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REVIEW

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Pyrolysis reactor design and biochar microstructure control for fertilizer performance: a review

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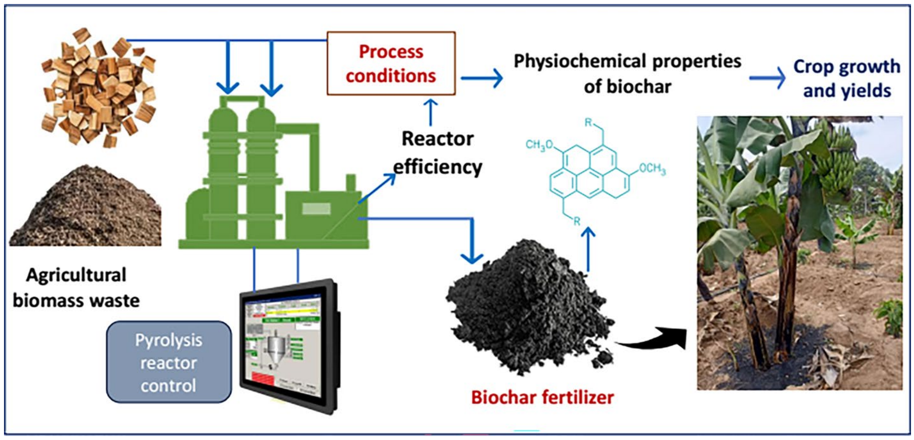
Abstract

Biochar obtained from biomass pyrolysis is increasingly being considered as a soil amendment because of its potential to enhance nutrient retention, improve soil structure, and support crop productivity under a wide range of farming conditions. However, finding good quality biochar for fertilizer application remains a challenge to the wider agricultural community. This is linked to the undefined biochar production pathways that link feedstock, process parameters, and reactor technologies for quality and quantity output. Despite extensive research on biochar production, systematic analysis linking specific reactor technologies to resultant biochar microcrystalline structure remains limited. Studies published between 2010 and 2026 were systematically examined to evaluate how different pyrolysis reactor configurations influence biochar properties relevant to fertilizer applications. These properties include surface area (> 100m^2/g), porosity (> 50 nm), surface homogeneity, hydrophilicity and H/C ratios (< 0.7). Comparative analysis highlights that slow pyrolysis in fluidized bed reactors tends to produce biochars with higher porosity and stability, whereas microwave and plasma-assisted systems achieve enhanced surface areas but face energy and scalability challenges. Constraints, including non-uniform thermal transfer, reactor fouling, and high energy demand, continue to limit large-scale adoption. Recent work on hybrid reactor systems and data-driven optimization approaches suggests potential ways to address these challenges by improving thermal control and consistency in biochar production. Based on these findings, the review outlines practical considerations for reactor development, with particular attention to hybrid configurations, automation, and digital support tools.

Keywords: Biomass pyrolysis, Reactor designs, BET surface area, Porosity, Fertilizer applications, Hybrid reactors

Graphical Abstract



1 Introduction

Increasing pressure on agricultural systems to enhance productivity while limiting environmental degradation has driven renewed interest in waste valorization strategies that also improve soil performance [1–5]. Biochar has been widely explored as a soil enhancer, owing to its physical and chemical characteristics that influence soil processes, nutrient dynamics, and long-term carbon storage [6]. Its unique physicochemical and structural properties, including high surface area, tunable porosity, aromaticity, and functional group chemistry, make biochar a versatile material capable of being applied as fertilizer [7–12]. Although there is not yet a universally accepted legal standard definition for fertilizer-grade biochar, in scientific and certification literature, it is generally understood as: Biochar specifically produced and characterized for use in agricultural soil to improve fertility, nutrient use efficiency, water retention, and supply plant nutrients, while meeting quality and safety standards for agronomic applications [13, 14]. In this review, "fertilizer-grade biochar" refers to biochar intentionally engineered for agricultural nutrient management and soil fertility improvement, characterized by moderate to high specific surface area (> 100 m^2/g), mesoporous structure (> 50 nm), H/C ratios generally below 0.7 for structural stability, cation exchange capacity (CEC) above 40 $cmol_c$/kg, and sufficient nutrient loading capacity for nitrogen, phosphorus, and potassium retention. These properties collectively determine the suitability of biochar as a nutrient carrier, moisture-retention medium, and soil-conditioning material.

Biochar with good crystalline surface area, H/C ratio, porosity, CEC, and alkaline pH (7–10) promotes nutrient adsorption and retention in the soil, improves soil structure for aeration, moisture retention and microbiota activity, which are essential for vigorous crop growth [15–17]. High nutrient loading capacity is desirable for nutrient adsorption, retention or biochar impregnation with other nutrient elements to suit specific crop requirements. Typical loadings for major nutrients in biochar

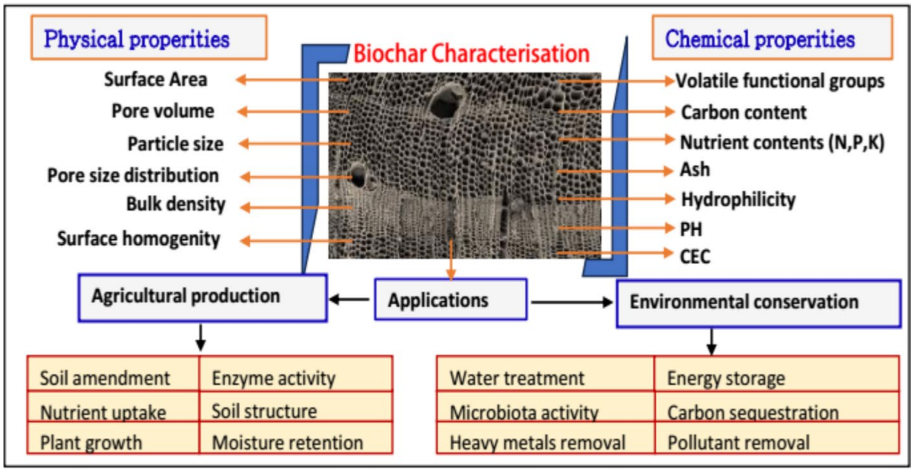


Fig. 1 Potential applications of biochar produced from the pyrolysis

include Nitrogen (5-80 mg-N/g), Phosphorous (2–40 mg—P/g), and Potassium (17–70 mg-K/g) [18]. Biochar is a versatile material useful in a wide range of applications, owing to its robust physical and chemical properties, as illustrated in Fig. 1 illustrates.

Amongst the many approaches explored for biochar production, pyrolysis has gained prominence as a thermochemical conversion pathway for valorizing diverse biomass feedstocks into multiple high-value products, notably bio-oil, syngas, and biochar [19–21]. Even though the agronomic benefits of biochar have been widely reported, variability in biochar quality and performance continues to constrain its agricultural application. One of the main reasons for this variability lies in the complex interplay between feedstock type, process conditions, and reactor configuration during pyrolysis [22, 23]. While a number of studies have characterized the influence of feedstock composition, pyrolysis temperature, residence time, and heating rate on the physicochemical attributes of biochar [24–26], less attention has been put on linking reactor design with the microcrystalline structure of the resulting material. The features and formation of the reactor, determine the precision and uniformity of the process parameters, which influence the physicochemical properties of biochar, thus leading to the necessity of focusing on reactor design in this review.

The microstructure including crystallinity, pore geometry, and the ratio of hydrogen-to-carbon (H/C) is a central determinant of biochar's capacity to function as a soil conditioner or slow-release fertilizer [9, 16]. This observation points to the importance of reactor heat transfer behavior, temperature gradients, and operational stability in determining the quality of biochar produced for agricultural use.

Previous reviews have provided valuable overviews of pyrolysis technologies, feedstock optimization, or general applications of biochar in environmental management and agriculture [27, 28]. However, most have either focused primarily on process parameters or on the agricultural performance of biochar without adequately bridging these two domains. For instance, comprehensive assessments have discussed pyrolysis temperature as the dominant factor shaping biochar porosity and aromaticity [29, 30], but the role of reactor hydrodynamics and heat distribution has often been treated descriptively rather than mechanistically. Others have evaluated the agricultural outcomes of biochar amendments, such as nutrient adsorption and soil pH regulation [13, 31–35], but without tracing these properties back to the underlying reactor-driven structural modifications. As a result, the relationship between reactor design features and fertilizer-relevant biochar properties is still insufficiently resolved in the existing literature. This has made it hard to translate reactor engineering innovations into agricultural outcomes. As illustrated in Fig. 2, a conceptual model that links reactor types and operational parameters for specific biochar attributes is desirable in future research and development.

This paper has put particular emphasis on understanding how pyrolysis reactor design governs the development of biochar microcrystalline features that are critical for fertilizer performance. By integrating knowledge from reactor engineering and agricultural science, the review advances that reactor configurations directly influence process conditions such as temperature gradients, residence times, and heating uniformity [36–39]; and that these operational variables in turn shape the crystallinity, porosity, and functional group composition of biochar [9, 11, 40, 41]. These structural traits are directly correlated with agricultural functions, including nutrient retention, cation exchange capacity (CEC), and resistance to microbial decomposition [13, 17, 42, 43]. This analysis demonstrates that the choices in reactor design, including hybrid configurations, can improve process control and consistency in the production of fertilizer-grade biochars.

A broad array of reactor technologies have been developed and tested for pyrolysis, ranging from conventional systems such as fixed-bed, ablative, and fluidized-bed reactors to emerging innovations like plasma-assisted, microwave-assisted, and solar-driven reactors [20, 44–46]. Each of these designs exhibits unique operational principles, energy efficiencies, and scaling potentials. Fluidized-bed reactors, for example, are

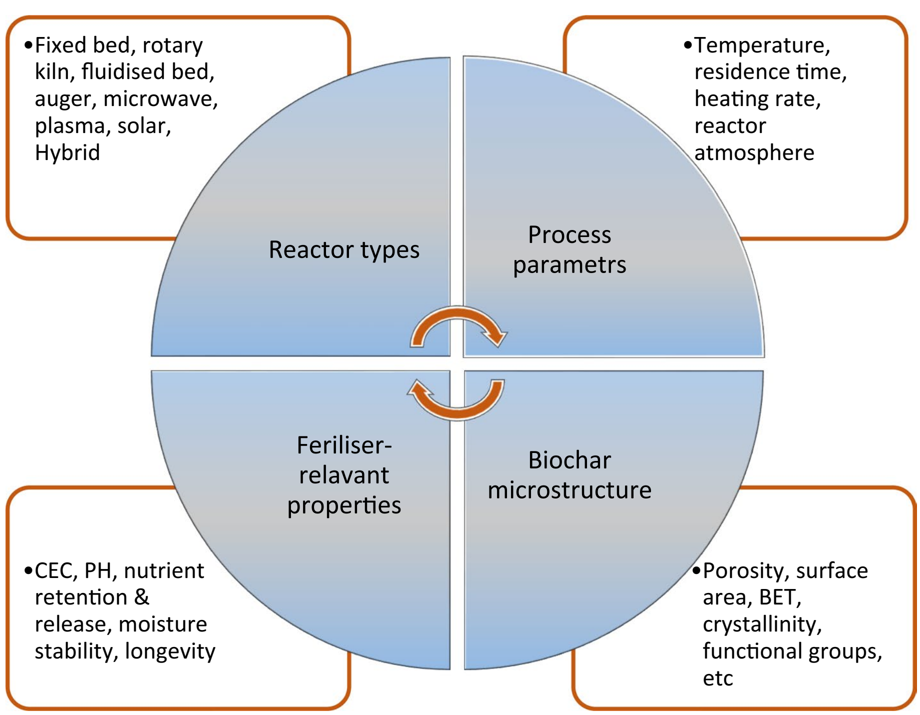


Fig. 2 Conceptual model—linking reactor types and parameters to fertilizer-relevant biochar properties

recognized for their robustness and scalability, but they often suffer from uneven temperature distribution at industrial scales [47–49]. Auger reactors can produce high-carbon-content biochars but are energy-intensive and costly to operate continuously [50–52]. Conversely, microwave- and plasma-assisted systems can achieve exceptionally high surface areas and uniform porosity [53–56], yet they are constrained by excessive power demand and limited scalability [57]. These differences emphasize the importance of analyzing reactor designs not only in terms of product yield but also with respect to their capacity to generate biochars with the desired microstructural properties for fertilizer applications.

Another dimension of this review involves situating reactor development within the broader research trends from 2010 to 2026. The earlier part of this period was characterized by proof-of-concept studies at laboratory scales, largely limited to conventional designs and descriptive reporting of outcomes [20, 58]. In the last five years, however, technological innovation has accelerated through the integration of hybrid reactor systems and digital tools such as artificial intelligence (AI) and machine learning (ML) [59–61]. Hybrid designs combining microwave and fluidized-bed systems, or plasma-assisted reactors, have been proposed as solutions to overcome the limitations of non-uniform heating and poor scalability [57, 62]. At the same time, AI algorithms are being increasingly deployed to optimize pyrolysis conditions, predict biochar properties, and reduce the experimental burden of reactor trials [63–65]. Recent studies have increasingly explored the integration of advanced control strategies and data-driven tools to improve reactor performance and biochar quality.

From an agricultural perspective, the link between reactor design and fertilizer performance is not merely theoretical. Biochar's value in soils is governed by its capacity to retain nutrients such as nitrogen, phosphorus, and potassium, while also providing favorable habitats for soil microbiota [16, 66]. The crystallinity and pore structure of biochar determine how these nutrients are adsorbed, released, and protected from leaching [9, 11]. Studies have shown that biochars with higher specific surface areas and well-developed pore systems significantly improve CEC and water retention, leading to enhanced crop growth [13, 17]. However, biochars produced in reactors with poor thermal distribution or excessive carbonization often exhibit graphite-like structures that limit functional group diversity and reduce agricultural utility [67, 68]. Thus, advancing reactor design is not only a matter of engineering efficiency but also of agricultural productivity and food security.

Therefore, the focus of this review is to triangulate the effect of reactor design and pyrolysis parameters on the physicochemical properties of biochar for fertilizer applications. By synthesizing over 350 publications spanning reactor engineering, biochar characterization, and agricultural studies, it identifies both the opportunities and persistent challenges in achieving reactor–structure–function linkages. Specifically, the review (i) examines the evolution of reactor designs from 2010 to 2026 and their operational principles, (ii) analyzes how these reactors shape microstructural attributes of biochar, (iii) highlights the agricultural implications of these structural traits for fertilizer performance, and (iv) explores emerging innovations as pathways toward standardized and scalable production. Unlike previous reviews that examined either pyrolysis parameters or agricultural applications independently, this review integrates reactor engineering, microstructural characterization, and fertilizer functionality into a unified analytical framework. The study further contributes a comparative benchmarking approach linking reactor technologies with quantitative indicators such as BET surface area, pore volume, energy consumption, and fertilizer relevance. This integrated approach underscores the urgent need for interdisciplinary collaboration among engineers, materials scientists, and agronomists to unlock biochar's full potential as a sustainable agricultural input.

2 Methods and materials

To ensure a comprehensive assessment of the relationship between pyrolysis reactor design and biochar microcrystalline structure, this review adopted a systematic secondary research methodology following established guidelines for narrative and systematic reviews. The review is structured to capture a wide range while ensuring clarity and consistency in literature selection and analysis. Literature search was conducted across multiple scholarly databases including Scopus, Web of Science, Google Scholar, IEEE Xplore, and ScienceDirect**.** These databases were selected due to their extensive coverage of engineering, materials science, agricultural, and environmental science publications. Searches were limited to peer-reviewed journal articles, conference proceedings, and authoritative book chapters to ensure credibility and technical depth. The search employed combinations of keywords and Boolean operators such as:

- "Pyrolysis reactors", "biochar", and "fertilizer applications"
- "Reactor design", "biochar microstructure", and "crystallinity"
- "Biomass pyrolysis", "surface area" and "porosity"
- "Advanced pyrolysis reactors", "AI optimization" and "machine learning"

These terms were iteratively refined to capture the intersection of reactor engineering and biochar agronomy. Filters were applied to restrict results to the period January 2010 to June 2026, ensuring coverage of both foundational studies and the most recent innovations, including plasma, microwave-assisted, and AI-driven reactor systems. Earlier studies (2010–2014) were included primarily for their foundational descriptions of pyrolysis reactor types and baseline data on process parameters such as temperature, residence time, and feedstock characteristics [20]. More recent developments and studies have been incorporated capturing advances in hybrid reactors, scale-up efforts, and machine learning applications [59, 61]. This broader timeframe not only improves representativeness but also highlights the trajectory of reactor innovations over time.

2.1 Inclusion and exclusion logic

Articles were screened for eligibility using pre-defined inclusion and exclusion criteria.

Inclusion criteria included peer-reviewed studies explicitly analyzing pyrolysis reactors and their influence on biochar properties; experimental or review papers reporting on microstructural attributes of biochar (e.g., BET surface area, pore volume, crystallinity indices, H/C and O/C ratios); publications addressing the agricultural implications of biochar structure for soil fertility, nutrient retention, or crop productivity; studies covering innovations in reactor design, including plasma, microwave-assisted, hybrid, or AI-optimized systems**;** Articles published between 2010 and 2026 in English.

Exclusion was based on: Non-peer-reviewed material (blogs, videos, news articles), which may provide anecdotal perspectives but lack methodological rigor; studies focused exclusively on biochar applications unrelated to fertilizers (e.g., biochar in electrodes, water filtration, or carbon capture without agricultural analysis); papers that did not provide sufficient experimental detail to evaluate reactor conditions or biochar structural outcomes; duplicates and studies reusing the same datasets without added analytical value.

2.2 Screening process and data analysis

The initial database search retrieved approximately 401 records. After duplicate removal, 375 unique articles were screened based on titles and abstracts. Of these, 117 (31.2%) were excluded for irrelevance (e.g. studies focusing solely on feedstock chemistry without reactor linkage). A total of 258 (68.8%) full-text articles were then reviewed in detail. Following the application of inclusion and exclusion criteria, 169 articles were retained for systematic analysis. This review focuses exclusively on peer-reviewed sources and incorporates a broader, more representative set of recent studies. Restricting the analysis to peer-reviewed sources strengthened the reliability and technical depth of the evidence considered. The data synthesis involved both quantitative tabulation and qualitative thematic analysis**.** Comparative tables were developed to summarize reactor-specific outcomes, including yield percentages, BET surface areas, and porosity ranges. Where multiple studies examined similar reactors, weighted averages were determined to reflect central tendencies. Qualitative analysis focused on identifying recurring challenges (e.g., non-uniform heat distribution, high energy demand) and mapping technological solutions proposed (e.g., microwave-assisted heating, improved insulation materials, AI-based predictive control). Figures were redrawn to illustrate reactor schematics, process flows, and thermal distributions, avoiding direct reproduction of copyrighted images. A PRISMA-style flow diagram was constructed to show the

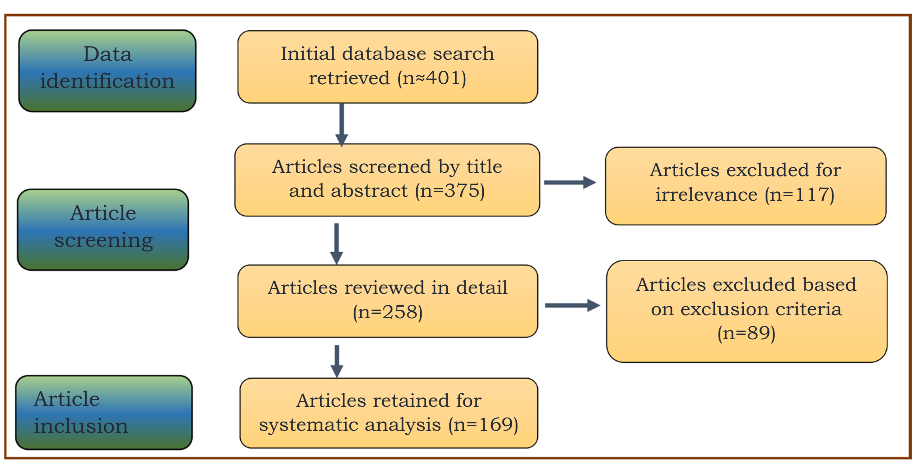


Fig. 3 PRISMA flow diagram of literature

selection process, documenting the number of records identified, screened, excluded, and included, as shown in Fig. 3.

2.3 Limitations of the review methodology

While this review sought to be comprehensive, several limitations must be acknowledged. First, restricting the search to English-language publications may have excluded relevant studies in other languages. Second, although peer-reviewed literature was prioritized, some experimental details (e.g., proprietary reactor designs) may not be fully disclosed in open-access sources. Finally, heterogeneity in reporting standards across studies made direct comparisons challenging. These limitations were mitigated by triangulating findings across multiple studies and focusing on convergent evidence rather than isolated results.

3 Biomass carbonization and pyrolysis

3.1 Fundamentals of biomass carbonization

Biomass carbonization is a thermochemical process through which organic feedstocks such as agricultural residues, forestry by-products, and municipal solid wastes are converted into carbon-rich solids, liquids, and gaseous products. The transformation is governed by complex reactions, including depolymerization, devolatilization, aromatization, and secondary cracking, which occur under controlled thermal environments in the absence or limitation of oxygen [25, 69, 70]. Among the carbonization routes, pyrolysis has emerged as the most versatile and controllable, offering the potential to optimize biochar properties for specific applications such as fertilizer enhancement and soil remediation [19, 24]. The importance of carbonization lies not only in its ability to divert biomass waste streams from open burning or landfilling but also in its capacity to generate biochars with functional microstructures. These microstructures comprising ordered and disordered crystalline domains, pores of varying size distributions, and surface functional groups are critical in determining the agricultural performance of biochar when applied to soils [11, 16]. Figure 4 illustrates the production process of Biochar fertilizer through pyrolysis of Biomass.

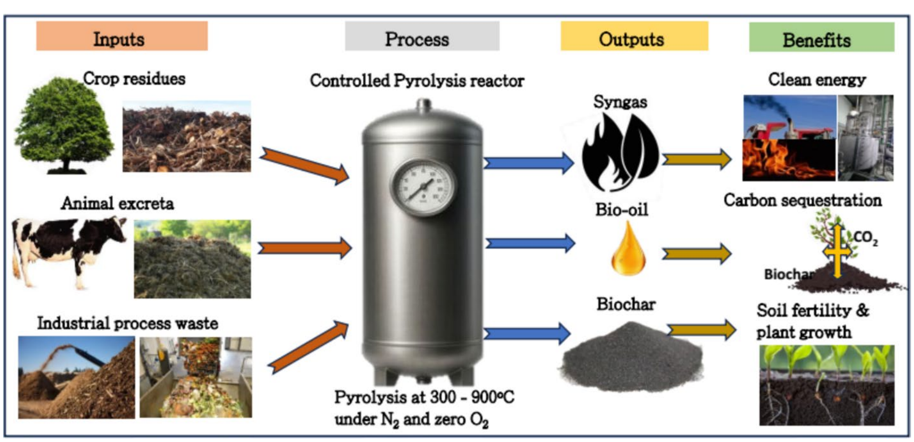


Fig. 4 Flow diagram of biomass pyrolysis for biochar production (Modified from [71])

3.2 Overview of pyrolysis

Pyrolysis is defined as the thermal decomposition of biomass in the absence of oxygen, typically at temperatures ranging from 300 to 900 °C**,** producing three primary products: biochar (solid), bio-oil (liquid), and syngas (gas)**.** The relative yields of these products are highly sensitive to process conditions, reactor configuration, and feedstock type [26, 52, 72]. Slow pyrolysis, conducted at lower heating rates and longer residence times, generally maximizes biochar production, whereas fast pyrolysis favors bio-oil yields due to rapid quenching of volatile products [30, 51, 73]. From a fertilizer perspective, pyrolysis is particularly important because it allows for tailoring the structural and chemical features of biochar. Factors such as pore development, BET surface area, elemental composition, and CEC are not only determined by feedstock composition but also by the reaction conditions imposed by the reactor [9, 29]. For instance, prolonged residence times at moderate temperatures can preserve more functional groups, whereas higher heating rates at elevated temperatures increase aromaticity and crystallinity, improving biochar stability but potentially reducing its nutrient retention ability [17, 49].

3.3 Key parameters in pyrolysis and their impact on biochar microstructure

3.3.1 Temperature

As indicated in Fig. 5, which was obtained through careful analysis of pyrolysis parameters from more than 100 research articles, temperature was widely acknowledged as the most critical factor influencing the yield and microstructure of biochar [24, 36, 74, 75]. The design of the reactor, heat source and circulation, insulation, and reaction environment are key determinants to the temperature efficiency of the process. Low pyrolysis temperatures (300–500 °C) typically produce biochars with high volatile matter, abundant oxygen-containing functional groups, and lower aromaticity. These biochars exhibit greater reactivity and nutrient exchange potential, making them suitable for short-term soil fertility improvements [16]. Conversely, higher temperatures (500–600 °C) generate biochars with high surface area (> $100 m^2 g^{-1}$), increased porosity (> 50 nm diameter), and more ordered crystalline structures with H/C rations > 0.7 [13, 16, 17, 37, 68]. Beyond

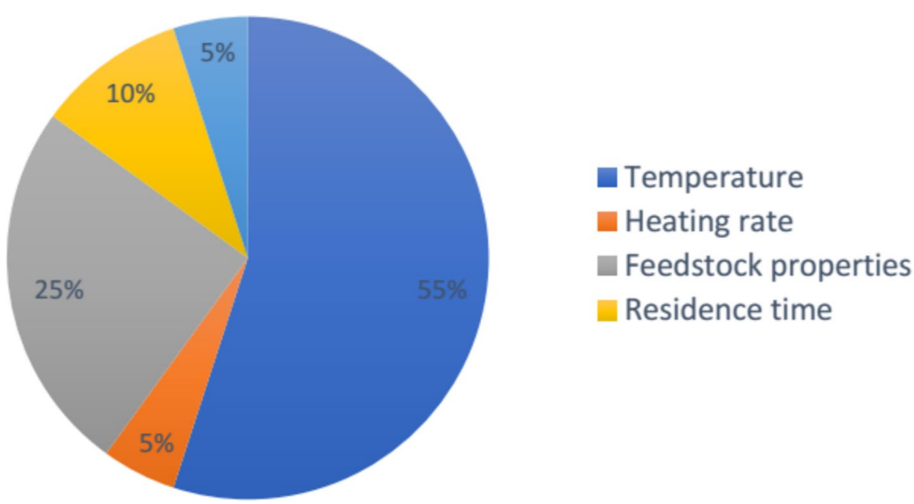


Fig. 5 Key process parameters that influence quality of pyrolysis products

600 °C, there is excessive carbonization, which reduces the organic functional groups in biochar that may limit immediate nutrient retention, and thus requiring post-modification or co-application with other fertilizers [67]. Several researches agree that biochar yields increase with temperature up to about 600 °C, beyond which they begin to reduce due to secondary decomposition of char. For example, in a study done by Zeng et al. [76] in the pyrolysis of beech wood, biochar yield reduced from 14% at 600 °C to 10% at 1200 °C.

3.3.2 Heating rate

Heating rate governs the kinetics of molecular breakdown during biomass decomposition. Slow heating allows gradual devolatilization, enabling better pore development and retention of mineral elements [25]. Fast heating, by contrast, results in rapid release of volatiles and formation of micropores but can cause collapse of mesopores [36], leading to reduced pore connectivity [9]. Studies have shown that moderate heating rates (~ 20 °C/s) achieve a balance between porosity and crystallinity, producing biochars optimized for nutrient adsorption [44, 77]. At the set heating rate, the surface crystalline structure of biochar highly depends on material size and heating temperature. Higher heating rates (> 30 °C/s) reduce yields, but also lower biochar surface areas (< $100 m^2/g$) compared to pyrolysis done at moderate heating rates and temperatures. This quality of biochar may not be suitable for fertilizer use.

3.3.3 Residence time

Residence time influences the degree of carbonization and crystallinity. For most fluidized bed reactors, the residence time for biomass ranges between 20 min and 5 h depending on the temperature ranges, heating rate and size of the feedstock [78, 79]. Extended residence times favor secondary reactions such as aromatization and graphitization, increasing the proportion of ordered carbon domains to achieve greater surface areas and pore volumes [55]. However, excessively long residence times may decrease the yield of reactive functional groups and crystalline surface area [13]. Optimal residence times typically fall within 20–60 min for slow pyrolysis aimed at fertilizer-quality biochars [67].

3.3.4 Reactor atmosphere

The type of carrier gas and atmosphere (inert vs. reactive) plays a significant role in shaping biochar microstructure. Nitrogen or argon atmospheres are commonly used to ensure inert conditions, minimizing oxidation during pyrolysis [45]. However, the use of reactive gases such as CO_2 or steam has been shown to enhance porosity and surface activation through in situ gasification effects [46]. This leads to higher BET surface areas and improved adsorption capacity, properties highly desirable for fertilizer applications.

Table 1 Proximate and ultimate analysis for biomass feedstock

Feed stock	Proximate analysis (%)			Ultimate analysis (%)					Lignocellulosic composition (%)			References
	Moisture	Ash	Volatile matter	C	H	N	S	O	Cellulose	Hemicellulose	Lignin	
Pine wood	14.5	0.9	71.5	49.9	6.7	0.2	0.01	43.1	40	29	28	[82]
Corn stalks	8.6	4.9	82.6	49.4	6.5	0.6		43.5	42	22	20	[83]
Corn cobs	7.8	1.5	72.9	46.9	6.1	0.6	-	44.9	50.5	31	15	[84]
Rice husks	6.3	10.8	80.5	43.9	5.9	0.4	-	49.7	30.4	28	36	[85]
Rice straw	9.3	8.5	79.2	45.8	6.2	0.5		47.5	38.1	31.1	26.35	[86]
Banana stem	7.9	9.4	89.4	33.5	6.4	0.8		49.9	38.5	25.4	5.8	[87]
Banana peels	11.6	9.3	88.2	35.7	6.2	1.9	20.8	45.9	9.9	41.4	8.9	[88]
Eucalyptus	8.2	9.3	75.6	38.9	6.4	2.1	-	50.2	52	25	25	[89]
Coffee shells	7.9	7.1	78.7	44.9	6.1	0.4	-	48.6	33.1	30	24.5	[90]
Peanut shells	7.9	12.8	79.1	41	7.4	2	0.6	28	-	-	-	[91]
Sugarcane bagasse	8.6	4.1	86	47.3	6.2	0.3	-	44.2	19–24	32–48	23–32	[20]
Waste tea leaves	5.8	4.3	-	52.7	6.3	2.6	0.8	38.2	17.5	41.3	41.2	[92]
Food wastes	92.4	10.2	71.3	41.7	7.5	3.5	-	37.1	-	-	-	[93]
Bamboo stem	7.1	11.8	71.6	39.9	5.8	1.1		53.1	43	22	24	[94]
palm oil shell	4.7	8.6	73.5	52.0	5.4	0.5	-	42.1	27.7	21.6	44	[95]
Walnut shells	8.7	1.3	77.4	49.6	5.6	0.2	0.3	44.2	31.2	16.6	41.9	[96]

3.3.5 Feedstock properties

Although not the central focus of this review, feedstock characteristics inevitably interact with pyrolysis parameters to determine biochar outcomes. Lignin-rich biomass tends to produce biochars with greater aromatic stability, whereas cellulose- and hemicellulose-rich materials generate biochars with higher volatile content and reactive functional groups [53, 66]. Thus, it is imperative that feedstock selection aligns with desired product outcomes [80, 81]. The mineral content of the feedstock can further influence crystallinity by catalyzing or inhibiting specific reactions during carbonization [22]. Table 1 provides a suitable guide for selection of biomass feedstocks for specific product requirements.

3.4 Linking pyrolysis parameters to fertilizer applications

The agricultural performance of biochar is directly tied to its structural attributes. Biochars with well-developed mesoporous networks and moderate aromaticity are most effective in improving nutrient retention and water-holding capacity [16, 17]. In contrast, highly crystalline, graphite-like biochars, though more stable in soils, often exhibit reduced CEC, limiting their short-term effectiveness as fertilizers unless chemically modified [30]. Recent studies underscore the need to match pyrolysis conditions with intended agricultural outcomes as shown in Table 2. For example, fluidized-bed reactors operating at 500–550 °C with moderate heating rates have been shown to yield biochars with BET surface areas exceeding 300 m^2/g, significantly enhancing phosphorus retention [48]. These findings highlight the potential of process optimization to tailor biochar properties for specific fertilizer applications.

3.5 Emerging trends and research gaps

Although good progress has been made in understanding pyrolysis and its impact on biochar, several knowledge gaps remain. Most studies continue to examine single parameters in isolation, whereas in practice, temperature, heating rate, and residence time interact synergistically. Moreover, comparative analyses across reactor types remain limited, often constrained to laboratory scales (< 1 kg of biomass/hr) without translation to industrial practice (1–5 tons/day) [57, 58, 97]. Another key limitation lies in the lack of long-term field validation linking microstructural attributes with sustained soil fertility and crop yields. Addressing these gaps will require integrating controlled experiments, reactor modeling, and field agronomy studies.

4 Reactor technologies

Pyrolysis reactor design plays a decisive role in determining the efficiency of thermal conversion, energy utilization, and ultimately the physicochemical and microstructural properties of biochar. While feedstock characteristics and process parameters are critical, reactor configuration dictates the thermal environment in which these parameters operate. Factors such as heat transfer mode, gas flow dynamics, solid residence time, and temperature distribution directly shape the porosity, crystallinity, and surface chemistry of biochar, which in turn affect its agricultural utility as a soil

Table 2 Comparative summary of pyrolysis parameters, their effects on biochar yield, microstructure, and implications for fertilizer use

Pyrolysis parameter	Effect on biochar yield	Effect on microstructure	Implication for fertilizer use	References
Temperature	In most reactions, biochar yield increases with temperature from 300 – 600 °C, beyond which there is significant drop	300 – 500 °C biochar has high volatile matter, more functional groups, less crystallinity 500 – 600 °C, improved aromaticity, surface area (> 100 m^2/g), porosity (> 50 nm) and H/C ratio (> 0.7) depending on reactor type, feedstock type & size	Moderate temperature biochars (500 – 600 °C) improve soil nutrient exchange Higher temperature biochars (> 600 °C) are stable but may require modification and enrichment for nutrient retention	[37, 67, 68, 76]
Heating rate	Higher heating rates (> 30 °C/s) reduce biochar yields and microstructure due to rapid devolatilization, micropore dominance, mesopore collapse	Slow heating (0.3 – 10 °C/s) is suitable for better pore development, and mineral retention Too fast can reduce CEC effectiveness	Moderate heating rates (~ 20 °C/s) balance porosity and crystalline surface area, thus good nutrient adsorption	[25, 44, 77]
Residence time	Fast pyrolysis characterized by higher heating rates of > 30 °C/s, and shorter residence time of 0.5 – 2 s has moderate yields (10–25%) compared to 28 – 32% for flash pyrolysis	Short time (< 2 s): less aromatization, more reactive groups Longer time (> 60 min): higher crystallinity, stability, but fewer functional groups	Optimal residence time (20–60 min) yields balance between stability and reactivity aimed at fertilizer-quality biochars Excessive times may reduce functional group availability	[67, 78, 79]
Reactor atmosphere	The fluidizing gas (N_2 or Ar) creates the inert atmosphere, minimizing oxidation and optimizing yields of pyrolysis products	Reactive gases (CO_2 or steam) enhance porosity and surface activation via in situ gasification	Reactive atmospheres create high surface area chars for improved nutrient and water adsorption Inert chars are more stable but less reactive	[45]
Feedstock properties	Feedstocks with high lignin content (32 – 45%) produce higher yield of biochar	Lignin-rich feedstocks produce stable, aromatic biochars Cellulose/hemicellulose-rich feedstocks produce higher volatiles and reactive groups High mineral content feedstock has catalytic influence on crystallinity	Choice of feedstock determines baseline properties for fertilizer application Blending feedstocks can optimize both stability and nutrient retention	[53, 66, 80, 81]

amendment and fertilizer carrier [9, 20, 52]. The efficiency with which these factors can be actuated is largely dependent on the design of the reactor. Key design aspects that differentiate reactors include; (i) source of heat for pyrolysis (electric heater, flue gases, electromagnetic radiation, solar, or radiofrequency radiation); (ii) nature of insulation (refractory clay bricks, fiber glass, alumina silica); (iii) type of operation (batch or continuous); (iv) method of introducing biomass into the reaction chamber; and (iv) nature of biomass to be pyrolyzed (particles or large pieces) [97]. This section provides a comprehensive analysis of reactor technologies, with focus on conventional systems and emerging innovations. Each reactor type is evaluated with respect to its operational principles, advantages, limitations, and the implications for biochar microstructure and fertilizer applications.

4.1 Fixed-bed reactors

Fixed-bed reactors are among the earliest designs employed for biomass pyrolysis and are characterized by their simplicity, low capital costs, and ease of operation. Feedstock is packed into a vertical or horizontal chamber, where it undergoes thermal decomposition under controlled heating and limited oxygen conditions [20, 21]. These reactors have simple designs, suitable for laboratory-scale studies and initial proof-of-concept research. However, they have poor scalability, uneven temperature gradients, and limited capacity for producing high-quality biochars with uniform crystallinity. This is mainly attributed to the uneven size and shape of biomass, as well as heat loss to the surrounding. Since the wooden biomass is packed and the reactor sealed, mixing is not practical, thus temperature gradients often arise in various pockets of the reactor. Given the simplicity and the stationary nature of the design, refractory clay bricks are often preferred for insulation, yet they have relatively higher thermal conductivity (2W/m.K) compared to other insulation materials such as fiber glass (0.03–0.06 W/m.K), and alumina-silica (0.1–0.2 W/m.K) [98]. According to Roman et al. [99], the energy consumption for typical fixed bed reactors is approximately 1475 MJ/ton relatively lower than most of the conventional reactors. Although, the slow pyrolysis in these systems favors higher char yields (26 – 38%), there is often incomplete carbonization leading to biochars with heterogeneous structural properties [30, 100, 101]. Biochars from fixed-bed reactors typically exhibit low BET surface area ranging between 7.5 and 65 m^2/g, and total pore volumes (0.02 – 0.3 cm^3/g) due to uneven heat transfer within the bed [102, 103]. For fertilizer applications, fixed-bed biochars often require post-treatment to improve nutrient retention capacities. Their heterogeneity limits reliability for standardized agricultural use [16].

4.2 Rotary kiln reactors

Rotary kiln reactors employ a rotating cylindrical chamber that continuously agitates feedstock as it undergoes thermal decomposition. This configuration improves heat distribution compared to fixed bed reactors and allows semi-continuous or continuous operation [58, 104–107]. Rotary kiln biochars exhibit relatively uniform particle sizes and enhanced porosity due to continuous mixing. However, high thermal inertia can result in excessive energy consumption (≈1800 MJ/ton) and difficulty in fine-tuning microcrystalline features [108]. They can be scaled up for industrial applications and production of activated biochar. The limitation to these is that they have high operational costs, mechanical wear, and potential fouling issues. Generally, rotary kilns are promising for large-scale biochar production but often produce chars with lower BET surface areas (38–127m^2/g), total pore volumes (0.17–0.24 cm^3/g), and porosity (7–7.5–15.8 nm) compared to fluidized bed systems, limiting their direct agricultural performance [48, 109]. Biochar from rotary kilns can be improved through activation, which has potential to enhance BET surface area and porosity. For example, in a study done by Don et. al [110], a rotary kiln was used to produce activated carbon from waste wood, using Goethite iron ore, which significantly increased the BET surface areas to more than 600m^2/g.

4.3 Fluidized-bed reactors

Fluidized-bed reactors (FBRs), as shown in Fig. 6, are widely studied due to their superior heat transfer and mixing efficiencies [111]. Biomass particles are suspended in an upward flow of inert gas, creating an environment of uniform temperature and rapid heat transfer [44, 52]. Biochars exhibit relatively higher BET surface areas (250 –700 m^2/g), higher pore volumes (> 0.4 cm^3/g), and moderate crystallinity compared to fixed bed and rotary kiln reactors [49, 112]. For example, Feng et al. [113] achieved high surface area (604 m^2/g) and pore volume (0.43 m^3/g) biochar by using a tubular bed reactor to pyrolyze sea weed, which is comparable to values (668 m^2/g) obtained by Don et al. [110]. However, extremely fine particles can be entrained in the gas flow, reducing overall quality and yield of bio-oil and biochar. To improve yield, a series of cyclone separators may be included in the design to effectively capture biochar, and a condenser unit to capture volatiles into bio-oil, thereby minimizing environmental pollution. FBRs possess excellent scalability, high uniformity, continuous operation but are limited by the complex fluid dynamics, risk of particle entrainment, and energy-intensive gas circulation [114, 115]. The thermal stability within the reaction chamber is often disrupted

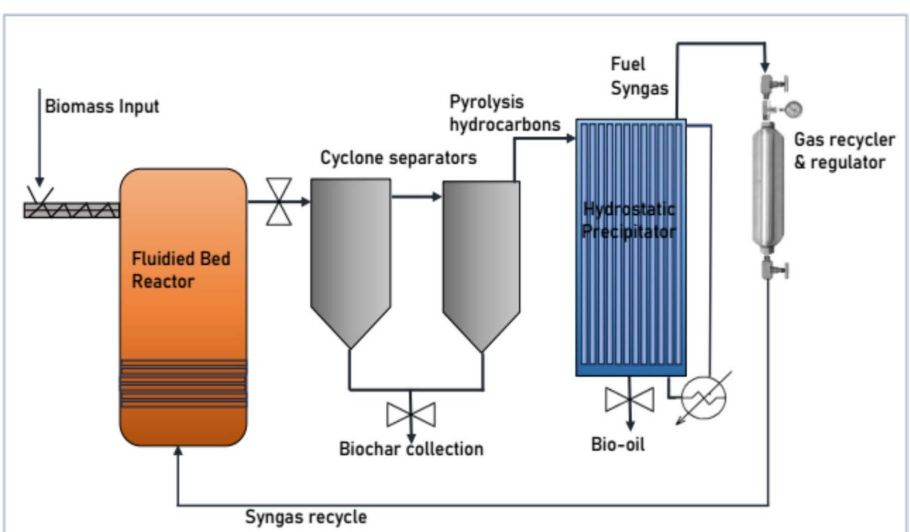


Fig. 6 Fluidized bed reactor

by the incoming fluidizing gas, whose flow must be carefully regulated to minimize the effect on temperature distribution within the reactor. In recent times, the introduction of heat recirculation concept with fluidized bed reactors has improved thermal stability and energy consumption to less than 1500 MJ/ton [116]. This is achieved in two ways: (i) combusting the collected char in the cyclone and heating up the fluidizing sand to sustain pyrolysis temperature; (ii) recirculation of the syngas to the furnace. These design approaches are critical to sustaining the pyrolysis temperature, but also reducing energy expenditure. However, option (i) is suitable for bio-oil production and not fertilizer, since the biochar will be burnt as secondary fuel [117]. In the design of FBRs for fertilizer production, a careful balance between biomass flow, inert gas velocity, and heat energy supply must be created to ensure structural stability and nutrient retention, making them suitable for producing standardized biochars at scale [9].

4.4 Auger reactors

Auger reactors (ARs) employ a rotating screw to convey biomass through the heated axis of the reactor chamber. Heat transfer occurs via conduction from heated reactor walls or through carrier gas [52]. The biomass is screwed through the reaction chamber, it decomposes into biochar, bio-oil and syngas. A typical AR design is incorporated with a pipe exit along the heated wall for capturing volatile gases, as well as for internal pressure balance [118]. Although ARs are robust, size reduction of biomass is important to facilitate efficient thermal transfer for complete pyrolysis. Their mixing capability improves energy balance for uniform heating across the reactor, and can be used for slow, intermediate and fast pyrolysis. Though these reactors are known for high biochar yields (20–60%), their non-uniform heating often leads to chars with high carbon content, but lower BET surface areas (< 15m^2/g) and total pore volumes (0.05–0.2 cm^3/g) compared to those from fluidized-bed and rotary kiln systems [25, 79, 119, 120]. The high carbon content reduces the H/C ratio, which is a key indicator of biochar stability and longevity in the soil. According to Jerzak et al.[97] and Meyer et al.[121], high ratios (> 0.7) indicate low surface area and porosity due to incomplete pyrolysis, whereas low ratios (< 0.4) indicate fully developed pores at temperatures > 500 °C, and thus biochar has greater potential to ameliorate and amend the soil for a longer time. ARs have compact design, adaptable for decentralized biochar production, and ability to handle diverse feedstocks. These have a limitation of producing lower surface areas biochar, potential blockages, high energy consumption (> 1600 MJ/ton) and limited scalability [51]. For fertilizers, auger-derived biochars require blending with nutrient-enriched materials to maximize agricultural benefits [13].

4.5 Ablative reactors

Ablative reactors utilize high-pressure contact between biomass particles and heated surfaces, where thermal energy is transferred via conduction. These systems are relatively rare in commercial biochar production due to their higher initial cost and operational expenses [104, 122]. They are known for high energy consumption due to higher surface heating requirements, coupled with excessive heat losses, constant mechanical contact pressure and agitation. Biochars produced from such systems are typically dense, with variable pore volumes (0.2 –0.5 cm^3/g) depending on particle contact with the heated surfaces. The strength of this type of reactors is their independence from carrier gas, and ability to process large particle sizes. However, they have limited scalability, mechanical complexity, and uneven char quality. Biochar from ablative reactors have lower BET surface area values ranging between 39 and 120 m^2/g compared to fluidized bed reactors [123]. They are usually operated at moderate temperatures (300–400 °C), and low heating rates, yet the constant rotation also drives up the energy requirement (≈ 2400 MJ/ton) [124]. Ablative reactors systems are more suited for lab-scale bio-oil production than commercial biochar fertilizer due to their poor control over microstructural features [30, 97].

4.6 Microwave-assisted reactors

Microwave-assisted pyrolysis has gained attention for its ability to achieve rapid and uniform heating through direct interaction of microwave energy with biomass [53, 54]. In the design of microwave systems, particle size and moisture content of the feedstock are key in effecting energy transfer during pyrolysis. Biomass with high moisture content tends to take longer time to decompose due to excessive microwave adsorption compared to dryer substrates. This requires pre-pyrolysis treatments such as grinding and drying. Typical lab-scale microwave assisted reactors generate biochars with BET surface areas ranging between 3.1 and 25 m^2/g, whereas for commercial systems, the values can potentially exceed 500 m^2/g [62, 125]. Enhanced surface area and porosity arise from volumetric heating, which minimizes thermal gradients. They have high heating efficiency, tunable energy input, and production of biochars with superior adsorption capacity [126, 127]. However, they have high energy demand (> 4000 MJ/ton), expensive infrastructure, and challenges in scaling beyond laboratory or pilot plants [128]. Microwave-derived biochars are particularly attractive for fertilizer applications, as their high porosity, supports nutrient retention and slow-release properties. However, scaling remains a bottleneck for widespread agricultural deployment [55]. Microwave technology has shown potential and suitability for integration with conventional reactors for improved thermal transfer at medium and large-scale operations.

4.7 Plasma-assisted reactors

Plasma-assisted reactors utilize ionized gases to achieve extremely high heating rates (10^3–$10^{4\ oC}$/s) and reactive environments [129]. During pyrolysis, the high energy radiation breaks down the molecular bonds, removing volatiles, and leaving amorphous biochars with average crystallinity, BET surface areas (250–300m^2/g), and unique surface chemistries due to quick devolatilization of the biomass material under high heating rates [130]. Raza et al. [45] found that typical plasma reactors operate in temperature ranges 2000–9000 °C at more than 2000W of power input. Due to high heating rates, biomass residence time is usually short, and there is excessive heat loss to the surroundings, which compromises complete pyrolysis in some sections of the reactor. However, they have very high energy requirements (> 2000 MJ/ton), costly equipment, and technical challenges in maintaining plasma stability [45]. Though still experimental, plasma-assisted biochars show promise for targeted fertilizer applications where highly active surfaces are required for nutrient immobilization. Thermal control and power efficiency are key design improvements that can foster increased utilization of plasma reactors at scale.

4.8 Hybrid reactors

Hybrid systems combine multiple heating modes such as microwave or plasma radiations with conventional heating methods such as flue gas, induction heater, solar, among others to overcome the limitations of individual conventional reactor designs [57, 62, 131]. In terms of microstructural outcomes**,** hybrid systems offer improved thermal control and optimization for pore development, crystallinity, and surface chemistry, achieving quality biochars for both stability and reactivity. These applications provide instantaneous controlled heating, which enhances grafting of surface groups of such as carboxyl, phenolic hydroxyl, lactone, quinone and ether. These serve as binding poles to facilitate smooth biochar integration with soil particles, which improves nutrient absorption potential, hydrophilicity, PH and CEC [132]. Hybrid reactors are potentially scalable and tunable biochar production with enhanced efficiency. However, they have a limitation of being highly complex, elevated costs, and limited industrial demonstrations to date. Nevertheless, hybrid reactors are considered the future of biochar engineering, particularly when integrated with AI and machine learning for predictive optimization of microstructure [59, 60]. Saliou et al. [61] used a microwave assisted fluidized bed reactor to carbonize tea waste, and the resulting BET surface area was 943 m^2/g at 500 °C, higher than 686m^2/g achieved by Jansuwan et al. [133] who pyrolyzed oil palm shell waste. The variation could be attributed to difference in biomass material, as well as experimental set up, and quantities involved. Figure 7 represents a schematic of more controllable and optimum hybrid models for quality biochar production.

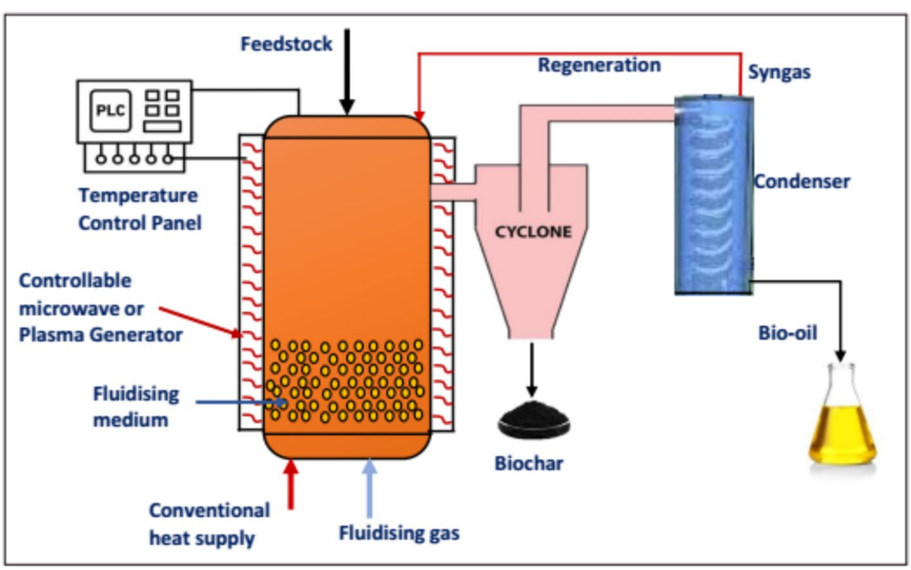


Fig. 7 Schematic of a controllable hybrid reactor model

Table 3 Comparative summary of reactor technologies, their advantages, limitations, physicochemical properties, and fertilizer suitability

Reactor design	Heating mechanism	Achievable temperatures (ºC)	Advantages	Limitations	Average total energy consumption (MJ/ton)	Biochar yield & physicochemical properties	Fertilizer suitability	References
Fixed-bed	Sand heating	300 – 600	Simple design, low investment & operational cost, Moderate temperature & pressure	Poor scalability, uneven heat transfer, heterogeneous char	1475	Moderate yields (26 – 38%), but low surface area (7.5–65 m^2/g), and total pore volumes (0.02–0.3 cm^3/g)	Requires activation to enhance crystalline surface area, and pore volumes	[99–101]
Rotary kiln	Heated char and sand	400 – 550	Scalable, continuous operation, high throughput, good mixing & fairly uniform transfer compared to fixed bed reactors	High energy demand, rapid mechanical wear, sensitive to material size	≈ 1800	Moderate biochar surface area (38 – 127 m^2/g), total pore volume (0.17–0.24cm^3/g) and porosity (7.5 – 15.8 nm); though higher yields (34 – 41%)	Potential for industrial fertilizer production through biochar activation	[108, 109]
Fluidized-bed	Flue gas, and recirculated syngas	400 – 600	Good heat transfer, continuous operation, and excellent scalability	High initial cost, risk of particle entrainment into bio-oil, intensive fluidizing gas circulation	1,000 -1500	High BET (250–700 m^2/g), greater pore volumes (> 0.4cm^3/g), and moderate biochar yields (18 – 25%)	Well-suited for biochar fertilizer biochar production through improved heat circulation, insulation, and optimized gas flow rate	[114, 115, 134]
Auger	Sand heating or fire tube	400 – 800	Compact design, continuous operation, high throughput, and handles diverse feedstocks	Sensitive to biomass size, risk of blockages, and limited scalability	800 -1600	Higher biochar yields (20 – 60%), with lower surface areas (< 15m^2/g), and moderate total pore volumes (0.05–0.4 cm^3/g)	Biochar may need enrichment, or activation	[51, 119, 120]

Table 3 (continued)

Reactor design	Heating mechanism	Achievable temperatures (°C)	Advantages	Limitations	Average total energy consumption (MJ/ton)	Biochar yield & physicochemical properties	Fertilizer suitability	References
Ablative	Wall heating	500 – 700	500 – 700	Mechanical complexity, limited scalability, and high energy consumption	≈ 2400	Dense chars with moderate surface area (39 – 120 m^2/g), and pore volumes (0.2 – 0.5 cm^3/g)	Not optimal for fertilizer biochars; more suited to bio-oil production	[123, 124, 135]
Microwave-assisted	Electromagnetic radiation	500 – 1000	Rapid uniform heating, high efficiency, tunable control	High electric power demand, expensive infrastructure, and scaling complexity	4000	High BET surface area at commercial operations (> 500 m^2/g), moderate pore volumes (0.1 – 0.3 cm^3/g), and moderate yields (25 – 35%)	Limited adoption for fertilizer production due to scaling complexities and investment	[125–127, 136]
Plasma-assisted	Radio-frequency radiation	> 1000	Extremely high heating rates, induces surface activation	Very high energy use, costly equipment, stability issues	2,109.6	Highly crystalline and high surface area biochars (250 – 300 m^2/g), though lower total pore volumes (0.1 – 0.2 cm^3/g)	Promising for specialized fertilizers, applicable in hybrid systems	[129, 130, 137]
Hybrid	Integrated	400 -700	Combines strengths of multiple systems, tunable properties	Complex, costly, few industrial-scale demonstrations	1000–5000	Tunable and tailored biochar surface area, porosity and yields	Most promising for standardized fertilizer biochars in the future	[131–133, 138]

The values presented represent comparative ranges synthesized from multiple peer-reviewed studies and are intended to provide benchmarking trends rather than absolute standardized reactor performance values

4.9 Comparative synthesis

Table 3 summarizes the comparative characteristics of different reactor technologies in terms of operational requirements, biochar yields and microstructural properties, and fertilizer relevance. Conventional reactors (fixed-bed, auger, rotary kiln) remain useful for small to medium-scale production but often yield biochars with lower BET surface areas, total pore volumes, and heterogeneous structures. Fluidized-bed systems are more scalable and produce relatively uniform biochars with higher BET and porosity values but can be energy-intensive. Although emerging technologies such as microwave and plasma reactors exhibit potential for superior porosity and microstructural control, they face scalability and operational cost challenges. Hybrid reactors represent the most promising avenue, offering the potential to combine scalability with advanced microstructural tailoring, thereby producing standardized fertilizer biochars. Comparative evaluation of the reactor systems indicates that fluidized-bed reactors currently provide the most balanced compromise between scalability, thermal efficiency, and production of fertilizer-relevant microstructures. Although microwave-assisted and plasma-assisted systems achieve superior BET surface areas and pore development, their high energy demand and limited industrial-scale deployment remain major barriers. Conversely, fixed-bed and rotary kiln systems remain economically attractive for decentralized applications but generally produce biochars with lower structural uniformity and reduced nutrient adsorption capacity.

Therefore, reactor choice must align with intended biochar applications. For nutrient-rich, short-term soil amendments, low-temperature fixed-bed or auger reactors may suffice. For long-term stability and high adsorption capacity, hybrid systems are preferable. The challenge ahead lies in scaling these advanced systems while ensuring cost-effectiveness and energy efficiency.

5 Results and discussion (critical review)

The analysis of peer-reviewed studies published between 2010 and 2026 clarifies the relationship between pyrolysis reactor design, process parameters, and the microstructural properties of biochar for fertilizer applications. This section synthesizes those findings, highlighting the ongoing debates within the literature.

5.1 Effect of reactor type on biochar physicochemical properties

The evidence from the reviewed studies shows that reactor configuration influences biochar surface area, pore structure, and the degree of carbon ordering [139–142]. While feedstock type and thermal conditions remain primary determinants, the thermal environment imposed by reactors modifies key features such as BET surface area, pore size distribution, aromaticity, and crystallinity. For instance, fixed-bed reactors**,** although simple and low-cost, they tend to produce biochars with heterogeneous microstructures due to poor heat transfer. This heterogeneity reduces their predictability in fertilizer applications [20]. On the other hand, rotary kilns improve homogeneity but are energy intensive, often producing chars with moderate porosity rather than high BET values [51]. Fluidized-bed systems consistently yield biochars with higher surface areas and uniform porosity, aligning well with nutrient adsorption requirements [44]. However, commercial microwave-assisted reactors have potential to outperform conventional designs by generating chars with BET surface areas exceeding 500 m^2/g, yet questions about scalability remain [54]. Plasma-assisted systems**,** though experimental, demonstrate unique surface activation processes that may tailor biochars for specialized fertilizers [46].

As summarized in Table 3, the suitability of a reactor for producing fertilizer biochar depends on balancing scalability, energy efficiency, and the desired structural characteristics. The reviewed studies collectively suggest that reactor-induced differences in BET surface area and pore architecture have direct implications for fertilizer functionality. Reactors capable of producing biochars with BET surface areas above 300 m^2/g and pore volumes exceeding 0.4 cm^3/g generally demonstrate superior nutrient adsorption and water retention performance. However, these improvements are often accompanied by higher operational energy requirements, emphasizing the trade-off between microstructural optimization and economic feasibility.

5.2 Process parameters and microstructural outcomes

The review confirms that temperature, heating rate, residence time, and reactor atmosphere are interdependent and collectively shape biochar microstructure. Temperature controls the degree of carbonization: low-temperature chars retain oxygenated functional groups and higher CEC, while high-temperature chars offer greater stability but reduced reactivity [24, 143, 144]. Heating rate influences pore architecture: moderate rates produce balanced mesopores, while extreme rates collapse structures [9, 145]. Residence time governs crystallinity and stability; excessive times reduce functional group availability despite enhancing aromaticity [55]. Reactive atmospheres (e.g. CO_2, steam) enhance porosity and activation, creating chars better suited for nutrient adsorption compared to inert atmospheres [45]. As summarized in Table 2, these findings demonstrate that careful control of pyrolysis parameters enables tailoring of biochar properties for either short-term nutrient retention or long-term soil conditioning.

5.3 Fertilizer-relevant properties of biochar

Biochar's role in agriculture hinges on its capacity to influence nutrient dynamics and soil physicochemical properties. The literature demonstrates that reactor and parameter driven microstructures determine nutrient retention, water holding potential, and PH. Biochars with mesoporous networks and high CEC improve nitrogen and phosphorus retention, and high nutrient carrier potential. For example, fluidized-bed biochars applied to sandy soils enhance phosphorus availability by 30–40% compared to non-amended controls [48, 146]. Several studies highlight the potential of biochars to act as carriers for synthetic fertilizers. Plasma-derived chars, with their activated surfaces, exhibit strong affinity for ammonium and phosphate ions, suggesting suitability for slow-release formulations [46, 147, 148]. Additionally, biochars with high microporosity improve soil water retention, particularly in arid zones. Microwave-derived biochars were reported to increase soil moisture content by up to 20% [54]. Another property is the soil pH and liming effects in case high-temperature biochars increase soil pH due to ash content and carbonates, benefiting acidic soils [16, 149].

5.4 Comparative analysis across reactor types

A key gap in the literature has been the limited comparative evaluation of reactor technologies and engineering on a uniform basis. Most studies investigated reactors in isolation, hindering direct cross comparisons. However, when critically assessed, fluidized-bed and microwave reactors emerge as optimal for producing high-surface-area, nutrient-retaining chars, whereas, rotary kilns remain attractive for scale-up, but the trade-off is lower porosity. Fixed-bed and auger reactors are better suited for decentralized, small-scale fertilizer production, though biochar heterogeneity may limit standardization. Hybrid reactors hold potential to combine advantages (e.g., scalability + microstructural control), but industrial demonstrations are lacking [57]. These comparisons show that no single reactor design consistently outperforms others across all fertilizer-relevant criteria, meaning that reactor choice must be matched with intended agricultural outcomes.

5.5 Challenges in establishing reactor–fertilizer linkages

Despite the progress made, the evidence from reviewed studies makes it clear that reactor design alone does not determine fertilizer performance, but also feedstock characteristics and soil conditions play important roles. Biochar's agricultural value is an emergent property of feedstock-process-reactor interactions [22, 150]. Several challenges persist: (i) Feedstock variability introduces uncertainty, where identical reactor conditions yield different biochars depending on lignin, cellulose, and mineral content. (ii) Scale-up challenges prevent laboratory findings from being directly extrapolated to industrial fertilizer production [151–153]. (iii) Heterogeneous characterization methods (different BET protocols, CEC tests, or porosity analyses) reduce comparability across studies. (iv) Agricultural validation is limited, and few studies link microstructural features with long-term crop yield improvements under field conditions.

5.6 Future opportunities and research directions

To address these gaps, future research needs to integrate multivariate approaches in which temperature, heating rate, and reactor type are simultaneously investigated to capture interaction effects rather than isolated parameters. Advanced reactor innovations such as microwave or plasma assisted hybrid systems should be tested at pilot scales, with techno-economic analyses assessing their viability for fertilizer biochar production. Comparative studies should be conducted that correlate BET surface area, porosity, and crystallinity with nutrient adsorption, desorption, and release dynamics. There is need for long-term agricultural trials which are essential to confirm laboratory-predicted benefits. Integration with specific cropping systems and soil types will enhance relevance. Life cycle and energy balance analyses are needed to ensure that advanced reactors do not impose prohibitive environmental or economic costs.

5.7 Synthesis

The literature supports a nuanced conclusion that reactor design exerts a significant but not exclusive influence on biochar's fertilizer performance. Instead, fertilizer suitability arises from a triangular interaction between feedstock characteristics, pyrolysis parameters, and reactor environment**.** By addressing methodological inconsistencies, incorporating advanced reactor technologies, and validating performance in agricultural contexts, it is possible to establish more robust reactor–microstructure–fertilizer linkages. This review provides a foundation for such efforts, while Tables 2 and 3 ensure a comparative framework that addresses prior criticisms of descriptive rather than analytical treatment.

6 Research prospects

Although good progress has been made in the study of biomass pyrolysis and biochar production, the integration of reactor design with microstructural optimization for fertilizer applications remains limited. The reviewed literature highlights a fragmented approach, where studies often isolate single parameters or focus narrowly on reactor types without bridging outcomes to long-term agricultural performance. This section outlines research prospects that can guide future investigations and innovations.

6.1 Advancing reactor engineering for biochar production

Further studies should therefore focus on developing reactor systems that can reliably produce fertilizer-grade biochars at scales relevant to real agricultural use. Conventional systems such as fixed-bed and rotary kilns have limitations in heat distribution and microstructural control. Fluidized-bed and microwave-assisted systems offer superior thermal management, but scaling challenges persist [52, 54]. Key research prospects include:

(i) *Hybrid reactor development*: combining microwave or plasma heating with fluidized-bed circulation may overcome individual limitations [57]. Such designs could deliver chars with both high porosity and scalable yields.

(ii) Dynamic reactor modeling in which computational fluid dynamics (CFD) and Multiphysics modeling can help predict microstructural outcomes under varying process conditions, reducing trial-and-error experimentation [154]. The developed models enhance prediction and control of thermal transfer efficiency, material flow dynamics, air and gas flow dynamics, safety, and general yield dashboard of the product materials. The application of machine learning techniques such as Support Vector Regression (SVR) and Particle Swarm Optimization (PSO) models may be useful in optimizing reactors for maximum product yields.

(iii) Decentralized reactor designs, where portable auger-based or modular microwave units could support rural farmers and decentralized fertilizer production in regions like Sub-Saharan Africa, where centralized infrastructure is limited.

6.2 Linking microstructure to fertilizer functionality

Future research must go beyond broad descriptions of "porosity" or "BET surface area" to establish quantitative correlations between microstructural attributes and nutrient dynamics**.** As summarized in Table 2**,** temperature, residence time, and atmosphere strongly influence pore architecture and functional group retention. However, there remains limited systematic mapping between these properties and fertilizer-relevant metrics such as: CEC and its impact on nitrogen retention, phosphorus binding capacity and desorption rates under varying soil pH conditions, and moisture retention in sandy versus clay soils.

Advanced characterization techniques (e.g. synchrotron-based spectroscopy, nanoscale tomography) should be integrated to capture microstructural heterogeneity at finer resolutions. Such work would provide the mechanistic evidence that critics argue is missing in current reactor–fertilizer linkages [155, 156].

6.3 Agricultural validation and long-term studies

Most current research evaluates biochar properties at the laboratory scale, using batch adsorption experiments or short-term soil incubation tests [16, 157]. Very few studies extend to multi-season or multi-year field trials**.** To ensure that reactor-optimized biochars deliver real agricultural benefits, research needs to: (i) Conduct long term trials so as to monitor nutrient release, soil fertility, and crop yield effects over multiple seasons; (ii) assess soil crop specificity since different soils (sandy, clayey, acidic, saline) respond differently to biochar amendments; tailored recommendations must be developed; (iii) evaluate fertilizer blends such as Hybrid fertilizers (biochar plus mineral NPK) which should be tested for slow-release potential, reduced leaching, and enhanced nutrient-use efficiency; and (iv) monitor environmental impacts including tracking greenhouse gas emissions (N_2O, CH_4) and heavy-metal immobilization to establish sustainability credentials.

6.4 Emerging frontiers in biochar research

Recent research is increasingly exploring the use of data-driven methods and Artificial Intelligence (AI) to improve reactor control and optimization, predict biochar properties, and reduce experimental uncertainty. ML and AI techniques such as predictive modelling, and optimization algorithms are potentially useful for simulation and control of biochar properties by optimizing pyrolysis parameters (heating rate, temperature, residence time, feed flow rate, and velocity of fluidizing gas) in respect to the desired yield and physicochemical characteristics of the products [158]. Several models such as Adaptive Neuro-Fuzy Interference system (ANFIS), Artificial Neural networks (ANN), Decision Trees (DT), Support Vector Machine (SVM), Multi-Layer Perceptron Neural Network (MLP-NN), and Least squares support vector regression (LSSVR), among others have been developed and applied in the prediction of various pyrolysis attributes such as operational conditions, biochar yield and microstructure, process energy consumption, and heat capacities.

For example, Mohsen et al. [159] effectively used the LSSVR model with Gaussian Kernel function to predict the heat capacities of various cellulosic biomass materials. It was noted in their study that this model is conservative on the samples' microstructure and crystallinity based on regulated temperature and other operational conditions. Li et al. [59] used MLP-NN and ANFIS to predict biochar yield and composition from various biomass materials. In their study, input parameters included the proximate and ultimate composition of specific biomass, pyrolysis temperature, heating rate and retention time, whereas the output parameters were biochar yield, proximate and ultimate composition. Balde et al. [61] used ANN, Gaussian Process Regression (GPR), DT and SVM to predict heating value, specific surface area and porosity of biochar. In their study, they pyrolyzed tea waste and nut shells using a lab scale microwave reactor and applied ML to optimize the operation. In their analysis, ANN model offered better predictions, with higher regressions ($R^2 \approx 0.9$) and lower prediction errors than SVM, DT and GPR. Comparable results were obtained by Cheng et al. [60], who used DT, ANN, SVM, and GPR models to optimize pyrolysis process of plastic waste into fuel. ANN and DT offered higher regressions ($R^2 = 0.8 - 0.92$), an indication for better simulation results probably if applied on biomass. Similar results were reported by Xiao and Zhu [63], who used Back Propagation ANN (BP-ANN) for prediction of activation energy for various biomass waste materials.

Recent machine learning studies have demonstrated promising predictive capability for optimizing pyrolysis operations and estimating biochar properties. ANN and DT models trained using operational datasets containing reactor temperature, heating rate, residence time, and feedstock composition have achieved prediction accuracies exceeding 90% ($R^2 > 0.90$) for BET surface area and biochar yield estimation. Similarly, Support Vector Regression (SVR) and ANFIS models have shown strong performance in predicting pore volume, carbon content, and syngas generation under varying reactor conditions.

Although, ML models can optimize multi-variate pyrolysis conditions through various pathways as shown in Fig. 8, their usefulness depends on the quality and quantity of available datasets. Studies indicate that predictive accuracy improves substantially when datasets exceed 400 experimental observations and incorporate multiple feedstock categories [161]. Hai et al. [162] pointed out that models such as ANN and ANFIS are often quite complex and time-consuming to build especially with small data sets. Larger datasets (> 400) and more features (> 10) offer more scope and resolution for model development, training, testing and validation pathways. Although

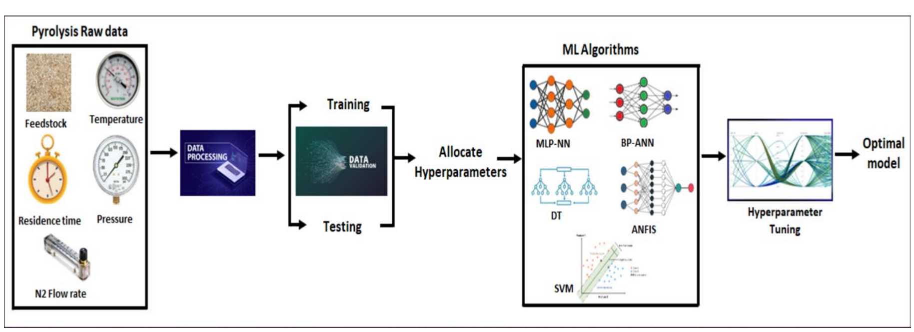


Fig. 8 ML application workflow for optimizing biomass pyrolysis

several studies have explored the use of ML and AI to predict pyrolysis operations, there is still need to build more robust models that are more accurate, transparent, and reproduceable. Most existing models remain constrained by limited dataset diversity, lack of external validation, and insufficient reproducibility across different feedstocks and reactor configurations [60, 64, 160, 161]. Future research should therefore focus on developing standardized open-access pyrolysis datasets capable of supporting transferable and scalable predictive models for biochar fertilizer production.

6.5 Policy, Market, and adoption prospects

To increase the adoption of biochar-based fertilizers will also require supportive policies, clear quality standards, and market incentives that encourage sustainable production practices [163–165]. Research prospects should therefore include: (i) development of clear quality metrics for fertilizer-grade biochars (BET, CEC, H/C, O/C, nutrient content, etc.) to build market trust. This will include standards and certification; (ii) policies to subsidize decentralized reactors or incentivize carbon credits for biochar producers; (iii) partnerships and integration with fertilizer companies to blend biochar into existing NPK formulations; (iv) training programs for farmers, extension workers, and agro-industries on biochar utilization.

6.6 Conceptual integration and roadmap

Future studies should test this conceptual framework through experimental designs that clearly link reactor conditions, biochar microstructure, and fertilizer performance. Tables 2 and 3 provide comparative frameworks to guide such efforts. By embedding these linkages into research designs, the field can move from descriptive case studies to predictive, transferable knowledge that supports fertilizer innovation. The research prospects outlined here emphasize that the future of pyrolysis and biochar research lies not in isolated parameter studies, but in integrated, multidisciplinary approaches. By advancing reactor design, deepening microstructural understanding, validating agricultural performance, and embedding sustainability and policy considerations, it will be possible to realize biochar's full potential as a next-generation fertilizer technology.

For sustainability and circular economy integration, research must also address the life-cycle and economic feasibility of advanced reactors. Studies done by Safarian [22], Li et al. [59], and Campbel et al. [166] bring out important questions of energy balance**,** carbon neutrality, and cost per ton of fertilizer biochar remain unresolved. According to Carvalho et al. [167], Rex et al. [168], and Chen et al. [169], the integration of pyrolysis systems into circular economy models such as coupling biochar production with waste to energy plants offers opportunities for resource efficiency.

6.7 Practical implications

The findings of this review are of academic importance and also have significant implications for practice across the agricultural, industrial, and policy domains. By linking reactor technologies to fertilizer-relevant biochar properties, this study offers guidance for multiple stakeholder groups:

Farmers and agricultural practitioners stand to benefit from the enhanced soil fertility. Biochars with tailored porosity and functional groups improve nutrient retention, thus reducing fertilizer losses and input costs. Farmers can further benefit from biochar-NPK blends that enhance nutrient-use efficiency and provide slow-release properties, especially under rain-fed or sandy soil conditions.

Industry and reactor developers The study offers a benchmark for production of robust and scalable reactor solutions, such as hybrid systems for commercial production of standardized pyrolysis outputs. Developing energy-efficient and high throughput designs will improve the economic viability of large-scale operations.

Product diversification Through carbon activation, industries can customize biochar treatments for specific niche market applications such as purification of liquids and gases, water treatment, manufacture of super capacitors and electrodes for electrochemical devices.

Biochar standardization Policymakers and regulators will require to establish quality standard metrics for biochar fertilizer. This will promote trust and adoption among farmers, processors and traders of biochar products and equipment. Policy frameworks for subsidies, tax waivers, or carbon credits can also stimulate investment in modern reactor technologies for sustainable fertilizer production.

Interdisciplinary collaboration between industry players, researchers, and academia Engineers, agronomists, and soil scientists should work jointly to establish reactor–microstructure–function linkages and balance all aspects in a circular economy. Such joint practices facilitate field trials and validation of laboratory experimental results or simulations into practical and improved models.

The AI question The continued application of advanced AI and ML tools in reactor technologies has potential to enhance the overall reactor performance efficiency, product optimization, and ultimately user-appetite for quality biochar production and/or utilization.

6.8 Conclusion

The findings synthesized in this study show that pyrolysis reactor design and operating conditions have a strong influence on the microstructural properties of biochar relevant to fertilizer use. It demonstrates that reactor architecture and operational conditions shape the crystallinity, porosity, and surface chemistry of biochar. These microstructural traits, in turn, govern fertilizer-relevant properties. It has been indicated that process parameters influence structural outcomes in systematic ways, notwithstanding strengths and limitations of different reactor technologies. Hybrid reactors emerge as the most promising pathways, offering the potential to merge efficiency with structural control, but they remain under-explored at industrial scale. However, reviewers' concerns are valid: biochar's agricultural value cannot be reduced to reactor design alone. Feedstock variability, soil conditions, and post-treatments also mediate outcomes, underscoring the need for integrated approaches. Further progress in this area will depend on coordinated efforts that combine standardized characterization, pilot-scale reactor testing, industrial-scale hybrid systems, policy integration and long-term agricultural validation. Pursuing this trajectory will require closer collaboration between engineers, materials scientists, agronomists, and policymakers to move from descriptive case studies toward predictive, scalable, and sustainable solutions. Therefore, reactor technologies hold great promise for producing fertilizer biochars, but realizing these potentials demands both technological innovation and agricultural validation. By evaluating reactor designs alongside microstructural properties, agricultural performance, and sustainability**,** biochar can move from a promising by-product of pyrolysis to a predictable and standardized input that enhances soil fertility, supports climate mitigation, and promotes food security.

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References

1. Khan S, Irshad S, Mehmood K, Hasnain Z, Nawaz M, Rais A, et al. Health crop production, and yield enhancement. A Review Plants. 2024;13(1):18. https://doi.org/10.3390/plants13020166.
2. Ndegwa JK, Gichimu BM, Mugwe JN, Mucheru-muna M, Njiru DM. Integrated soil fertility and water management practices for enhanced agricultural productivity. Int J of Agro. 2023. https://doi.org/10.1155/2023/8890794.
3. Getahun S, Kefale H, Gelaye Y. Application of precision agriculture technologies for sustainable crop production and environmental sustainability : a systematic review. The Scientific World J. 2024. https://doi.org/10.1155/2024/2126734.
4. Krasilnikov P, Taboada MA 2022 Fertilizer Use , Soil Health and Agricultural Sustainability Agriculture 16–20.
5. Moharm AE, El Naeem GA, Soliman HMA, Abd-Elhamid AI, El-Bardan AA, Kassem TS, et al. Fabrication and characterization of effective biochar biosorbent derived from agricultural waste to remove cationic dyes from wastewater. Polymers. 2022. https://doi.org/10.3390/polym14132587.
6. Hu J, Yang S, Cornelis WM, Zhang M, Huang Q, Qiu H, et al. Microstructure and Microorganisms Alternation of Paddy Soil. Interplay of Biochar and Water-Saving Irrigation. 2025. https://doi.org/10.3390/plants14101498.
7. Kuryntseva P, Karamova K, Galitskaya P, Selivanovskaya S. Biochar functions in soil depending on feedstock and pyrolyzation properties with particular emphasis on biological properties. Agriculture. 2023. https://doi.org/10.3390/agriculture13102003.
8. Jia A, Song X, Li S, Liu Z, Liu X, Han Z, et al. Biochar enhances soil hydrological function by improving the pore structure of saline soil. Agriculture Water Manag. 2024. https://doi.org/10.1016/j.agwat.2024.109170.
9. Elnour AY, Alghyamah AA, Shaikh HM, Poulose AM, Al-Zahrani SM, Anis A, et al. Effect of pyrolysis temperature on biochar microstructural evolution, physicochemical characteristics, and its influence on biochar/polypropylene composites. Appl Sci. 2019;9:7–9. https://doi.org/10.3390/app9061149.
10. Kaur H, Singh G, Yeasmin M, Ramadass K, Van ZL, Vinu A. Engineered biochar-attapulgite clay composite: A novel slow-release phosphorus fertilizer. Chem Eng J. 2025;520:165791. https://doi.org/10.1016/j.cej.2025.165791.
11. Wang Y, Yin R, Liu R. Characterization of biochar from fast pyrolysis and its effect on chemical properties of the tea garden soil. J Anal Appl Pyrolysis. 2014;110:375–81. https://doi.org/10.1016/j.jaap.2014.10.006.

12. Karimi M, Shirzad M. Biomass/Biochar carbon materials for CO_2 capture and sequestration by cyclic adsorption processes. A review and prospects for future directions. 2022. https://doi.org/10.1016/j.jcou.2022.101890.
13. Kumar Yadav N, Vijay Kumar I, Kumar V, Sharma K, Singh Choudhary R, Singh Butter T, et al. Biochar and their impacts on soil properties and crop productivity: a review. J Pharmacogn Phytochem. 2018;7:49–54.
14. Divyangkumar N, Panwar NL. Standardization, certification, and development of biochar based fertilizer for sustainable agriculture_ An overview. Environ Pollut Manag. 2024;1:186–202. https://doi.org/10.1016/j.epm.2024.10.001.
15. Mukherjee A, Zimmerman AR, Harris W. Geoderma Surface chemistry variations among a series of laboratory-produced biochars. Geoderma. 2011;163:247–55. https://doi.org/10.1016/j.geoderma.2011.04.021.
16. Alkharabsheh HM, Seleiman MF, Battaglia ML, Shami A, Jalal RS, Alhammad BA, et al. Biochar and its broad impacts in soil quality and fertility, nutrient leaching and crop productivity: A review. Agronomy. 2021. https://doi.org/10.3390/agronomy11050993.
17. Dong X, Zhang S, Wang X, Pu,. Benefits of organic manure combined with biochar amendments to cotton root growth and yield under continuous cropping systems in Xinjiang. China Sci Rep. 2020;10(1):10. https://doi.org/10.1038/s41598-020-61118-8.
18. Cui X, Li X, Wang J, Wang X, Yu F, Yang G, et al. Technology A review on the production of nutrient-enriched biochar : Insights from the evolution of nitrogen, phosphorus, and potassium. Crit Rev Environ Sci Technol. 2025. https://doi.org/10.1080/106433892457991.
19. Heidari M, Dutta A, Acharya B, Mahmud S. A review of the current knowledge and challenges of hydrothermal carbonization for biomass conversion. J Energy Inst. 2019;92:1779–99. https://doi.org/10.1016/j.joei.2018.12.003.
20. Jahirul MI, Rasul MG, Chowdhury AA, Ashwath N. Biofuels production through biomass pyrolysis- A technological review. Energies. 2012;5:4952–5001. https://doi.org/10.3390/en5124952.
21. Kumar K, Panwar NL. Pyrolysis technologies for biochar production in waste management: a review. Clean Energy. 2024;8:61–78. https://doi.org/10.1093/ce/zkae036.
22. Safarian S. Performance analysis of sustainable technologies for biochar production: A comprehensive review. Energy Rep. 2023;9:4574–93. https://doi.org/10.1016/j.egyr.2023.03.111.
23. Rambhatla N, Panicker TF, Mishra RK, Manjeshwar SK, Sharma A. Biomass pyrolysis for biochar production: Study of kinetics parameters and effect of temperature on biochar yield and its physicochemical properties. Results Eng. 2025;25:103679. https://doi.org/10.1016/j.rineng.2024.103679.
24. Xu C, Tan X, Zhao J, Cao J, Ren M, Xiao Y, et al. Optimization of biochar production based on environmental risk and remediation performance: Take kitchen waste for example. J Hazard Mater. 2021;416:125785. https://doi.org/10.1016/j.jhazmat.2021.125785.
25. Toscano Miranda N, Lopes Motta I, Maciel Filho R, Wolf Maciel MR. Sugarcane bagasse pyrolysis: A review of operating conditions and products properties. Renew Sustain Energy Rev. 2021;149:111394. https://doi.org/10.1016/j.rser.2021.111394.
26. Aboelela D, Saleh H, Attia AM, Elhenawy Y, Majozi T, Bassyouni M. Recent advances in biomass pyrolysis processes for bioenergy production: optimization of operating conditions. Sustain. 2023. https://doi.org/10.3390/su151411238.
27. Nematian M, Keske C, Ng'ombe JN,. A techno-economic analysis of biochar production and the bioeconomy for orchard biomass. Waste Manag. 2021;135:467–77. https://doi.org/10.1016/j.wasman.2021.09.014.
28. Thengane SK, Kung K, Hunt J, Gilani HR, Lim CJ, Sokhansanj S, et al. Market prospects for biochar production and application in California. Biofuels, Bioprod Biorefining. 2021;15:1802–19. https://doi.org/10.1002/bbb.2280.
29. Dokoohaki H, Miguez FE, Alluqmani SM, Saedoon H, Bergero C, Wise M. Pyrolysis and fast pyrolysis on the quality of lignocellulosic and lignin-based biochar a review on the comparison between slow pyrolysis and fast pyrolysis on the quality of lignocellulosic and lignin- based biochar. Mater Sci Eng. 2021. https://doi.org/10.1088/1757-899X/1051/1/012075.
30. Leng L, Huang H. An overview of the effect of pyrolysis process parameters on biochar stability. Bioresour Technol. 2018;270:627–42. https://doi.org/10.1016/j.biortech.2018.09.030.
31. Sun J, Tu S, Lu X, Li X. Coupling of Biochar and Manure Improves Soil Carbon Pool Stability. Pore Structure, and Microbial Diversity Agronomy. 2025;15(6):1–18.
32. Mahmoud AA, El-sayed AA, Fathy IN, Fawzy S, Alturki M 2025 Evaluation of rice husk biochar influence as a partial cement replacement material on the physical , mechanical , microstructural , and radiation shielding properties of ordinary concrete Scientific Reports 15 1 27229
33. Verso XXX, Rubel RI, Intended BCNF, Microbial A, Rubel RI, Wei L, et al 2024 Biochar-Compost-Based Controlled-Release Nitrogen Fertilizer Intended for an Active Microbial Community Frontiers of Agricultural Science And Engineering https://doi.org/10.15302/J-FASE-2023XXX.
34. He Z, Wang W, Kang B, Yin Y, Yang J. Effects of biochar and microbial organic fertilizers on agricultural productivity and their microbial mechanisms under heavy metal. Stress. 2025. https://doi.org/10.3390/toxics13110997.
35. Ramesh K, Raghavan V. Agricultural waste-derived biochar-based nitrogenous fertilizer for slow-release applications. ACS Omega. 2024. https://doi.org/10.1021/acsomega.3c06687.
36. Li Y, Xing B, Ding Y, Han X, Wang S. A critical review of the production and advanced utilization of biochar via selective pyrolysis of lignocellulosic biomass. Bioresour Technol. 2020;312:123614. https://doi.org/10.1016/j.biortech.2020.123614.
37. Rowland SM, Martinez R, Wrasman CJ, Iisa K, Nimlos MR, Griffin MB. Thermal reactivity of bio-oil produced from catalytic fast pyrolysis of biomass. Energy Fuels. 2024. https://doi.org/10.1021/acs.energyfuels.4c03430.
38. Altıkat A, Alma MH, Altıkat A, Bilgili ME. A comprehensive study of biochar yield and quality concerning pyrolysis conditions. A Multifaceted Approach. 2024. https://doi.org/10.3390/su16020937.
39. Zou X, Debiagi P, Ahsan M, Zhai M, Faravelli T. Journal of Analytical and Applied Pyrolysis Impact of high-temperature biomass pyrolysis on biochar formation and composition. J Anal Appl Pyrolysis. 2024;179:106463. https://doi.org/10.1016/j.jaap.2024.106463.

40. Kalina M, Sovova S, Svec J, Trudicova M, Hajzler J, Kubikova L, et al. The effect of pyrolysis temperature and the source biomass on the properties of biochar produced for the agronomical applications as the soil conditioner. Materials. 2022. https://doi.org/10.3390/ma15248855.
41. Wijitkosum S. Influence of Pyrolysis Temperature and Time on Biochar Properties and Its Potential for Climate Change Mitigation. J of Human Earth and Future. 2023;4(472):85.
42. Biney M, Gusiatin MZ 2024 Biochar from Co-Pyrolyzed Municipal Sewage Sludge (MSS): Part 1 : Evaluating Types of Co-Substrates and Co-Pyrolysis Conditions Materials https://doi.org/10.3390/ma17143603.
43. Werner C, Lucht W, Kammann C, Braun J. Land - neutral negative emissions through biochar - based fertilization — assessing global potentials under varied management and pyrolysis conditions. Mitig Adapt Strateg Glob Chang. 2024;29:1–28. https://doi.org/10.1007/s11027-024-10130-8.
44. Paavani K, Agarwal K, Alam SS, Dinda S, Abrar I. Advances in plastic to fuel conversion: reactor design, operational optimization, and machine learning integration. Sustain Energy Fuels. 2024. https://doi.org/10.1039/d4se01045k.
45. Raza M, Inayat A, Ahmed A, Jamil F, Ghenai C, Naqvi SR, et al. Progress of the pyrolyzer reactors and advanced technologies for biomass pyrolysis processing. Sustain. 2021;13:1–42. https://doi.org/10.3390/su131911061.
46. Ischia G, Orlandi M, Fendrich MA, Bettonte M, Merzari F, Miotello A, et al. Realization of a solar hydrothermal carbonization reactor: A zero-energy technology for waste biomass valorization. J Environ Manage. 2020;259:110067. https://doi.org/10.1016/j.jenvman.2020.110067.
47. Campusano B, Jabbour M, Abdelouahed L. Thermodynamic analysis of biomass pyrolysis in an Auger reactor coupled with a fluidized-bed reactor for catalytic deoxygenation. Processes. 2025. https://doi.org/10.3390/pr13082496.
48. Bandara JC, Moldestad BME, Eikeland MS. Circulating fluidized bed reactors – Experimental optimization of loop-seal aeration and parametric study using CPFD simulations. Powder Technol. 2022;405:117495. https://doi.org/10.1016/j.powtec.2022.117495.
49. Rasaq WA, Okpala COR, Igwegbe CA, Białowiec A. Navigating pyrolysis implementation—a tutorial review on consideration factors and thermochemical operating methods for biomass conversion. Materials. 2024. https://doi.org/10.3390/ma17030725.
50. Hasan MM, Rasul MG, Jahirul MI, Khan MMK. Fast pyrolysis of municipal green waste in an Auger reactor effects of residence time and particle size on the yield and characteristics of produced oil. Energies. 2024. https://doi.org/10.3390/en17122914.
51. Campuzano F, Brown RC, Martínez JD. Auger reactors for pyrolysis of biomass and wastes. Renew Sustain Energy Rev. 2019;102:372–409. https://doi.org/10.1016/j.rser.2018.12.014.
52. Mohan D, Pittman CU, Philip S. Pyrolysis of Wood/Biomass for Bio-oil: A Critical Review Dinesh. Prog Energy Combust Sci. 2017;62:848–89.
53. Ao W, Fu J, Mao X, Kang Q, Ran C, Liu Y, et al. Microwave assisted preparation of activated carbon from biomass: A review. Renew Sustain Energy Rev. 2018;92:958–79. https://doi.org/10.1016/j.rser.2018.04.051.
54. Mong GR, Chong CT, Ng JH, Chong WWF, Lam SS, Ong HC, et al. Microwave pyrolysis for valorisation of horse manure biowaste. Energy Convers Manag. 2020;220:113074. https://doi.org/10.1016/j.enconman.2020.113074.
55. Muvhiiwa R, Kuvarega A, Llana EM, Muleja A. Study of biochar from pyrolysis and gasification of wood pellets in a nitrogen plasma reactor for design of biomass processes. J Environ Chem Eng. 2019;7:103391. https://doi.org/10.1016/j.jece.2019.103391.
56. Masood HM, Ashraf J, Shahzad K, Khan RU, Imran N, Zafar Z 2025 Recent advancements , challenges in recycling of waste plastic using microwave assisted catalytic co-pyrolysis of biomass and waste plastic for production of value added chemicals : a review Journal of Thermal Engineering https://doi.org/10.14744/thermal.0000971.
57. Rodriguez J, Morona L, Erans M, Buttress AJ, Nicholls M, Batchelor AR, et al. Solving the microwave heating uniformity conundrum for scalable high-temperature processes via a toroidal fluidised-bed reactor. Chem Eng Process - Process Intensif. 2024;202:109838. https://doi.org/10.1016/j.cep.2024.109838.
58. Nunez Manzano M, Gonzalez Quiroga A, Perreault P, Madanikashani S, Vandewalle LA, Marin GB, et al. Biomass fast pyrolysis in an innovative gas-solid vortex reactor: Experimental proof of concept. J Anal Appl Pyrolysis. 2021;156:105165. https://doi.org/10.1016/j.jaap.2021.105165.
59. Li Y, Gupta R, You S. Machine learning assisted prediction of biochar yield and composition via pyrolysis of biomass. Bioresour Technol. 2022;359:127511. https://doi.org/10.1016/j.biortech.2022.127511.
60. Cheng Y, Ekici E, Yildiz G, Yang Y, Coward B, Wang J. Applied machine learning for prediction of waste plastic pyrolysis towards valuable fuel and chemicals production. J Anal Appl Pyrolysis. 2023;169:105857. https://doi.org/10.1016/j.jaap.2023.105857.
61. Balde MS, Karakış R, Ateş A. Estimation of specific surface area and higher heating value of biochar and activated carbon produced by pyrolysis and physico-chemically assisted pyrolysis of biomass using an artificial neural network (ANN). Biomass Convers Biorefinery. 2025. https://doi.org/10.1007/s13399-025-06728-w.
62. Leite JCS, Suota MJ, Ramos LP, Lenzi MK, Luz LFL. Development of a microwave-assisted bench reactor for biomass pyrolysis using hybrid heating. ACS Omega. 2024;9:24987–97. https://doi.org/10.1021/acsomega.4c02050.
63. Xiao K, Zhu X. Machine learning approach for the prediction of biomass waste pyrolysis kinetics from preliminary analysis. ACS Omega. 2024. https://doi.org/10.1021/acsomega.4c04649.
64. Hai A, Bharath G, Patah MFA, Daud WMAW, K. R, Show PL, et al. Machine learning models for the prediction of total yield and specific surface area of biochar derived from agricultural biomass by pyrolysis. Environ Technol Innov. 2023;30:103071. https://doi.org/10.1016/j.eti.2023.103071.
65. Liu C, Balasubramanian P, An J, Li F. Machine learning prediction of ammonia nitrogen adsorption on biochar with model evaluation and optimization. Npj Clean Water. 2025. https://doi.org/10.1038/s41545-024-00429-z.
66. Chen X, Liu L, Yang Q, Xu H, Shen G, Chen Q. Optimizing biochar application rates to improve soil properties and crop growth in saline-alkali soil. Sustain. 2024;16:1–16. https://doi.org/10.3390/su16062523.
67. Mafu LD, Neomagus HWJP, Everson RC, Strydom CA, Carrier M, Okolo GN, et al. Chemical and structural characterization of char development during lignocellulosic biomass pyrolysis. Bioresour Technol. 2017;243:941–8. https://doi.org/10.1016/j.biortech.2017.07.017.

68. Wang Remón J, Jiang Z, Ding W. Recent advances in the preparation and application of biochar derived from lignocellulosic biomass: a mini review. Polymers. 2024;16:1–22. https://doi.org/10.3390/polym16060851.
69. Liu H, Liu X, Wang H, Zheng Y, Zhang H, Shi J, et al. High-performance sodium-ion capacitor constructed by well-matched dual-carbon electrodes from a single biomass. ACS Sustain Chem Eng. 2019;7:12188–99. https://doi.org/10.1021/acssuschemeng.9b01370.
70. Singh H, Northup BK, Rice CW, Prasad PVV. Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: a meta-analysis. Biochar. 2022;4:1–17. https://doi.org/10.1007/s42773-022-00138-1.
71. Zul F, Moosa A, Nazir MM, Ferrante A, Ashraf M, Nafees M, et al. Biochar : An emerging recipe for designing sustainable horticulture under climate change scenarios. Frontiers in Plant Sci. 2022. https://doi.org/10.3389/fpls.2022.1018646.
72. Mariyam S, Alherbawi M, McKay G, Al-Ansari T. A predictive model for biomass waste pyrolysis yield: Exploring the correlation of proximate analysis and product composition. Energy Convers Manag X. 2025;25:100831. https://doi.org/10.1016/j.ecmx.2024.100831.
73. Yaashikaa PR, Kumar PS, Varjani S, Saravanan A. A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. Biotechnol Reports. 2020;28:e00570. https://doi.org/10.1016/j.btre.2020.e00570.
74. Shen Y. A review on hydrothermal carbonization of biomass and plastic wastes to energy products. Biomass Bioenerg. 2020;134:105479. https://doi.org/10.1016/j.biombioe.2020.105479.
75. Saletnik B, Saletnik A, Bajcar M, Zaguła G, Puchalski C 2024 Influence of temperature and duration of pyrolysis process on calorific value of cereal straw biochar and dust explosive index. Int Agrophysics https://doi.org/10.31545/intagr/188306.
76. Zeng K, Minh DP, Gauthier D, Weiss-Hortala E, Nzihou A, Flamant G. The effect of temperature and heating rate on char properties obtained from solar pyrolysis of beech wood. Bioresour Technol. 2015;182:114–9. https://doi.org/10.1016/j.biortech.2015.01.112.
77. Xiong Z, Wang Y, Syed-Hassan SSA, Hu X, Han H, Su S, et al. Effects of heating rate on the evolution of bio-oil during its pyrolysis. Energy Convers Manag. 2018;163:420–7. https://doi.org/10.1016/j.enconman.2018.02.078.
78. Marathe PS, Westerhof RJM, Kersten SRA. Effect of pressure and hot vapor residence time on the fast pyrolysis of biomass: experiments and modeling. Energy\& Fuels. 2020. https://doi.org/10.1021/acs.energyfuels.9b03193.
79. Solar J, de Marco I, Caballero BM, Lopez-Urionabarrenechea A, Rodriguez N, Agirre I, et al. Influence of temperature and residence time in the pyrolysis of woody biomass waste in a continuous screw reactor. Biomass Bioenerg. 2016;95:416–23. https://doi.org/10.1016/j.biombioe.2016.07.004.
80. Tan H, Lee CT, Ong PY, Wong KY, Bong CPC, Li C, et al. A review on the comparison between slow pyrolysis and fast pyrolysis on the quality of lignocellulosic and lignin-based biochar. IOP Conf Ser Mater Sci Eng. 2021;1051:012075. https://doi.org/10.1088/1757-899x/1051/1/012075.
81. Pandey D, Daverey A, Arunachalam K. Biochar : Production, properties and emerging role as a support for enzyme immobilization. J Clean Prod. 2020;255:120267. https://doi.org/10.1016/j.jclepro.2020.120267.
82. Li W, Dang Q, Brown RC, Laird D, Wright MM. The impacts of biomass properties on pyrolysis yields, economic and environmental performance of the pyrolysis-bioenergy-biochar platform to carbon negative energy. Bioresour Technol. 2017;241:959–68. https://doi.org/10.1016/j.biortech.2017.06.049.
83. Schwarzbauer JAN, Gajica G. Pyrolysis of corn stalks : the potential of using bio-oil as a fuel. J Serbian Chem Soc. 2024;89:1675–87. https://doi.org/10.2298/JSC240110043I.
84. Adekanye T, Dada O, Kolapo J 2022 Pyrolysis of maize cob at different temperatures for biochar production : Proximate , ultimate and spectroscopic characterisation. Res Agric Eng https://doi.org/10.17221/106/2020-RAE.
85. Hidayat; A R, Nissa RC, Sukamto; Nuraini L, Nurtanto M, SW, et al. Analysis of rice husk biochar characteristics under different pyrolysis temperature Analysis of rice husk biochar characteristics under different pyrolysis temperature. Earth Environ Sci. 2023. https://doi.org/10.1088/1755-1315/1201/1/012095.
86. Huang YF, Te CP, Kuan WH, Lo SL. Microwave pyrolysis of lignocellulosic biomass: Heating performance and reaction kinetics. Energy. 2016;100:137–44. https://doi.org/10.1016/j.energy.2016.01.088.
87. Abdullah N, Mohd R, Syairah N, Aziz M, Rabie M, Disa N. Heliyon Banana pseudo-stem biochar derived from slow and fast pyrolysis process. Heliyon. 2023. https://doi.org/10.1016/j.heliyon.2023.e12940.
88. Kabenge I, Omulo G, Banadda N, Seay J, Zziwa A, Kiggundu N. Characterization of banana peels wastes as potential slow pyrolysis feedstock. J Sustain Dev. 2018;11:14. https://doi.org/10.5539/jsd.v11n2p14.
89. Xu J, Liu B, Hou H, Hu J. Pretreatment of eucalyptus with recycled ionic liquids for low-cost biorefinery. Bioresour Technol. 2017;234:406–14. https://doi.org/10.1016/j.biortech.2017.03.081.
90. Inayat A, Rocha-meneses L, Said Z, Ghenai C. Activated carbon production from coffee waste via slow pyrolysis using a fixed bed reactor. Environ Clim Technol. 2022;26(720):9. https://doi.org/10.2478/rtuect-2022-0055.
91. Braza CEM, Crnkovic PM. Physical - Chemical characterization of biomass samples for application in pyrolysis process. Chem Eng Trans. 2014;37:523–8. https://doi.org/10.3303/CET1437088.
92. Gurten II, Ozmak M, Yagmur E, Aktas Z. Preparation and characterisation of activated carbon from waste tea using K 2CO 3. Biomass Bioenerg. 2012;37:73–81. https://doi.org/10.1016/j.biombioe.2011.12.030.
93. Rago YP, Surroop D, Mohee R. Assessing the potential of biofuel (biochar) production from food wastes through thermal treatment. Bioresour Technol. 2018;248:258–64. https://doi.org/10.1016/j.biortech.2017.06.108.
94. Chen JH, Xu JK, Huang PL, Sun RC. Effect of alkaline pretreatment on the preparation of regenerated lignocellulose fibers from bamboo stem. Cellulose. 2016;23:2727–39. https://doi.org/10.1007/s10570-016-0983-1.
95. Abnisa F, Arami-Niya A, Daud WMAW, Sahu JN. Characterization of bio-oil and bio-char from pyrolysis of palm oil wastes. Bioenergy Res. 2013;6:830–40. https://doi.org/10.1007/s12155-013-9313-8.
96. Yuan T, He W, Yin G, Xu S. Comparison of bio-chars formation derived from fast and slow pyrolysis of walnut shell. Fuel. 2020;261:116450. https://doi.org/10.1016/j.fuel.2019.116450.

97. Jerzak Wojciech, Esther Acha, Bin L. Comprehensive review of biomass pyrolysis: conventional and advanced technologies, reactor designs, product compositions and yields, and techno-economic analysis. Energies. 2024. https://doi.org/10.3390/en17205082.
98. Ratnakar RR, Sun Z, Balakotaiah V. Effective thermal conductivity of insulation materials for cryogenic LH 2 storage tanks : A review. Int J Hydrogen Energy. 2022;48:7770–93. https://doi.org/10.1016/j.ijhydene.2022.11.130.
99. Tabakaev R, Astafev A, Shanenkova Y, Dubinin Y, Yazykov N, Yakovlev V. Biomass and bioenergy thermal effects investigation during biomass slow pyrolysis in a fixed bed reactor. Biomass and Bioenergy. 2019;126(26):33. https://doi.org/10.1016/j.biombioe.2019.05.010.
100. Roksana Muzyka, Szymon Sobek, Mariusz Dudziak, Miloud Ouadi, Marcin S. A comparative analysis of waste biomass pyrolysis in Py-GC-MS and fixed-bed reactors. Energies. 2023. https://doi.org/10.3390/en16083528.
101. Romero CM, Arce GLAF, Avila I. Biomass and Bioenergy Optimization of slow pyrolysis process parameters using a fixed bed reactor for biochar yield from rice husk. Biomass and Bioenergy. 2020. https://doi.org/10.1016/j.biombioe.2019.105412.
102. Lu S. Pore structure and environmental serves of biochars derived from different feedstocks and pyrolysis conditions. Environ Scie and Pollution Res. 2018;25(30):30401–9.
103. Pongsa U, Lumsakul P, Jamesang O, Saengkhiao P, Sangrayub P, Pumchan W. Feasibility study of coconut shell biochar production using community-scale biochar kiln. J of Metals Materials and Miner. 2023;33(2):128–13.
104. Visscher F, van der Schaaf J, Nijhuis TA, Schouten JC. Rotating reactors - A review. Chem Eng Res Des. 2013;91:1923–40. https://doi.org/10.1016/j.cherd.2013.07.021.
105. Fu P, Bai X, Yi W, Li Z, Li Y. Fast pyrolysis of wheat straw in a dual concentric rotary cylinder reactor with ceramic balls as recirculated heat carrier. Energy Convers Manag. 2018;171:855–62. https://doi.org/10.1016/j.enconman.2018.06.035.
106. Li J. The optimal of pyrolysis process in the rotating cone reactor and pyrolysis product analysis. Int Conf Challenges Environ Sci Comput Eng CESCE. 2010;2010(1):530–3. https://doi.org/10.1109/CESCE.2010.74.
107. López G, Olazar M, Aguado R, Bilbao J. Continuous pyrolysis of waste tyres in a conical spouted bed reactor. Fuel. 2010;89:1946–52. https://doi.org/10.1016/j.fuel.2010.03.029.
108. Skryja P, Rotary Hopjan J, Kiln,. A unit on the border of the process and energy industry — current state and perspectives. Sustainability. 2022. https://doi.org/10.3390/su142113903.
109. Vali N, Zabihi S, Shamim S, Mohsenzadeh A, Pettersson A. Slow - pyrolysis of municipal sewage sludge : biochar characteristics and advanced thermodynamics. Biomass Convers Biorefinery. 2025;15:21045–65. https://doi.org/10.1007/s13399-025-06680-9.
110. Ibana D, Singh P, Nikoloski AN. Sustainable production of activated carbon from waste wood using goethite iron ore. Sustain. 2025. https://doi.org/10.3390/su17020681.
111. Cuevas AB, Leiva-Candia DE, Dorado MP. An Overview of pyrolysis as waste treatment to produce eco-energy. Energies. 2024;17:2852. https://doi.org/10.3390/en17122852.
112. Aghaei-dinani R, Asasian-kolur N, Harasek M. Energy-efficient biochar activation in a fluidized bed reactor using air mixed atmospheres. Molecules. 2026. https://doi.org/10.3390/molecules31040724.
113. Zhang F, Miao J, Liu W, Xu D, Li X. Heteroatom embedded graphene-like structure anchored on porous biochar as efficient metal-free catalyst for ORR. Int J Hydrogen Energy. 2019. https://doi.org/10.1016/j.ijhydene.2019.09.239.
114. Jayamini HPA, Dassanayake KMM, Senavirathna GRU, Liyanage D. Design and development of a pyrolysis reactor to produce biochar at industrial scale. Eng J Inst Eng Sri Lanka. 2024;57:31–44. https://doi.org/10.4038/engineer.v57i1.7637.
115. Tran QK, Le ML, Ly HV, Woo HC, Kim J, Kim SS. Fast pyrolysis of pitch pine biomass in a bubbling fluidized-bed reactor for bio-oil production. J Ind Eng Chem. 2021;98:168–79. https://doi.org/10.1016/j.jiec.2021.04.005.
116. Direktor LB, Zaichenko VM, Is RL. Comparison of the Efficiency of the reactors for low-temperature pyrolysis of biomass. Therm Eng. 2020;67:296–303. https://doi.org/10.1134/S0040601520050043.
117. Treedet W, Suntivarakorn R. Design and operation of a low cost bio-oil fast pyrolysis from sugarcane bagasse on circulating fl uidized bed reactor in a pilot plant. Fuel Process Technol. 2018;179:17–31. https://doi.org/10.1016/j.fuproc.2018.06.006.
118. Solar J, Caballero BM, Alexander L, Acha E, Arias PL. Pyrolysis of forestry waste in a screw reactor with four sequential heating zones : influence of isothermal and nonisothermal profiles. Ind Eng Chem Res. 2021. https://doi.org/10.1021/acs.iecr.1c01932.
119. Rego F, Xiang H, Yang Y, Ordovás JL, Chong K, Wang J, et al. Investigation of the role of feedstock properties and process conditions on the slow pyrolysis of biomass in a continuous auger reactor. J Anal Appl Pyrolysis. 2022. https://doi.org/10.1016/j.jaap.2021.105378.
120. Altundoğan HS, Tanyıldızı MŞ, Kalender M, Elçiçek S, Pehlivan D. A novel screw - type pyrolysis system for selectively producing value - added chemicals from lignocellulosic biomass. Biomass Convers Biorefinery. 2025. https://doi.org/10.1007/s13399-024-05791-z.
121. Meyer S, Genesio L, Vogel I, Schmidt H, Someus E, Shackley S, et al. Biochar standardization and legislation harmonization IN legislation. J Environ Eng Landsc Manag. 2017. https://doi.org/10.3846/16486897.2016.1254640.
122. Park HC, Lee BK, Yoo HS, Choi HS. Influence of Operating Conditions for Fast Pyrolysis and Pyrolysis Oil Production in a Conical Spouted-Bed Reactor. Chem Eng Technol. 2019;42:2493–504. https://doi.org/10.1002/ceat.201900082.
123. Suman S, Gautam S. Environmental Effects Pyrolysis of coconut husk biomass : Analysis of its biochar properties. Energy Sources, Part A Recover Util Environ Eff. 2017;00:1–7. https://doi.org/10.1080/15567036.2016.1263252.
124. Ajien A, Idris J, Sofwan N, Husen R, Seli H 2023 Coconut shell and husk biochar : A review of production and activation technology , economic , financial aspect and application Waste management & Research 41 1 37–51

125. Qiu T, Li C, Guang M, Zhang Y. Porous carbon material production from microwave - assisted pyrolysis of peanut. Carbon Res. 2023. https://doi.org/10.1007/s44246-023-00079-9.
126. Foo KY, Hameed BH. Preparation of activated carbon from date stones by microwave induced chemical activation: Application for methylene blue adsorption. Chem Eng J. 2011;170:338–41. https://doi.org/10.1016/j.cej.2011.02.068.
127. Frediani M 2016 Microwave assisted pyrolysis of kraft lignin at reduce pressure in a multimode oven Mattia
128. Zhang B, Wu J, Deng Z, Yang C, Cui C, Ding YA. Comparison of energy consumption in hydrothermal liquefaction and pyrolysis of microalgae. Trends in Renewable Energy. 2017;3(1):76–85.
129. Kumar Nema S, Nema S, Jain V, Ganeshprasad K, Sanghariyat A, Soni S, et al 2016 Plasma Processing for Textile View project Plasma Pyrolysis Technology and its Evolution at FCIPT, Institute for Plasma Research, India. Plasma Technol https://doi.org/10.13140/RG.2.1.3435.6880.
130. Ashour B, Ali SM, Farahat MG. Fabrication and detection of carbon-based nanomaterials derived from biomass sources: processes and applications. Egypt J Chem. 2025;68:117–29.
131. Amjed MA, Sobic F, Romano MC, Faravelli T, Binotti M. Techno-economic analysis of a solar-driven biomass pyrolysis plant for bio-oil and biochar production. Sustain Energy Fuels. 2024. https://doi.org/10.1039/d4se00450g.
132. Wallace CA, Afzal MT, Saha GC. Effect of feedstock and microwave pyrolysis temperature on physio - chemical and nano - scale mechanical properties of biochar. Bioresour Bioprocess. 2019. https://doi.org/10.1186/s40643-019-0268-2.
133. Kanokporn J, Saysunee, Jumrat; Teerasak, Punvichai; Seppo, Karrila; Tule, Sirikitputtisak; Nitipong S 2023 com Properties of Bio-oil and Bio-char from High-intensity Microwave-assisted Pyrolysis of Oil Palm Shell Waste Bioresources 18 1 1420–35
134. Vasalos IA, Lappas AA, Kopalidou EP, Kalogiannis KG 2016 Biomass catalytic pyrolysis : process design and economic analysis Wiley Interdisciplinary Reviews: Energy and Environment 5 3 370 383
135. Bartłomiej, Igli´nski; Wojciech, Kujawski; Urszula K. Pyrolysis of Waste Biomass : Technical and Process. Energies. 2023. https://doi.org/10.3390/en16041829.
136. Haeldermans T, Campion L, Kuppens T, Vanreppelen K, Cuypers A, Schreurs S. Bioresource Technology A comparative techno-economic assessment of biochar production from different residue streams using conventional and microwave pyrolysis. Bioresource Technology. 2020;318:124083.
137. Rana T, Kar S. Assessment of energy consumption and environmental safety measures in a plasma 2 pyrolysis plant for eco-friendly waste treatment. J Energy Inst. 2024. https://doi.org/10.1016/j.joei.2024.101617.
138. Zhou N, Zhou J, Dai L, Guo F, Wang Y, Li H, et al. Bioresource Technology Syngas production from biomass pyrolysis in a continuous microwave assisted pyrolysis system. Bioresour Technol. 2020;314:123756. https://doi.org/10.1016/j.biortech.2020.123756.
139. Das O, Afriyie R, George G, Jiang L, Xu Q, Esmaeely R, et al. Biomass and Bioenergy Flammability and mechanical properties of biochars made in different pyrolysis reactors. Biomass and Bioenergy. 2021;152:106197. https://doi.org/10.1016/j.biombioe.2021.106197.
140. Monfared ZG, Hellström JGI, Umeki K. Effect of particle irregularity and particle size distribution on the morphology of packed beds of biochar particles. Scientific Reports. 2025. https://doi.org/10.1038/s41598-025-99495-7.
141. Pahnila M, Koskela A, Sulasalmi P, Fabritius T. A Review of pyrolysis technologies and the effect of process parameters on biocarbon properties. Energies. 2023. https://doi.org/10.3390/en16196936.
142. Landrat M, Abawalo M, Piko K. Assessing the potential of teff husk for biochar production through slow pyrolysis : effect of pyrolysis temperature on biochar yield. Energies. 2024. https://doi.org/10.3390/en17091988.
143. Mishra RK. Sustainability Pyrolysis of waste pinewood sawdust using Py-GC- MS : effect of temperature and catalysts on the pyrolytic product composition. Rsc Sustainability. 2025. https://doi.org/10.1039/d5su00665a.
144. Nath B, Chen G, Bowtell L, Nguyen-Huy T. Pyrolysis of wheat straw pellets in a pilot-scale reactor: Effect of temperature and residence time. Energy Sci Eng. 2024. https://doi.org/10.1002/ese3.1833.
145. Parthasarathy P. Effect of heating rate on the pyrolysis of camel manure. Biomass Conversion and Biorefinery. 2023. https://doi.org/10.1007/s13399-021-01531-9.
146. Trenkner M, Kiesel A, Bauerle A 2025 Resources B. urban and rural areas : a case study of recycling fertilizers from urban https://doi.org/10.1002/bbb.2801.
147. Islam R, Lin R. Economic assessment of biochar - based controlled - release nitrogen fertilizer production at different industrial scales. Waste and Biomass Valorization. 2025;16:6833–49. https://doi.org/10.1007/s12649-025-03096-4.
148. Abiola WA, Diogo RVC, Tovihoudji PG, Mien AK, Schalla A. Research trends on biochar- based smart fertilizers as an option for the sustainable agricultural land management : Bibliometric analysis and review. Frontiers in Soil Sci. 2023. https://doi.org/10.3389/fsoil.2023.1136327.
149. Litskas VD. Environmental impact assessment for animal waste organic and synthetic fertilizers. Nitrogen. 2023. https://doi.org/10.3390/nitrogen4010002.
150. Salas MÁ, Sica P, Rydgård M, Sitzmann TJ, Onyango J, El Mahdi J, et al. Current challenges on the widespread adoption of new bio-based fertilizers : insights to move forward toward more circular food systems. Frontiers in Sustain Food Systems. 2024. https://doi.org/10.3389/fsufs.2024.1386680.
151. Heinrich T, Park H, Orozco R, Ding Z, Álvarez-lópez V, Mosquera-losada MR, et al. Biochar production from late-harvest grass – Challenges and potential for farm-scale implementation. Sustain Prod Consum. 2023;37:256–67. https://doi.org/10.1016/j.spc.2023.02.019.
152. Volpi MPC, Silva JCG, Hornung A, Ouadi M. Review of the current state of pyrolysis and biochar utilization in Europe : a scientific perspective. Clean technologies. 2024;6(1):152–75. https://doi.org/10.3390/cleantechnol6010010.

153. Luo P, Zhang W, Xiao D, Hu J, Li N, Yang J. Biochar-based fertilizers : advancements, applications, and future directions in sustainable agriculture-a review. Agronomy. 2025;15(5):1104. https://doi.org/10.3390/agronomy15051104.
154. Shirzad M, Karimi M, Silva JAC, Rodrigues E. Moving bed reactors : challenges and progress of experimental and theoretical studies in a century of research. Industrial \& Eng Chem Res. 2019. https://doi.org/10.1021/acs.iecr.9b01136.
155. Zubairu AM, Ocansey CM, Gangwar RK, Szegi TA, Boros N, Sebők A, et al. Overview of biochar role in remediating soil salinity stress in crops. Discover Sustain. 2025. https://doi.org/10.1007/s43621-025-01875-6.
156. Marin F, Tanislav OM, Constantinescu M, Roman A, Bucura F, Oancea S, et al. Biochar for soil fertility and climate mitigation : review on feedstocks, pyrolysis conditions, functional properties, and applications with emerging AI integration. Agriculture. 2025. https://doi.org/10.3390/agriculture15222345.
157. Abukari A, Cobbinah P. Turkish journal of agriculture - food science and technology can biochar made from rice husk affect savanna soils ' ph, electrical conductivity, and soil respiration ? Turkish J of Agri-Food Sci and Tech. 2024;12(978):83.
158. Munzeiwa WA, Tsekoa P, Kammies LRD, Chelechele K, Oluwalana-sanusi AE, Chaukura N. Influence of biomass baseline potential on biochar properties and performance for targeted applications. Carbon Letters. 2025. https://doi.org/10.1007/s42823-025-00892-9.
159. Karimi M, Khosravi M, Fathollahi R. Determination of the heat capacity of cellulosic biosamples employing diverse machine learning approaches. Energy Sci Eng. 2022. https://doi.org/10.1002/ese3.1155.
160. Fu Y, Cleall P, Jin F. Optimising biochar from agricultural residues : Predicting elemental composition with machine learning. Renew Energy. 2026;256:124071. https://doi.org/10.1016/j.renene.2025.124071.
161. Liu M, Tao J, Mu L, Su H, Peng H, Cheng Z, et al. Machine learning - driven predictions of biochar yield and NPK composition : insights into biomass pyrolysis with data augmentation and model interpretability. Carbon Res. 2025. https://doi.org/10.1007/s44246-025-00229-1.
162. Hai A, Bharath G, Fazly M, Patah A. Environmental Technology & Innovation Machine learning models for the prediction of total yield and specific surface area of biochar derived from agricultural biomass by pyrolysis. Environ Technol Innov. 2023;30:103071. https://doi.org/10.1016/j.eti.2023.103071.
163. Janaranjana S, Bandara H. Exploring the potential of biochar in enhancing U S agriculture. Regional Sci and Environ Economics. 2025. https://doi.org/10.3390/rsee2030023.
164. John V, Rita A, Braga DO, Kellen C, De Oliveira A, Sousa HM, et al. Investigation prospects, and economic scenarios for the use of biochar in small-scale agriculture in tropical. Agricultutre. 2025. https://doi.org/10.3390/agriculture15151700.
165. Libardi N, Castilhos AB De 2024 Biochar : From Laboratory to Industry Scale-An Overview Brazilian Context, and Contributions to Sustainable Development Processes 12 5 1006 https://doi.org/10.3390/pr12051006.
166. Campbell RM, Anderson NM, Daugaard DE, Naughton HT. Financial viability of biofuel and biochar production from forest biomass in the face of market price volatility and uncertainty. Appl Energy. 2022;230:330–43. https://doi.org/10.1016/j.apenergy.2018.08.085.
167. Carvalho J, Nascimento L, Soares M, Ribeiro A, Faria L, Silva A, et al. Circular Economy Perspective. Processes. 2022. https://doi.org/10.3390/pr10122684.
168. Rex P, Rahiman K, Ismail M, Meenakshisundaram N, Barmavatu P, Bharadwaj AVSLS 2023 Agricultural Biomass Waste to Biochar : A Review on Biochar Applications Using Machine Learning Approach and Circular Economy ChemEngineering 7 3 50.
169. Chen B, Zeng H, Yang F, Yang Y, Qiao Z, Zhao X, et al. Functional biochar as sustainable precursors to boost the anaerobic digestion of waste activated sludge from a circular economy perspective : a review. Biochar. 2024. https://doi.org/10.1007/s42773-024-00345-y.

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