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Agricultural Utilization of Biochar: A Review of Production Technologies

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A B S T R A C T

Biochar production has gained significant attention lately due to its potential to sequester carbon, improve soil fertility and mitigate climate change. Various production technologies have been developed to convert biomass into biochar, each with its unique characteristics and advantages. This review provides a comprehensive overview of the current biochar production technologies aiming to synthesize existing knowledge and identify research gaps with a focus on their potential to contribute to the United Nations Sustainable Development Goals (SDGs) 2, 12, 13 and 15. The scope of this review encompasses various biochar production techniques including slow pyrolysis, fast pyrolysis, gasification and torrefaction. The effects of production conditions such as temperature, residence time, and feedstock types on biochar properties and yields are discussed. The prospects of using biochar in the agricultural system were discussed. Additionally, challenges and opportunities associated to scaling up biochar production technologies are highlighted. The findings of this review have implications for the development of sustainable biochar production practices and environmental management strategies.

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Introduction

Surging global demand for sustainable agricultural practices, climate change mitigation and environmental management has led to a surge of interest in biochar production technologies (Roberts et al. 2023).

Biochar, a carbon-rich material produced from the thermal decomposition of biomass, has been recognized for its potential to sequester carbon, improve soil fertility and support sustainable agriculture (Sohi et al., 2010). Biochar has a long history dating back to ancient civilization where it was used to improve soil fertility and support agriculture (Saleem et al., 2023). The modern concept of biochar production, however has evolved significantly over the past two decades, driven by advances in thermal conversion technologies and growing concerns about climate change (Khan et al., 2021).

Today, biochar production involves various technologies including slow pyrolysis, fast pyrolysis, hydrothermal carbonization and gasification (Kumar et al., 2020). The evaluation of biochar processes has shifted from a primary focus on charcoal production to a more holistic approach, considering the interplay between biochar properties, soil biota and ecosystem services (Sohi et al., 2010). Recent advances in biochar production technologies have enabled the production of high-quality biochars with tailored properties, optimized for specific applications (Vaghela and Kapupara, 2024).

This review synthesizes the current state of knowledge on biochar production technologies, highlighting their principles, advantages and limitations. By examining the evolution of biochar production and the impact of modern technologies, this review aims to provide a comprehensive understanding of the field and its potential to contribute to the achievement of the United Nations Sustainable Development Goals (SDGs) 2, 12, 13 and 15 by supporting sustainable agriculture, climate change mitigation and environmental management.

Torrefaction, slow pyrolysis, gasification and fast pyrolysis are the thermochemical conversion processes primarily utilized for biochar production under different operational factors (Wang et al., 2020). The chemical components and the physical state of the biomass are irreversibly changed to form biochar in the absence or oxygen-limited at specified temperatures and pressure conditions. The biomass chemical constituents go through the cross-linking process, decomposition and depolymerization transforming feedstocks/biomass into a carbon-rich solid product known as biochar and other byproducts including bio-oil or tar, combustible gases and additional compounds depending on the reaction conditions (Chakhtouna et al., 2022) Biochar has the propensity to add to the economic viability of developing cellulosic bioenergy production systems, as shown by its multiple advantages (Ren et al., 2022; Qin et al., 2022; Ezz et al., 2021). In contrast, biochar addition can sustainably store carbon (C) in the soil and decrease the net emissions of greenhouse gases (Han et al., 2022; Shakoor et al., 2021), soil physicochemical and biological characteristics (Khan et al., 2022; Rashid et al., 2021), reduces sediments, pollutants and nutrient loss (Yuan et al., 2022; Wu et al., 2021). Biochar addition to the soil do not store only C but also rebuild critical organic matters lost during the removal of biomass from the agricultural system for the production of energy.

Therefore, biochar has the potential to boost agricultural productivity and environmentally sustain the generation of a biomass system. Biochar can also boost bioenergy sustainability economically in corporations by balancing feedstock costs with revenues generated from selling biochar. Though, biochar influences the soil, agronomic and environmental factors have not been examined thoroughly. Although biochar can generate some income and boost agricultural and environmental sustainability, the bioenergy and food production sectors will remain unwilling to invest in biochar unless the exact implications on soil characteristics and crop yields are demonstrated.

To fully generate biochar on a commercial base, specific advantages to soil qualities and crop yields must be shown and these benefits must be linked to biochar characteristics, its utilization and financial potential. The most critical component to achieving this possibility is comprehending how biochar is produced and how the production process influences its functionality. Their advantages to crop productivity, soil and the environment will be compromised unless they are repetitive and reliable.

Therefore, the purpose of this review was to evaluate biochar production technologies and correlate the methods to biochar yield and characteristics, and also link biochar characteristics with their advantages to the agricultural systems. This review evaluated biochar production technologies such as gasification, slow pyrolysis, torrefaction and fast pyrolysis. The utilization of biochar in the agricultural system and its influences on soil health and plant development were summarised. The drawbacks of existing biochar research were discussed.

Biochar Production Technologies

Biochar has distinct physicochemical characteristics that rely on the thermochemical working conditions and the inherent character of biomass. Numerous modules and pyrolyzers have been created for biomass production to increase the quantity and product quality. The concepts of these pyrolyzers are analogous, however, they vary in oxygenation, rate of heating, and final temperature application, which could influence the quality and quantity of final products. The different categories of thermochemical processes used in biochar production include slow pyrolysis, fast pyrolysis, torrefaction and gasification (Figure 1). The quantity and biochar quality generated in these production processes vary greatly depending on the varying reaction settings, notably the amount of oxygen supplied.

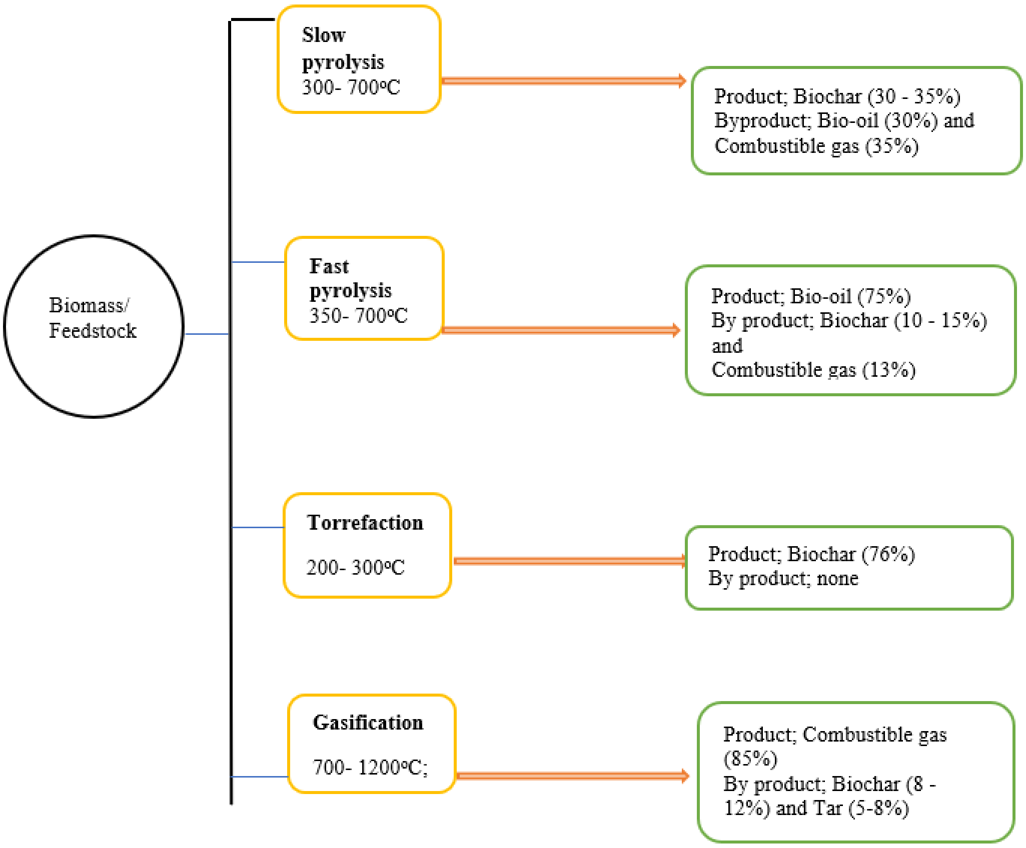

Figure 1. Biochar production technologies (modified from Wang et al., 2020).

Slow Pyrolysis Process

Biochar can be generated from different organic and non-organic materials including agricultural residue, forest residue, algal biomass and industrial waste has been widely used as the source of biochar via slow pyrolysis (Aishwarya et al., 2022; Wang et al., 2020). In this process, biomass is decomposed at 350–500 °C to provide adequate residence time for biomass pyrolysis vapour and surges its subsidiary cracking stages. The quality of biochar is mostly associated with its pH level, nutrient content, carbon content, specific surface area and porosity but is closely linked to its carbon content (Shackley et al., 2014; Yao et al., 2018). The higher quality biochar consists of high carbon content obtained from the relatively high pyrolysis temperature, longer residence time and lower heating rate (Table 1). For instance, Mousa et al. (2016) reported that wood-derived biochar at 750–900 °C and > 30 min residence time is highly preferred. The carbon content of redcedar heart wood biochar generated at 500 °C and 6 °C/min heating rate was 88.88% however the increased heating value of biochar attained 32.95 MJ/kg indicating that biochar quality was better (Yang et al., 2016).

In slow pyrolysis, a higher pyrolysis temperature is critical to boosting biochar quality so that more volatiles are extracted from biochar, thereby increasing its carbon content. Furthermore, decreasing the heating rate encourages better heating conduction, which favours the carbon deposition reaction and consequently increases the production of biochar (Veses et al., 2015). The particle size, the existence of a catalyst, and the pyrolysis atmosphere are the other operating factors of biomass slow pyrolysis that directly influence the quality and quantity of biomass (Veses et al., 2015). Furthermore, feedstock has a significant impact on the quantity and quality of biochar. Using forest plants as the precursor, at 500 °C, 60 min residence time and 10 °C/min heating rate biochar yield is around 30% (Solar et al., 2016). In comparison, biochar derived from lignin contained 45.69 % biochar yield emphasising that the lignin content is an essential factor for biochar quantity (Farrokh et al., 2018). Studies have illustrated that biochar yield depends on the lignin and ash contents of feedstock (Wan et al., 2020; Sun et al., 2017; Lee et al., 2013).

In addition to biochar production, the slow pyrolysis process at a relatively high temperature could also produce bio-oil as a product or a byproduct while the pyrolysis vapours released from the feedstock consist of condensable and non-condensable components. Wood vinegar also known as condensable components could be extracted as bio-oil owing to the existence of acetic acid. The bio-oil collected mostly comprises acids, phenols, esters and ketones (Qing et al., 2022; Setter et al., 2020). The bio-oil consists of different chemical contents that could be collected and utilized for its value-added bioproducts (Mora et al., 2022; Norrrahim et al., 2022; Vigneshwar et al., 2022). Generally, the earth or metal kilns are employed as fixed bed pyrolysis reactors for the production of biochar during feedstocks are loaded and heated for several hours or days in an airtight kiln (Pelaez-Samaniego et al., 2022). A kiln is an oven type often constructed from clay or metal that generates enough heat in the slow pyrolysis process. The solid reactants in these fixed-bed pyrolysis reactors may not consistently be heated and the exchange of gas-solid in a fixed-bed reactor is weak. In industries, auger pyrolysis reactors are widely utilized owing to their not demanding efforts in construction and operations (Brown et al., 2021).

Furthermore, by controlling the screw's spinning speed, the residence time of biomass in the auger pyrolysis reactor is regulated and biochar is continuously produced (Pal et al., 2022). Garcia-Perez et al. (2007) reported that the batch and continuous auger reactors in slow pyrolysis had the same biochar yield of 30 and 31 wt%. Thus, indicating that both pyrolysis rectors had similar reactions resulting in the biochar production. In addition to the auger pyrolysis reactor, the continuous pyrolysis reactor comprising the bubbling fluidized bed has been investigated for biomass slow pyrolysis. Patel et al. (2019) used the slow pyrolysis process to generate biosolid in a bubbling fluidized bed reactor at 60 min of residence time. Although pyrolysis is an endothermic process, the vapour produced during the slow pyrolysis process frequently is uncondensed yet burns immediately to supply heat for the operating process, regardless of the reactor type utilized.

Table 1. Biochar physicochemical characteristics and yield produced from slow pyrolysis

Feedstock	Temperature (ºC)	Residence time (min)	Heating rate (°C/min)	Yield (%)	Biochar composition (%)				Reference
					C	H	N	S	
CH	350	30	0.5	39.82	69.96	3.63	3.58	0.24	Setter et al., 2020
CM	300	120	10	58.00	51.30	4.52	1.70	-	Yu et al. (2017)
PW	350	30	15	34.70	72.36	4.7	-	-	Ronsse et al., 2013
PS	500	60	10	35.5	60.12	9.21	0.42	0.92	Qurenshi et al., 2019
WNS	500	60	15	~ 30.0	77.97	3.22	1.13	-	Gupta et al., 2019
CST	530	several	30	~ 24.0	92.83	1.49	0.84	0.06	Delgado et al., 2013
A	500	60	10	~ 32.0	77.97	3.22	1.13	-	Gupta et al., 2020
WS	475	180	8	-	69.90	2.50	-	-	Heikkinen et al., 2019
L	500	480	5	45.69	85.90	3.56	1.23	0.12	Furrokh et al., 2018
RW	500	20	10	24.25	87.17	1.23	0.40	-	Halim et al., 2016
NPSC	450	60	20	38.30	52.39	2.57	2.23	0.12	Dhanavath et al., 2019
RHW	500	30	6	21.00	88.88	2.6	0.35	0.4	Yang et al., 2016
HC	500	60	10	23.3	85.79	3.89	0.23	-	Yu et al., 2019
RSW	500	30	6	30.90	85.80	2.40	0.35	0.35	Yang et al., 2016

Notes: CH, coffee husk; CM, cow manure; PW, pine wood; PS, palm shell; WNS, walnut shell; CST, corn straw; A, algae; WS, wheat straw; L, lignin; RW, rubber wood; NPSC; neem press seed cake; RHW, redcedar heart wood; HC, hinoki cypress; RSW, redcedar sap wood.

Table 2. Biochar physicochemical characteristics produced from fast pyrolysis using different pyrolyzers

Feedstock	Pyrolyzer	Temperature (°C)	Yield (%)	Biochar composition C	H	N (%)	S	O	Reference
RH	CSB	500	26.40	45.20	1.5	0.40	-	-	Alvarez et al., 2015
CS	FBR	550	-	73.39	4.34	1.19	0.92	20.16	Wang et al., 2014
WS	ATTSR	550	26.56	56.00	2.30	1.00	-	-	Funke et al., 2019
PSD	FBR	500	-	71.63	4.16	3.14	0.25	20.82	Peng et al., 2012
CC	BFB	550	19.40	73.60	3.15	0.87	0.02	22.36	Mullen et al., 2010
YP	FBR	550	6.21	77.30	3.31	0.76	-	18.63	Hwang et al., 2015
DF	BFB	500	12.23	76.86	2.57	0.36	0.12	20.09	Wu et al., 2016
LN	LSP	450	15.87	69.59	2.93	-	-	11.61	Ghysels et al., 2019
SS	FBR	550	26.82	66.03	2.38	0.52	-	31.07	Yin et al., 2013
B	HCC	550	25.45	80.77	4.40	-	-	14.83	Kajita et al., 2010
BM	BFB	400	54.12	33.42	3.12	2.63	-	60.83	Choi et al., 2017

Note: RH, rice husk; CS, corn stalk; WS, wheat straw; PSD, pine sawdust; CC, corn cob; YP, yellow poplar; DF, douglass fit; LN, lvory nut; SS, sweet sorghum; B, bamboo; BM, brown macroalga, CSB, cornical spouted bed; FBR, fluidised bed reactor; ATTSR, air tight twin screw reactor; BFB, bubbling fluidised bed; LSP, lab-scale pyrolyser; HCC, horizontal crew conveyor

Fast pyrolysis process

In contrast to the slow pyrolysis process, fast pyrolysis is generally produced in batch reactors and occurs in a continuous system. This process incorporates 1000 °C/min heating rates to reach a pyrolysis temperature of about 500 °C with < 2s residence time (Papari et al., 2021). The biomass particles swiftly decompose in the fast pyrolysis process, producing pyrolysis vapours and 10-15 wt% biochar yields. The condensable substance is extinguished and gathered in the pyrolysis vapours and a dark-brown liquid is collected known as bio-oil and the byproduct is biochar. The higher pyrolysis temperature conditions decrease biochar yields by encouraging the emission of gaseous volatile matters, whereas higher heating rates have an analogous effect. The feedstocks are swiftly heated and the pyrolysis vapours generated are speedily transferred from the pyrolysis reactor during higher heating rates. In high-temperature regions the pyrolysis vapours consist of shorter residence time, thereby decreasing the deposition amount of carbon content. For example, Angin (2013) reported that increasing the heating rate from 10-50 °C/min declined safflower seed biochar yield by 3–8%.

Chen et al. (2016) also reported that by surging the heating rate from 10- 50°C/min at 400 °C the poplar wood biochar yield reduced from 34.83 to 31.95 wt%. Similarly, studies by Aguado et al. (2000) showed that biochar yield declined from 38.8-26.4% by surging the heating rate from 5 to 40 °C/min. Also, increasing the pressure could boost biochar yield by extending the vapour residence time inside the feedstock particles accelerating the char-forming processes (Thengan et al., 2022). For instance, high-pressure reactors can lead to 41-62% of biochar yield (Antal et al., 1996). Wang et al. (2013) observed that pyrolyzing pine sawdust in a closure fixed bed reactor surged biochar yield from 24.9 wt% to 27.5 wt%. Furthermore, (Table 2) summarises the various fast pyrolysis factors and pyrolyzer designs on the biochar yield and biochar quality varying extensively depending on the feedstock utilized.

The emission of volatile substances from the biomass particles at higher pyrolysis temperatures increases biochar's carbon content and specific surface area. Zhao et al. (2018) reported that rapeseed stem-derived biochar from 200 to 700 °C increased in specific surface area from 1 to 45 m^2 /g. Furthermore, Peng et al. (2012) reported that pinewood-derived biochar from 550 to 750 °C increased in carbon content from 70.68% to 78.75%. In fast pyrolysis operations, the heating rate consists of complex implications on biochar quality. The explanation by Onay (2007) shows that biochar generated at a higher heating rate exhibits higher carbon levels and specific surface area than biochar generated at a low heating rate owing to the differences in heating rates resulting in changes in the devolatilization rate and thereby modifying biochar structure. Similarly, Chen et al. (2016) discovered that boosting the heating rate surged biochar carbon levels whereas the BET surface area of biochar initially increased and gradually decreased. Conversely, some studies have shown that high heating rates decrease biochar-specific surface area and pore volume due to the swift depolymerization at the biochar surface (Anand et al., 2022; Mohan et al., 2014; Toledano et al., 2014). These findings suggest that high heating rates boost biochar carbon levels yet have no influence on the BET-specific surface area of biochar.

Many pyrolysis reactors such as the auger or screw reactors, bubbling fluidized bed, rotary cone, circulating fluidized bed and ablative reactors have been proven useful for producing higher bio-oil yield in a fast pyrolysis process (Kapoor et al., 2022; Raza et al., 2021; Qureshi et al., 2018). To avert pyrolysis vapour cracking reactions, biochar should be segregated from the pyrolysis vapours instantaneously. Bridgwater (2012) reported that the fluidized bed reactor, rotary cone, or ablative reactors produce about 15 wt% byproduct biochar during pyrolysis however, Raclavska et al. (2015) observed that the auger/screw reactor can surge biochar yield up to 25 wt%.

Gasification Process

Gasification typically occurs at temperatures ranging from 700 to 1000 °C, during which biomass is incompletely burned with different gasifying agents including air, pure oxygen, or steam and oxygen to form a gas product. Han and Kim (2008) reported that in the biomass gasification process, there is a need to concentrate on how to boost the quality and quantity of syngas by minimizing pollutants such as nitrogen oxides, tar, sulfur dioxide and fly ash. Shackley et al. (2014) reported that the carbon content of biochar generated by biomass gasification is directly linked to its quality.

Table 3. Biochar physicochemical characteristics produced from gasification using different pyrolyzers

Feedstock	Pyrolyser	Temperature (°C)	Composition of biochar (%) C	H	N	S	O	Reference
WC	DSG	950	79.67	2.72	0.27	-	17.34	Benedetti et al., 2018
CCS	FBG	850	88.76	1.45	0.41	-	9.38	Millan et al., 2019
RS	DFBR	800	64.76	0.67	1.98	0.11	32.48	Xu et al., 2019
DMG	LSDT	1200	56.57	3.45	1.55	0.37	38.06	Hernendez et al., 2020
WP	NPTR	750	84.43	1.90	0.18	-	13.49	Muvhiiwa et al., 2019
BB	BDFB	800	77.54	0.67	-	-	21.79	Morin et al., 2016
P	RCC	750	86.34	1.09	0.35	-	12.22	Patuzzi et al., 2016
JC	HQT	950	95.45	0.76	0.53	-	3.26	Bai et al., 2014
PI	FBR	850	84.36	2.81	0.45	0.18	12.20	Huang et al., 2013

Notes: WC, wood chip; CCS, coconut shells; RS, raw straw; DMG, Dealcoholized marc of grape; WP, wood pellet; BB, beech bark; P, pellet; JC, Japanese cedar; PI, pine; DSG, dual stage gasifier; FBG, Fluidized bed gasifier; DFBR, dual fixed bed reactor; LSDT, lab-scale drop tube; NPTR, nitrogen plasma torch reactor; BDFB, batch dense fluidized bed; RCC, rising co-current; Horizontal quartz tube; FBR, fixed bed reactor

The feedstock properties, equivalence ratio (ER), pressure and gasifying agent influence biochar quality. Benedetti et al. (2018) stated that the ER value is the most critical parameter that influences the gasification process, and based on the biomass physicochemical characteristics the optimum value is from 0.25–0.28. Mostly, surging ER increases gasification temperature affecting biochar quality (Table 3). In recent times biochar yield and quality as a function of ER have been widely studied. Yao et al. (2018) found that surging ER from 0.1-0.6 reduced biochar yield from 0.22 to 0.14 kg/kg biomass and slightly decreased the carbon content of biochar generated from 88.17% - 71.16%.

A report from Muvhiiwa et al. (2019) showed that biochar produced at 700 °C reduced its carbon content from 89% to 80% and at 900 °C carbon content of biochar reduced from 93% to 86% after increasing the oxygen flow rate from 0.15 to 0.6 kg/h. These findings illustrate that in the gasification processes increasing ER decreases biochar carbon content and biochar yield. The more oxygen is added to the gasifier the higher the ER value resulting in both positive and negative influences on biochar quality. From one point of view, the heterogeneous reactions are enhanced to transform extra carbon from the solid state to gaseous species thereby promoting the development of micropores and surging biochar-specific surface area (Zhang et al., 2021). From another point of view, additional oxygen molecules during the gasification process could result in biochar ablation thus surging its ash content and decreasing its quantity and mechanical strength.

The fluidized bed gasifier also consists of the bubbling fluidized bed gasifier and the circulating fluidized bed gasifier have all been built. Recently, Thomson et al. (2020) reviewed the development of these biomass gasifiers and their performances. The small-scale gasifiers employ air as the gasifying agent and are generally autothermal and atmospheric. The different gasifier designs slightly influence biochar characteristics and quantity as compared to ER. Many studies revealed that the biochar carbon content primarily depends on the ER rather than the gasifier types (Lu et al., 2021; Mishra and Upadhyay, 2021; Hernández et al., 2020). James et al. (2018) constructed the top-lit updraft gasifier to produce 39.3% of biochar yield from rice hulls. Furthermore, Adeniyi et al. (2019) constructed a top-lit fixed-bed updraft gasifier to produce 14.29 wt% biochar yield from elephant grass, and the biochar-specific surface area was 475 m /g.

Torrefaction Process

Torrefaction is another emerging thermal-chemical process primarily employed for the production of char products that could be utilized as a soil amendment and/or fuel (Abhishek et al., 2022). Generally, the torrefaction process involves heating biomass feedstock at temperatures between 200 and 300 °C in an inert atmosphere < 50 °C/min and between 20–120 min residence time (Bolan et al., 2022). About 30% of some highly reactive volatile chemicals are converted into torrefied vapour during this process (Afailal et al., 2023; Isemin et al., 2022; Osman et al., 2021). In this process, the target product is the dark brown solid fuel comprising 90% initial energy content and about 1.3% of the torrefied biochar and energy densification could be accomplished (Saha et al., 2022). The torrefied biochar could have an energy density comparable to coal (22–23 MJ/kg) for heating and the production of power (Lin et al., 2021). Torrefaction typically requires the burning of volatile substances in a gas combustor to provide the necessary energy.

The high temperatures and extended residence time in the torrefaction process are necessary for the torrefaction process to produce torrefied biochar with a high energy density; however, these factors also reduce the torrefied biochar quality and energy yield. A report by Niu et al. (2019) illustrates that maintaining the solid yield between 60–80% could represent the optimum torrefaction condition for biomass to produce biochar with a moderately high heating value, energy yield and mass-energy density. Szwaja et al. (2019) stated that the physicochemical characteristics of biomass comprising ash content, moisture content and higher heating value influence torrefied biochar quality. Niu et al. (2019) explained that moisture content is the most critical variable in the torrefaction process as it mainly controls the energy input.

Biomass feedstock is widely recognized constituting lignin, cellulose and hemicellulose. Several studies have been conducted on the torrefaction of these three essential components to determine the critical parameter for torrefied biochar yield. Chen et al. (2019) reported that the biochar yield from hemicellulose torrefaction recorded the lowest among the three essential components. Wang et al. (2018) reported that surging torrefaction temperature and residence time increases the lignin content and decreases hemicellulose and cellulose contents in the torrefied biochar. Though biomass residence time is critical for torrefied biochar quality, the torrefaction temperature has a greater effect than the duration (Kai et al., 2019). Increasing torrefaction temperatures for different feedstock types led to higher carbon content and lower hydrogen content of the biochar product (Table 4). The explanation by Pala et al. (2014) illustrates that the primary degradation reactions such as dehydration and decarboxylation significantly contribute to mass loss in the torrefaction process. Moreover, many studies have been conducted on biomass torrefaction processes using different agents such as air or N_2. Brachi et al. (2019) reported that the torrefied biochar mass and energy yields in an oxidative torrefaction are low compared to non-oxidative treatments.

In comparison, the torrefied biochar consists of reduced moisture content and volatile content owing to the earlier biomass feedstock only undergoing mild pyrolysis at 200 °C for 20 min. The feedstock may quickly be dried nor yet exposed to different chemical processes at a low torrefaction temperature. Nonetheless, due to its benefits, torrefied biochar continues to receive a lot of interest. For example, the bulk of the moisture in biomass feedstock may be extracted, reducing transportation costs and increasing feedstock storage duration. The energy density of the torrefied biomass is increased by decomposing the reactive hemicellulose component from the feedstock (van der Stelt et al., 2011). The torrefied biomass is easier to crush into fine powders to be utilized in pulverized coal-fired power plants than fresh feedstocks (Barskov et al., 2019).

Biochar Applications In Agricultural Systems

The Effects of Biochar on Soil Physicochemical Properties

The effects of biochar on soil physical characteristics have been widely studied, for example, the addition of biochar in the soil mixtures can enhance soil bulk density, porosity, packing and surge soil aeration and the net soil surface area (Chetri and Reddy, 2021; Munawar et al., 2021). Furthermore, biochar addition alters soil-water connections by enhancing water infiltration, water holding capacity, soil aggregate stability and soil-preparation workability (Haq et al., 2021; Abukari, 2019). Many studies have revealed that reducing bulk density and surging soil porosity may assist in transferring water, gases and heat in soils and enhance soil quality (Ahmad et al., 2022; Alkharabsheh et al., 2022; Almendro-Candel et al., 2018). The variation in soil physical properties could be ascribed to biochar's large surface area and low bulk density as a result of its extensive poor size dispersion (Leng et al., 2021; de Jesus Duarte et al., 2019).

Biochar application to soil improves soil structural quality and soil aggregation while also influencing soil chemical parameters. The addition of biochar to the soil could modify its pH (Abukari & Cobbinah, 2024). In light of the alkaline composition of many biochars, the positive influence is more noticeable in acidic soils (Palansooriya et al., 2019). Dai et al. (2017) reported that soil acidity is improved through (1) the alkalinity of biochar, cation release including K, Ca, Mg and Na are the primary parameters for the surge in pH; (2) mineral elements such as Ca, K, Mg, Na, and Si in feedstocks produce oxides or carbonates in the pyrolysis process reducing exchangeable acidity and surging pH by reacting with H^+ and monomeric Al species in acid soils; (3) functional group including –COO– and –O– significantly contributes to the alkalinity of biochar; (4) high pH buffering capacity owing to the higher cation exchange capacities (CECs) releases cation including K, Ca, Mg, and Na from biochar primarily increases pH. The application of biochar to soil can modify soil pH which results in a change in nutrient solubility thus modifying nutrient availability. Zahedifar and Moosavi (2020) reported that the addition of biochar surges soil pH leading to higher availability of primary and secondary nutrients such as K, P, Ca and Mg. Biochar addition also reduces Al toxicity in acidic soils due to the increased pH of biochar (Abukari et al., 2022; Das and Ghosh, 2020; Shetty and Prakash, 2020). Soil CEC is an important attribute of soil fertility. The addition of biochar enhances soil CEC.

Table 4. Biochar physicochemical characteristics and yield produced from torrefaction

Feedstock	Temperature (°C)	Mass yield (%)	Energy Yield (%)	Biomass composition (%)		Biochar Composition (%)		Reference
				C	H	C	H	
B	210	95.34	97.36	46.12	6.11	48.54	6.08	Ma et al., 2019
CSV	200	97.10	98.52	-	-	45.8	5.5	Medic et al., 2012
PC	225	89.00	94.00	47.21	6.64	49.47	6.07	Phanphanich and Mani, 2011
PT	230	82.00	91.00	52.09	5.79	59.00	5.49	Krysanova et al., 2019
OPP	260	94.50	94.50	54.93	6.33	57.31	6.33	Brachi et al., 2019
SCB	200	79.00	98.00	32.50	5.01	34.50	4.98	Kanwal et al., 2019
SCG	200	97.00	98.07	52.99	7.29	53.94	7.28	Zhang et al., 2018
LR	210	92.00	99.30	42.5	6.41	44.50	6.41	Xin et al., 2018
RSW	200	94.35	98.52	42.57	5.84	45.06	5.46	Kai et al. (2019)
SBK	225	90.40	96.93	49.09	6.06	55.40	5.53	Wang et al. (2017)
BCP	230	86.00	90.50	48.78	6.27	50.06	6.09	Wang et al. (2017)
EFB	200	87.50	90.30	43.00	6.00	46.20	5.50	Lam et al. (2019)
PP	250	77.00	88.00	46.50	5.10	56.40	6.00	Cardona et al. (2019)
MAR	200	89.35	91.98	36.49	6.12	41.27	5.95	Zhang et al. (2018)

Notes: B, bamboo; CSV, corn stover; PC, pine chips; PT, peat; OPP, olive pomace pellets; SCB, sugar cane bagasse; SCG, Spent coffee grounds; LR, licorice residues; RSW, rice straw; SBK, spruce bark; BCP, biomass chips, EFB, empty fruits bunches; PP, plant parts; MAR, macroalga residues.

The increased CEC of biochar-amended soils could be due to the increased specific surface area of biochar, aromatic carbon oxidation and carboxyl groups development in the biochar, and superiority of negatively charged surface functional groups (Ji et al., 2022; Palansooriya et al., 2019). Increased soil CEC improves soil nutrient retention and enhances nutrient availability to plant roots (Abukari and Duwiejuah, 2019; Laird et al., 2010). Furthermore, as explained previously, cations such as K, Ca, Mg, and Na released from biochars owing to enhanced CEC are primary contributors to higher soil pH. El-Nagger et al. (2019) reported a positive correlation between the increase in soil CEC, application rate and biochar ash content following its addition.

The Effects of Biochar on Soil Nutrition And Fertility

Biochar can serve as a source or sink for nutrient availability following its addition to the soil (Bolan et al., 2022; Hossain et al., 2020) since biochar nutrients are derived from the feedstock types (Palansooriya et al., 2019). The addition of biochar into agricultural soil demonstrates to be a sustainable approach for the enhancement of nutrient cycling, facilitating the interaction of biochar and plant roots thereby influencing the development of roots and the general performance of plants (Bolan et al., 2022; Gujre et al., 2021; El-Naggar et al., 2019; Purakayastha et al., 2019). Similarly, when exogenous nutrients are loaded on biochar, it could be utilized as a slow-release fertilizer for releasing nutrients (Mahmoud et al., 2022; Yang et al., 2021). Besides the nutrients such as N, P, K, Ca, Mg, S, Fe, Mn, Cu, Zn, and Si produced from feedstock, macro and miro nutrients such as Cu^{2+}, $Fe^{2/3+}$, Mn^{2+}, Zn^{2+} can also be absorbed. Owing to biochar's large surface area and porous microstructure, biochar-bound nutrients are gradually released (Tahery et al., 2022; Jia et al., 2021). The porous networks inside the biochar generate structural impediments such as physical wrapping or chemical sorption allowing nutrients with slow desorption to be absorbed by plants (Anwari et al., 2020; Yu et al., 2019; Xiao et al., 2018).

Biochar-based slow-release fertilizer surges nutrient bioavailability, boosts nutrient use efficiency and crop yield, and decreases leaching and runoff (Das and Ghosh, 2021; Zhou et al., 2021). The utilization of biochar directly interferes with agricultural soils and contributes to the critical nutrient cycling processes through physicochemical interactions and microbial activities (Garbuz et al., 2022; Kumar et al., 2022; Nguyen et al., 2022; Xiong et al., 2021). Nielson et al. (2018) suggested that the porous characteristics and the heterogeneous surface functional groups of biochar can contribute to ligand exchange reactions, surface complexation and the diffusion-controlled adsorption of elements thereby controlling the dynamics of plant available nutrients in soils. For instance, the nitrogen (N) cycle in soils is influenced indirectly following the addition of biochar leading to a reduction in N leaching and surges in N fertilizer. This is a result of inorganic forms of N adsorption onto biochar reduces ammonia and nitrate losses from the soil and permits nutrient retention and also releases nutrients gradually (Tsai and Chang, 2020). Although biochar is C-rich containing a high C/N ratio, its addition to agricultural soils promotes the decomposition of native soil organic matter by microorganisms. Because of the priming effect, N is essential throughout this process (Kuzyakov et al., 2019).

Biochar addition into agricultural soils boosts N utilization efficiency, and surges the total and available N but reduces the build-up of N efficiency by regulating the mineralisation of organic N, nitrification/denitrification, ammonia and volatilization (Cordovil et al., 2021). Mandel et al. (2018) reported that following the application of biochar modifies the cation and anion exchange capacities of soils thus influencing the retention of N. Biochar also influences soil phosphorus (P) transformation since it acts as a C source. For example, Xu et al. (2018) reported a positive correlation with improved soil microbial activity, decreased soil acidity, or improved CEC following the decreased $NaHCO_3^-$ extractable P concentrations owing to high C:P ratios of biochar in P immobilization. Furthermore, Liang et al. (2006) suggested that biochars that consist of high ion exchange capacity could modify the availability of P by influencing cations activities that interact with P or boost anion exchange capacity. Besides, the utilization of certain biochars can surge soil pH and modify Al^{3+}, Fe^{3+}, Fe^{2+}, Ca^{2+} and Mg^{2+} concentrations that are accountable for altering its availability and producing P complexes. Purakayastha et al. (2019) reported that biochar is rich in K and can retain K in the soil owing to its high CEC. The addition of biochar can indirectly contribute to the retention of soil nutrients founded on its properties including specific surface area, pH, porosity and CEC (Neogi et al., 2021; Diatta et al., 2020). Consequently, biochar addition to soils offers different extra advantages for nutrient recycling of plants including decreasing leaching and surging retention and use efficiency thus boosting the fertility levels of soil (Ndoung et al., 2021).

The Effects of Biochar on Plant Development

The addition of biochar to agricultural soils influences soil physical characteristics that in due course influence plant development. The efficiency of biochar utilization in boosting the productivity of crops in fertile soils is generally marginal in degraded and nutrient-poor soils (Abukari et al., 2020; Laghari et al., 2016; Hussain et al., 2017). The factors such as the supply of nutrients by biochar, increased fertilizer utilization efficiency, soil pH, moisture retention, nutrient retention and bioavailability, decreased soil tensile strength and improved soil structure. Also, they encourage favourable rhizosphere conditions for the earthworm population and microbiota can contribute to a surge in plant development after biochar to nutrient-deficient soils (Abukari, 2019; Yu et al., 2019, Yuan et al., 2019; Gwenzi et al., 2017; Abukari, 2014). In general, root establishment and development are major challenges for plants growing in poor soils. The improved soil characteristics affect the root area and stimulate root growth. The plant root in soil that increases in volume aids in capturing extra nutrients and increases plant development (Hallett et al., 2022; Abukari et al., 2018**)**.

The most common concern in agricultural settings is plant stress. Reports have shown that biochar has a promising possibility for reducing both biotic and abiotic plant stresses (Ahluwalia et al., 2021; Kavitha et al., 2018). For example, Kavitha et al. (2018) reported that the addition of biochar to soil boosts the antioxidant response of quinoa in solving the multiplex drought and salt build-up conditions through surging plant-promoting hormones. The addition of biochar to saline and sodic soils has the advantage of lessening the adverse effects of salts due to the more surface charges on biochar could replace Na, K, Ca, and Mg thereby reducing exchangeable sodium percentage levels (Tan et al., 2022). Furthermore, biochar addition can stimulate microbial activities to reduce plant pathogenicity which hinders plant survival. The discharge of volatile organic compounds from microbial inhibitors deters soil pathogens thus increasing the development of plants (Russo et al., 2022).

Limitations of Biochar Utilization

Despite its potential benefits, biochar utilization is not without limitation. One major constraint is the high production cost, which can make it economically unviable, particularly when using advanced technologies or high-quality feedstocks (Meyer et al., 2011). Additionally, biochar production requires significant energy inputs which can lead to greenhouse gas emissions and negate some climate change benefits (Woolf et al., 2010). Furthermore, the availability and quality of feedstocks can be limited by factors like land use, water availability and biomass quality (Lehmann &Joseph, 2009).

The storage and handling of biochar can also be challenging due to its powdery nature and potential for dust explosions (Kumar et al., 2020). Moreover, the lack of standardization in biochar production can lead to inconsistent quality and properties (IBI, 2014). There are also concerns about potential environmental impacts of biochar production and application, including soil contamination, water pollution and altered ecosystem processes (Sohi et al., 2010).

Scalability and commercialization of biochar production are also significant challenges, as the industry is still in its infancy (Meyer et al., 2011). Limited public awareness and acceptance of biochar can also hinder its adoption (Lehmann &Joseph, 2009). Furthermore, the regulatory framework surrounding biochar production and use are still evolving and can vary by country or region (IBI, 2014). Finally, despite growing research interest, there are still significant gaps in our understanding of biochar's properties, behaviours and impacts on ecosystems (Sohi et al., 2010).

Conclusion

Biochar yield and quality produced via biomass thermochemical conversion processes widely vary owing to changes in the amount of oxygen supply, heating rate, and reaction temperature. In general, biochar yield reduces as the heating rate or the amount of oxygen supply increases. The advantageous effects of biochar utilization in the agricultural system, including increased soil quality and plant development, have been extensively described however varied or the existence of contradictory results, consequently, the advantages of biochar additions frequently limit biochar type, application dosage, soil type and conditions, and the type of crop. Systematic research is required to understand the links between biochar production processes, biochar properties, and biochar performance in agricultural settings.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contributions

Both authors contributed.

Data availability statement

All data supporting this study are available within the paper

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