct combustion of pyrolysis gases to generate heat a more attractive option due to its energy and cost advantages. An increasingly important consideration in the choice of heat supply

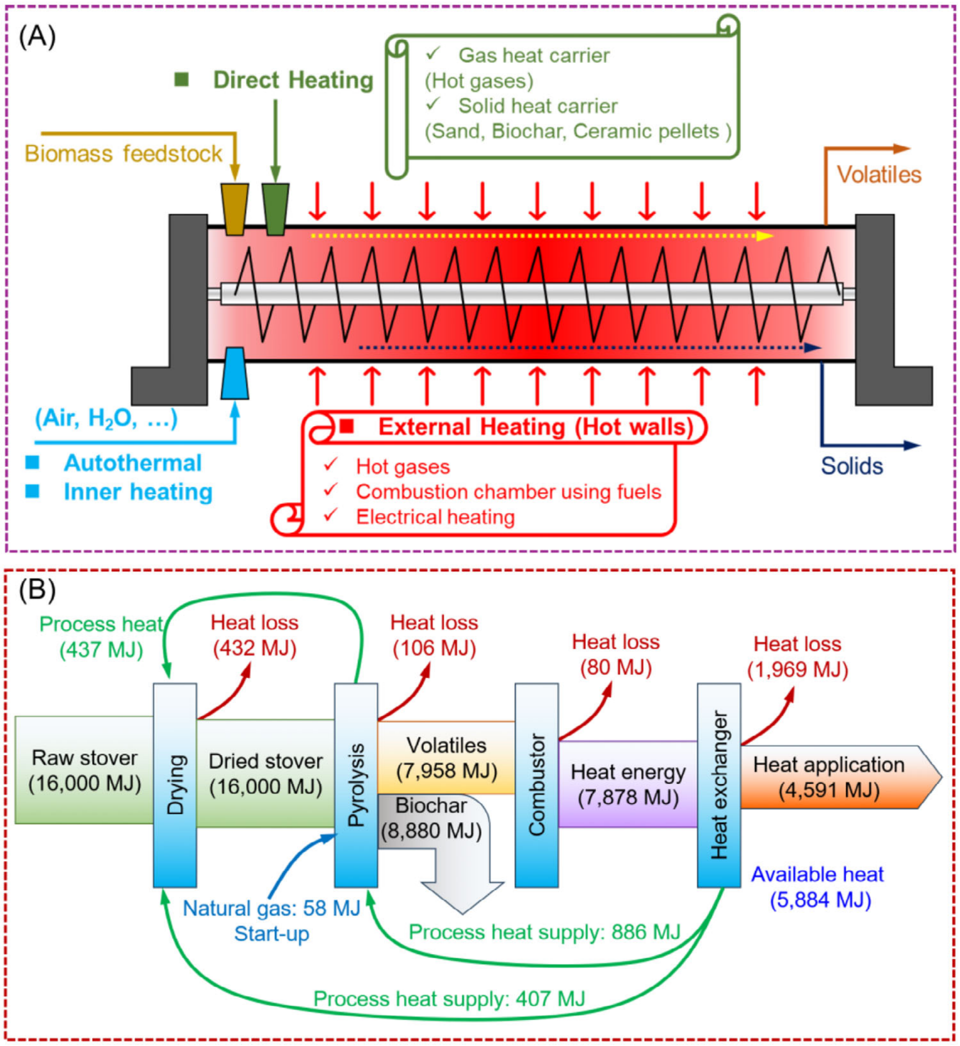


FIGURE 21 | Heat and energy management: (A) heat transfer pathways in rotary kiln and auger reactors as representative reactor configurations, data from ref [188]; and (B) representative energy flow (MJ/t dry feedstock) in an integrated biochar production system with bioenergy cogeneration via pyrolysis of stover, data from ref [288].

is the sustainability of energy sources. Electricity, especially from renewable sources like wind, solar, and hydropower, is becoming a more attractive option as efforts to reduce carbon emissions intensify. Electrically heated systems powered by green electricity may align better with sustainability goals than gas-heated systems in the future. Additionally, the potential for further processing of coproduct bio-oils and gases for valuable chemical production should be explored. As sustainability becomes a priority, integrating CO_2 capture and utilization into pyrolysis processes could enable carbon-negative operations and even net zero emissions, supporting broader environmental objectives [297].

6.2 | Energy Balance and Techno-Economic Performance

When scaling up a pyrolysis process, it is crucial to evaluate both the energy balance and the associated techno-economic factors of the entire system. Biomass feedstocks vary significantly in their chemical composition, ash content, moisture content, and physical shape, which are influenced by the type, source, and season of the biomass. These variations affect not only product yields and their physicochemical properties under similar pyrolysis conditions but also the energy balance and economic viability of the process. For example, scaling up pyrolysis for sewage sludge presents different challenges compared to scaling up for wood chips. Sewage sludge, with its high moisture content, requires pretreatment such as hydrothermal processing, mechanical filtration, and/or drying before effective pyrolysis can occur [298, 299]. In contrast, woody biomass typically needs only pre-drying. Furthermore, products derived from sewage sludge generally have lower heating values compared to those from woody biomass, leading to the need for additional energy input during sludge processing [150]. These distinctions underscore the importance of carefully considering feedstock characteristics when scaling up pyrolysis to ensure energy efficiency and economic viability [119].

A study that assessed the energy balance for biochar production from various biomass feedstocks such as late stover, early stover, switchgrass, and yard waste found a positive net energy balance, meaning that each feedstock generated more energy than it consumed [288]. An example energy flow diagram of biochar production from late stover is shown in Figure 21B [288]. In this process, late stover biomass is collected, transported, crushed, and dried, possessing a heating value of 16 000 MJ/t dry feedstock. The pretreated biomass undergoes slow pyrolysis at 450°C, resulting in the production of biochar (8880 MJ) and gas and oil (7958 MJ). A small amount of natural gas (about 58 MJ/t) is used for the initial start-up of the pyrolysis reactor burner. The pyrolysis volatiles are combusted in a thermal oxidizer at high temperatures to generate 7878 MJ of heat energy. This heat energy can be applied on-site through a heat exchanger and air ducting system (4591 MJ), and the remaining part is utilized in the drying (407 MJ) and pyrolysis (886 MJ) stage for incoming biomass. Biochar represents a significant portion of the feedstock energy, accounting for approximately 50% of the total energy output. The overall efficiency from biomass to available heat is estimated to be 36.7%. This information underscores the favorable energy balance and environmental benefits associated with biochar production from pyrolysis.

Similarly, in biochar production from palm oil empty fruit bunches at a capacity of 20 t/day, it has been demonstrated that the energy generated from pyrolysis gases is 2.75 times greater than the energy required for the entire system, including milling, drying, pyrolysis, biochar transport, and electricity needs [300]. Moreover, energy balance calculations for biochar production plants in Figures 19 and 20 from cocoa, coffee, nut shells, and SL pyrolysis also reveal a positive net energy, showing that pyrolysis products are sufficient to power the process without external energy inputs. In commercial biomass pyrolysis plants, energy from the combustion of pyrolysis gases and bio-oils is often enough to sustain the process, and excess heat can provide additional benefits. For instance, one Pyreg system, capable of treating 2200 t of residual biomass annually, not only provides the energy for its own operations (autothermal and self-sustaining) but also generates up to 4.5 million kWh of heat energy per year, enough to supply 180 households [285]. Similarly, a Carbofex plant with a capacity of 500 kg/h wood chips can produce up to 8000 MWh of clean energy for a municipal heating network [301]. These examples underscore the potential of biomass pyrolysis not only to be energy self-sufficient but also to generate surplus energy, making it a compelling solution for sustainable biomass utilization and biochar production at industrial scales.

The commercialization of large-scale biochar production is likely to face economic challenges that must be addressed for widespread adoption. The economic feasibility of biochar technology is influenced by several key factors, including (1) energy inputs and needs for pyrolysis plants, (2) value of biochar applications, (3) greenhouse gas (GHG) offsets, and (4) yield and value of other co-produced chemicals [119]. Numerous studies have conducted techno-economic assessments of biomass pyrolysis processes, with findings indicating that the net present value for biochar production can be positive, suggesting economic viability [300, 302]. Profitability in biochar production is largely influenced by the market price of biochar and the prevailing demand and revenues from the export of renewable, carbon natural energy. Certain biomass feedstocks, such as yard waste and livestock manure, have demonstrated potential for cost-effective biochar production [303]. Ultimately, the profitability of biochar hinges on optimizing the economic balance between costs related to feedstock collection, pyrolysis processing, transportation, and applications and the revenues generated from energy products, biochar, and other value-added by-products [304]. To enhance the net margins of biochar production, it is essential to explore cost-effective feedstock sources such as the utilization of waste biomass with a net negative price through avoided gate fees and implement efficient processing technologies. However, establishing economically viable thermochemical conversion facilities presents ongoing challenges, particularly in terms of biomass availability, market uncertainties, and regulatory compliance. This endeavor demands a multidisciplinary approach, incorporating expertise in engineering, chemistry, biology, and business. Careful planning, extensive testing, and continuous optimization are essential to successfully scale-up biomass pyrolysis processes and harness their potential for sustainable energy and chemical production.

7 | Sustainable Biochar Systems and Pathways to Deployment

Biochar is increasingly recognized as a multifunctional renewable carbon material with applications in carbon sequestration, soil enhancement, pollution mitigation, and advanced materials. However, evaluating its sustainability at industrial scale requires assessment beyond laboratory performance, encompassing feedstock sourcing, process efficiency, environmental impacts, economic viability, and deployment pathways. Sustainable biochar systems therefore prioritize waste or rapidly renewable biomass, energy-efficient pyrolysis, heat recovery, and integration with renewable or bioenergy systems to minimize life-cycle emissions. This section examines biochar deployment from a systems perspective, focusing on environmental impacts, market development and applications, and its role as a CDR strategy.

7.1 | Environmental Impacts and Life Cycle Assessment (LCA)

Scaling biochar production from pilot to commercial deployment introduces environmental challenges that must be evaluated across the full life cycle (Figure 22) [305]. During pyrolysis, gaseous by-products such as CO_2 and CH_4, and volatile organic compounds are generated. Although these emissions can be effectively managed in controlled systems, larger reactors increase emission volumes and require more advanced gas treatment and monitoring strategies. In addition, variability in feedstock composition at industrial scale complicates emissions standardization and reactor optimization, highlighting the importance of process control in minimizing environmental impacts [306]. Transportation represents another critical yet often underestimated contributor to life cycle emissions [307]. As production scales up, longer transport distances for biomass feedstocks and biochar products increase fuel consumption and associated GHG emissions, potentially offsetting part of the carbon sequestration benefit. Optimized logistics, decentralized production, and regional biomass utilization are therefore essential for reducing system-level emissions.

Biochar application to soils also influences GHG fluxes through interactions with soil microbial processes [308]. Although biochar generally suppresses CH_4 emissions and can reduce N_2O release by improving soil aeration and nitrogen cycling, outcomes vary depending on soil properties, biochar characteristics, and application practices [309]. Consequently, environmental performance cannot be generalized and requires site-specific LCA evaluation. Importantly, the long-term stability of biochar remains a key parameter governing net climate benefit. The development of engineered biochar introduces additional environmental considerations [310]. Chemical or physical modifications may enhance adsorption or nutrient retention but can also introduce risks related to contaminant leaching, dust exposure, or secondary emissions during disposal or reuse stages. Comprehensive LCA frameworks must therefore account for production, application, and end-of-life phases to ensure that performance enhancements do not compromise overall environmental sustainability.

7.2 | Sustainable Applications and Market Development

The expanding range of biochar applications is driving rapid market growth, primarily through its function as a performance-enhancing material rather than solely as a carbon sink. Biochar properties vary widely depending on feedstock and pyrolysis conditions, enabling tailored applications across multiple sectors. Agriculture currently represents the largest market segment [311]. Biochar improves soil structure, water retention, nutrient availability, and microbial activity, leading to enhanced crop productivity and reduced fertilizer demand [312]. Currently, China and the United States are leading the way in agricultural biochar use and as sustainable farming gains traction, the agricultural biochar market is projected to grow significantly [313]. Biochar's agricultural potential was first evidenced in Amazonian soils, where charcoal additions created *Terra preta*—dark, fertile soils supporting significantly better plant growth than surrounding soils [314]. Inspired by this, biochar products are now marketed as soil improvers or premixed amendments to mimic *Terra preta*. Companies like Sonnenerde (Austria), Carboverte (Germany), Pacific Biochar (USA), and SouthWest Biochar (USA) exemplify this trend. Biochar fertilizers range from biochar-coated conventional fertilizers (Point2Hectare, Germany; Jinhefu, China) to biochars enriched with synthetic or biological nutrients (Green Man Char, Australia; Carbon Gold, UK) and biochars from nutrient-rich feedstocks, such as manure (Sonnenerde, Austria).

Beyond agriculture, biochar is gaining adoption as a sustainable sorbent material for water treatment, where it offers a renewable alternative to coal-derived AC for removing heavy metals and organic contaminants [315, 316]. This opens up market opportunities in sectors focused on environmental cleanup and wastewater treatment, with municipalities and industries managing pollution and waste being potential large-scale consumers of biochar. In the construction sector, biochar incorporation into cementitious materials and bricks reduces embodied carbon while improving insulation and durability [317, 318]. As the construction sector increasingly seeks eco-friendly materials, biochar-based products represent a promising growth avenue. Other emerging applications include biochar as an animal feed additive to promote animal health and reduce methane emissions from ruminants, with companies like CarboVerte (Germany) and FarmChar (Australia) offering such products. Biochar's lightweight, adsorbent properties also make it ideal for green roof systems [319], and it is being explored as an additive in polymers [320] and as a replacement for fossil coal or coke in the metallurgy industry [321].

Despite growing demand, market expansion depends on improving pyrolysis efficiency, establishing reliable biomass supply chains, and developing standardized quality certifications. Regulatory clarity and consistent product specifications are particularly important for enabling large-scale commercialization and market confidence. Biochar's diverse applications in agriculture, environmental remediation, construction, and energy production drive it increasingly growing market opportunities. By leveraging pyrolysis by-products and participating in carbon credit markets, biochar producers can enhance profitability and support a more sustainable economy. As research and technology continue to advance, biochar is poised to become a key player in the global shift toward sustainability and climate resilience.

7.3 | CDR Potential and Carbon Economy

Distinct from conventional material markets, biochar's long-term climate value derives from its role as a durable carbon sink. Its highly aromatic carbon matrix, formed during pyrolysis, resists biological and chemical degradation, enabling centennial-scale carbon storage, as evidenced by persistent charcoal in Amazonian *Terra preta* soils. This inherent stability establishes biochar as one of the most mature and scalable engineered CDR pathways. The economic potential of biochar increasingly hinges on carbon removal accounting and credit mechanisms. Global industry revenue reached approximately $610 million in 2023 and is projected to expand rapidly (Figure 22B) [258], supported by both product sales and carbon credit generation. Although carbon credits represent a major growth driving force, many producers have yet to monetize these removal benefits, indicating substantial upside as verification standards mature and corporate decarbonization demand rises. Notably, the biochar sector received only 12% of CDR-directed funding, yet accounted for over 90% of carbon removal in voluntary carbon markets in 2023 [322]. Enhanced investment, particularly in market development and large-scale production facilities, could further strengthen biochar's role as a critical climate mitigation technology.

Biochar currently accounts for the majority of carbon removal within voluntary carbon markets among novel CDR technologies. As shown in Figure 22B, global biochar production reached at least 0.37 Mt in 2023 [258], and with projections estimating growth to 1.73 Mt by 2029 [321]. Country-level analyses identify China, the United States, Brazil, and India as major contributors due to abundant biomass resources [324]. Realizing this potential requires scaling standardized production systems capable of delivering consistent material quality and verifiable carbon storage. Increased investment, improved monitoring methodologies, and integration with industrial decarbonization strategies will be critical for positioning biochar as a cornerstone technology in global CDR portfolios. To meet growing demand and fulfill its role in climate mitigation and sustainable development, deploying large-scale biochar production technologies that ensure stable quality and consistent output is critical.

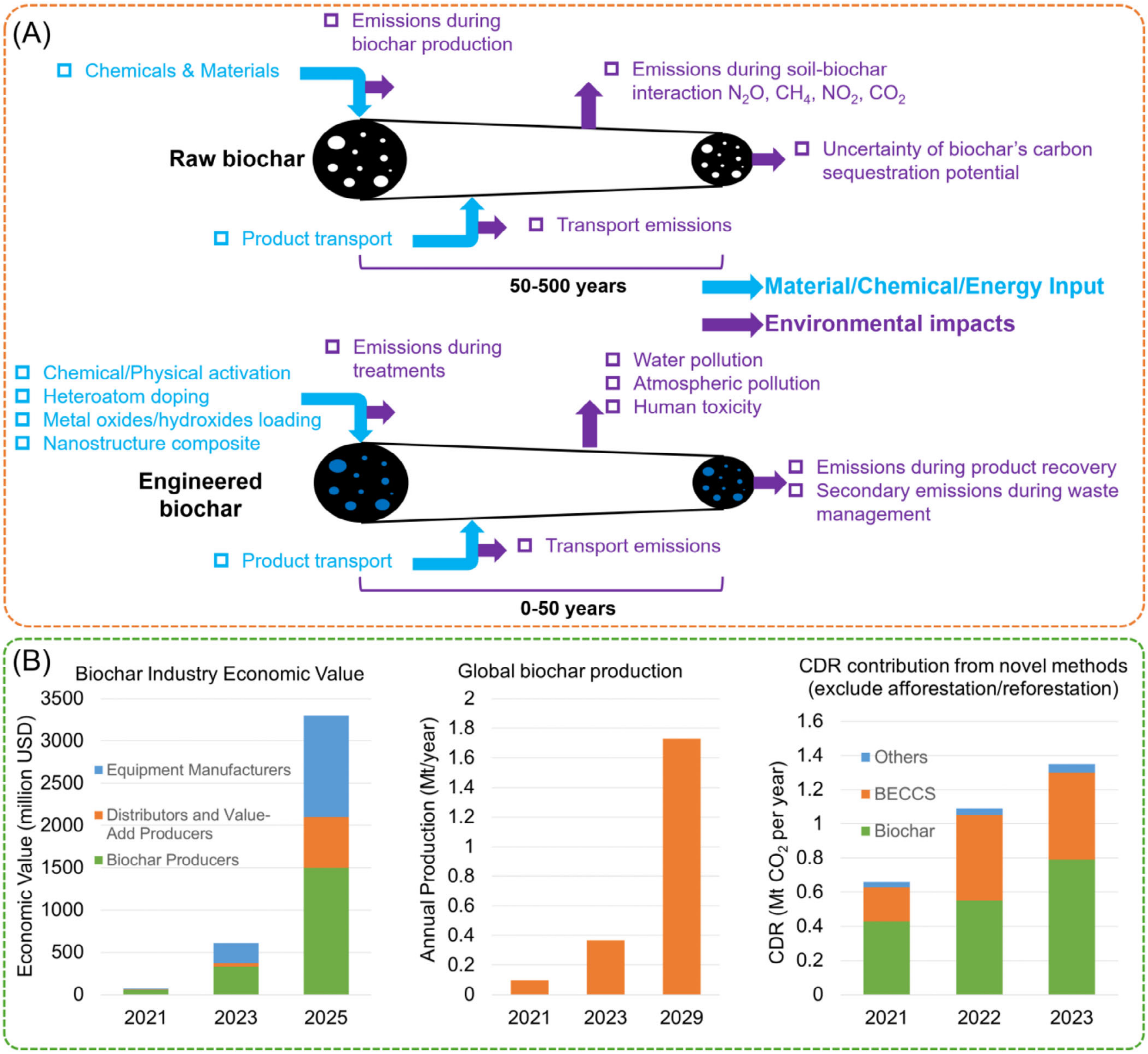


FIGURE 22 | Environmental and economic sustainability of biochar: (A) environmental concerns of the biochar system and (B) biochar industry economic value, global biochar production, and CDR contribution from novel methods (excluding afforestation/reforestation), data from refs [258, 323]. BECCS, bioenergy with carbon capture and storage; CDR, carbon dioxide removal.

7.4 | Regulatory Frameworks and Biochar Certification

The expansion of biochar production and markets requires robust regulatory and certification frameworks to ensure environmental integrity, product reliability, and market transparency. However, governance structures remain fragmented or underdeveloped in many regions, creating uncertainty for large-scale deployment. Standardization efforts can be broadly categorized into three interconnected dimensions: product certification, process certification, and carbon removal certification supported by monitoring, reporting, and verification (MRV) systems.

7.4.1 | Product Certification

As a tradable material applied across agriculture, environmental remediation, and construction, biochar must satisfy consistent quality and safety standards. Yet regulatory classification remains inconsistent, with biochar frequently regulated under legacy categories such as charcoal or soil amendments, leading to legal ambiguities [325]. Within Europe, national regulations historically differed, resulting in cases where biochar approved in one country was restricted in another. For example, the German Fertilizer Ordinance (2012) permitted only charcoal derived from untreated wood with high carbon content, excluding alternative feedstocks. Subsequent updates under the EU Fertilizer Product Regulation introduced the category of CMC14 (pyrolysis and gasification materials), representing an important step toward harmonization.

To address the lack of unified legislation, EBI has implemented self-regulation through the European Biochar Certificate, which establishes minimum quality standards for biochars based on their intended use. By now, the EBC also had regulatory success in Switzerland, which now requires that every biochar must be EBC certified to be legally applied. Although industrial self-regulation can have benefits, large scale implementation of biochar will eventually require state regulation to increase trustworthiness and transparency in the market. Additionally, beyond basic safety standards, functional certifications could categorize biochar by performance in specific applications, unlocking further market potential.

7.4.2 | Process Certification

In addition to product certification, process control and monitoring will be equally important. Quality management systems (QMS) for pyrolysis plants, including the utilization of existing industrial standards such as ISO 9000 (for quality management) and ISO 14060 (for GHG emissions management), and standards for sampling and testing will ensure continuously improving production processes through internal management systems. Furthermore, biochar production is inevitably integrated within several value chains; the most notable is biomass utilization. Several regulations aimed at increasing the transparency of value chains already exist and will be further expanded in the near future to counter biodiversity losses through overexploitation of biomass resources. This is especially relevant for the implementation of large-scale biochar production to ensure ongoing environmental benefits.

7.4.3 | Carbon Credit Certification and MRV Systems

Biochar's role as a CDR technology makes credible carbon accounting central to its economic viability. Certification of carbon removal requires cradle-to-grave assessment of production, application, and long-term carbon stability. In the absence of comprehensive regulation, voluntary schemes such as Puro.Earth, C-Sink, Verra, and CCER have pioneered methodologies for issuing biochar-based carbon credits, establishing early markets while methodologies continue to evolve. A major challenge lies in developing standardized accounting approaches that ensure transparency and comparability across jurisdictions. The European Union's emerging Carbon Removal Certification Framework aims to harmonize methodologies for biochar and other CDR pathways, potentially introducing minimum stability thresholds, process emission constraints, and operational requirements affecting reactor design, energy integration, and plant sitting. Policy choice, such as limits on feedstock transport distance or requirements for financial additionality, may significantly influence optimal plant scale and business models. At the global level, integrating biochar carbon removals into national GHG inventories remains unresolved. International climate agreements rely on national accounting systems, whereas many current certification approaches operate through private or voluntary markets. Aligning these frameworks will be essential for enabling Gt-scale deployment while maintaining environmental credibility.

8 | Conclusions and Perspectives

The production and application of sustainable biochar materials are rapidly advancing, with significant progress made in recent years. The future development of biomass pyrolysis technologies holds considerable promise, as it plays a crucial role in the transition toward more sustainable and environmentally friendly energy and chemical production. Here are some key trends and potential developments to expect in the coming years.

8.1 | Commercialization and Scaling Up

The development and adoption of commercial biomass pyrolysis technologies are becoming increasingly vital. With growing interest in biochar applications across various fields, including energy conversion and storage and carbon capture and reduction, it is likely that biomass pyrolysis technologies will undergo scaling up and commercialization. This expansion will involve the construction of larger and more efficient pyrolysis plants designed for industrial-scale production of biochar-based materials. For instance, renewable biomass stands out as a sole green and economically attractive carbon source to produce hard carbons, which are gaining significant attention as carbon anodes for lithium and sodium-ion batteries [326, 327]. As the development of energy storage applications and markets continues to gain momentum, both academia and industry are increasingly focused on promoting continuous large-scale pyrolysis technologies for producing carbon materials from biomass. Furthermore, regarding biochar applications in soil remediation and carbon sequestration, only commercially viable pyrolysis technologies with substantial production capacity and cost-effectiveness can effectively address the challenges posed by large-scale applications [328]. Conversely, the development of scalable and cost-efficient biomass pyrolysis technologies will, in turn, facilitate the large-scale industrial biochar applications. Hence, there is a strong impetus to persistently foster the commercialization of pyrolysis technologies for mass-producing low-cost yet high-performance biochar materials.

8.2 | Rational Design and Controllable Synthesis

The rational design and controllable synthesis of high-performance and high-value-added biochar-derived functional materials represent an inevitable trend [30, 329]. Achieving the precise synthesis of biochar materials with desired structures and performances to meet diverse application requirements stands as a pivotal task [11]. For instance, applications in water treatment and catalysis necessitate biochar materials with high porosity and specific surface area to maximize their adsorption and catalytic capabilities [330]. Excellent conductivity and porous structure are preferred for electromagnetic interference shielding and microwave absorption applications [76, 331–335]. In biochar anodes, the well-tailored textures (closed pores and defects) and large microcrystalline interlayer spacing are favored [327, 336]. Undoubtedly, biochar materials with precisely controlled structures and versatile properties hold the potential to provide innovative solutions to energy and environmental challenges. Accompanying the advancement of precise pyrolysis methods and novel reactors, the integration of machine learning technology, advanced characterization techniques, deeper understanding of pyrolysis mechanisms, and theoretical calculations with experimental work is essential. This integration can establish the relationship between structure and performance, aiding in the precise synthesis of biochar materials. Therefore, developing efficient and large-scale controllable synthetic methods for high-performance biochar materials is highly desired to meet increasing demands across various applications.

8.3 | Advanced Pyrolysis Techniques

Most biomass pyrolysis processes for biochar production involve low temperatures (500–1000°C) and moderate heating rates (100–1000°C/min). However, as the demand for high-performance biochar materials has grown, so has interest in utilizing higher temperatures and heating rates for thermal treatment [337]. For instance, in advanced energy storage applications, biochar materials carbonized at temperatures ranging from 1200°C to 1400°C exhibit optimal structural properties that greatly enhance their performance in lithium and sodium-ion battery cells [327]. Moreover, ultrahigh temperatures, reaching 2000–3000°C, promote the graphitization of biochar, resulting in exceptionally high electrical conductivity and well-defined crystal carbon structures [338, 339]. Emerging unconventional pyrolysis technologies are also gaining attention, such as the Joule heating method and laser heating method [203, 340, 341]. These methods feature rapid heating and cooling rates (>2000°C/s), uniform heating, and extremely high temperatures, up to 3000°C [203, 340, 342]. They have the potential to produce biochar materials with unexpected structures and properties. For example, noncontact microwave pyrolysis can synthesize porous graphitic carbon nanostructures from wood and cotton [343], whereas flash Joule heating can yield high-quality graphene from biomass [341]. Additionally, Joule heating has been employed to create highly conductive graphitized carbon fiber [339] and graphitic carbon [344] from bamboo fiber and lignin. Consequently, the pyrolysis of biomass under extreme conditions, involving ultrahigh temperatures and ultrafast heating rates, is gaining increasing attention. Exploring the behaviors and performance of biomass pyrolysis under these conditions and scaling up unconventional pyrolysis technologies represent intriguing trends for the future.

In conclusion, the growing interest in converting biomass into biochar is driven by its economic advantages, sustainability benefits, and rising demand across energy and environment sectors. Recognizing the intrinsic value of biomass resources and optimizing their utilization are essential for advancing sustainable energy development. Promoting the widespread use of biomass as a carbon source for high-value biochar materials is therefore of significant importance. As an important branch of ETC, future endeavors should focus on enhancing biomass conversion into functional carbons, particularly by advancing large-scale production and applications of biochar, developing more efficient, environmentally friendly, and cost-effective methods for high-performance biochar, and exploring biomass conversion under extreme thermal conditions. To bridge the gap between laboratory research and industrial needs, efforts should be made to establish connections, thus facilitating the translation of biochar research into cost-effective large-scale production. Progress toward industrialization will be critical for realizing the full potential of biochar technologies. We hope this review provides a comprehensive framework that clarifies pyrolysis technologies and inspires the development of innovative processes for continuous and scalable biochar production.

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Conflicts of Interest

The authors declare no conflicts of interest.

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