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Effects of pyrolysis temperature and feedstock type on biochar characteristics pertinent to soil carbon and soil health: A meta-analysis

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Abstract

Biochar amendment to soil is utilized globally as an approach to enhance carbon storage and to improve soil functioning. However, biochar characteristics and related improvements of soil functioning depend on biochar production conditions. Systematic evaluation of corresponding biochar characteristics is needed for more targeted and efficient biochar application strategies. Herein, we systematically review the effects of biochar pyrolysis temperature (175–950°C) and feedstock (corn stover, switchgrass and wood) on selected biochar characteristics (carbon content, H/C ratio, nitrogen content, pH, specific surface area, ash content and pore volume). These specific characteristics were selected as being pertinent to soil organic carbon sequestration and soil health improvement. Despite numerous studies on these topics, few have numerically quantified the effects of pyrolysis temperature. Our results show that high pyrolysis temperature (>500°C) increased carbon content and pore volume for wood biochar compared with low pyrolysis temperature (≤500°C). The high pyrolysis temperature decreased the H/C ratio and nitrogen content but increased pH, specific surface area and ash content regardless of feedstock. Compared with corn stover biochar and switchgrass biochar, wood biochar had higher carbon content and larger specific surface area but lower nitrogen and ash contents regardless of pyrolysis temperature. The higher biochar carbon content might be derived from higher lignin and cellulose contents of wood feedstock. Wood feedstock had 76%–109% more lignin and 27%–47% more cellulose than corn stover and switchgrass. Corn stover biochar had higher pH, and switchgrass biochar had larger pore volume than wood biochar. Our study indicates that the targeted production of biochar with specific characteristics can be facilitated by the selection of pyrolysis temperature and feedstock type. For amending soil with biochar, more operationally defined biochar production conditions and feedstock selection might be a way forward to wider acceptance and better predictability of biochar performance under field conditions.

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KEYWORDS

ash content, biochar carbon, feedstock type, H/C ratio, nitrogen, specific surface area

1 | INTRODUCTION

Biochar is produced by thermal conversion of organic materials (biomass) in an oxygen-depleted environment, that is pyrolysis (IBI, 2015). Pyrolysis condition and feedstock type introduce significant variations in nutrient content, pH and structure of the biochar product (Leng et al., 2021; Tomczyk et al., 2020). These characteristics are critical for the effectiveness of using biochar as a means to mitigate climate change and improve soil health (Gujre et al., 2021; He et al., 2017; Lehmann et al., 2021; Woolf et al., 2010). Specifically, the effective implementation of biochar as a climate-mitigating tool depends on its carbon content and long-term perseverance in soil (Lehmann et al., 2021). Biochar is also used as a tool to reduce soil nitrogen losses from global croplands by decreasing N₂O emission and NO₃ leaching (Liu et al., 2019). Furthermore, observed effects of biochar application on soil health improvement can be explained by increased soil pH in acidic soils and nutrient retention via adsorption on biochar surfaces and capture into biochar pores (Joseph et al., 2018; Kannan et al., 2021; Zeeshan et al., 2020). Biochar pores can also hold air or water, increasing soil water holding capacity but reducing soil bulk density and penetration resistance (Joseph et al., 2018; Kannan et al., 2021; Kroeger et al., 2021; Lehmann et al., 2011). Additionally, biochar can be used as a sorbent for contaminant immobilization (Luo et al., 2022), and the environmentally persistent free radicals formed during pyrolysis of lignin, cellulose and hemicellulose can help to degrade contaminants (Ruan et al., 2019).

Rendering these benefits to soil, biochar can be prepared from various feedstock from forest products or crop residues among other biomass types. Feedstock derived from different plants varies in contents of lignin, cellulose and hemicellulose, which thermally decompose at different temperatures because of their different thermal stabilities. Lignin can be decomposed within a wide range of 150–900°C because of its complex structure; cellulose mainly decomposes at 280–400°C and hemicellulose at 220–315°C (Weber & Quicker, 2018; Yang et al., 2007). Different pyrolysis temperatures, in the range of 175–950°C, have been used to optimize biochar characteristics depending on feedstock materials. Pyrolysis temperature and feedstock type are the major influencing factors of biochar characteristics (Hassan et al., 2020). Even at the

same pyrolysis temperature, biochar derived from different feedstock types can develop distinct characteristics (Pariyar et al., 2020; Schimmelpennig & Glaser, 2012; Weber & Quicker, 2018). It can be challenging to select the most appropriate pyrolysis temperature and feedstock to produce biochar for an intended purpose.

Recent advances in our understanding of biochar production warrant a systematic evaluation of the implications of pyrolysis temperature and feedstock type for biochar characteristics. Herein, we performed a comprehensive meta-analysis on published studies that measured one or more biochar characteristics with specified pyrolysis temperature and feedstock type. The pyrolysis temperatures ranged 175–950°C in the selected studies. We divided these temperatures into two categories: high pyrolysis temperature (>500°C) and low pyrolysis temperature (≤500°C) to produce meaningful statistical results in consideration of data availability and to provide data that can be used for outlining more standardized biochar production conditions. We chose 500°C as the threshold because cellulose and hemicellulose will be completely decomposed at 500°C. We selected three feedstock types (corn stover, wood and switchgrass) with different lignin, cellulose and hemicellulose contents.

Our primary goal was to quantify and compare the effects of pyrolysis temperature and feedstock type on biochar carbon content, H/C ratio, nitrogen content, pH, specific surface area, ash content and pore volume. These characteristics were selected because they are the most pertinent to the purposes of soil organic carbon sequestration and soil health improvement and the most commonly reported in the literature. Despite numerous studies on these topics, few have numerically quantified the effects of pyrolysis temperature. Most review articles provided comprehensive data on biochar characteristics (Ahmed et al., 2016; Hussain et al., 2017; Leng et al., 2021; Luo et al., 2022; Sun et al., 2021) but lack a numerical summary and synthesis of these data. Therefore, a more quantitative method, such as meta-analysis, is needed to synthesize currently published data. Meta-analyses can provide the effect sizes of high pyrolysis temperature on different feedstock, making more straightforward and direct evaluation and comparison of the effects. Therefore, we compiled 1703 observations from 72 independent publications and then conducted a two-way ANOVA and a meta-analysis on these data.

2 | MATERIALS AND METHODS

2.1 | Literature search and data compilation

We conducted an exhaustive literature search using the Web of Science database (Clarivate) with keywords “biochar,” “corn stover,” “switchgrass,” “wood” “pyrolysis temperature”, etc. See Table S1 for the searched terms and their logical combinations. The most recent search was on 10 June 2022. For each study returned by the search, we evaluated the title and abstract to determine whether it contained original data, reported at least two of the biochar characteristics of interest (carbon content, H/C ratio, nitrogen content, pH, specific surface area, ash content and pore volume), and specified pyrolysis temperature and feedstock type. Studies that meet these criteria were examined in detail. This process identified 1703 observations from 72 independent studies. See Tables S2–S4 for the fully documented data from these studies.

Our study had two treatments: pyrolysis temperature and feedstock type. Pyrolysis temperature had two levels: high and low temperatures. The low pyrolysis temperature in our study was defined as $\leq 500^{\circ}\text{C}$ and the high pyrolysis temperature $> 500^{\circ}\text{C}$. Feedstock type had three levels: corn stover, switchgrass and wood, representing biomass from crop residue, bioenergy grass and forest product. The wood in our study included eucalyptus, willow, oak and general wood pellet or sawdust. See Table S5 for the specific wood material in each study. Feedstock composition was investigated by contents of lignin, cellulose and hemicellulose. Contents of lignin, cellulose and hemicellulose in feedstock were reported in 19 of the 72 biochar studies, and additional eight studies were added by appending the search terms “lignin content,” “cellulose content” and “hemicellulose content” to each feedstock search. See Table S6 for feedstock composition reported in the 27 studies.

2.2 | Statistical analyses

A two-way mixed model ANOVA was used to determine the main and interaction effects of feedstock and pyrolysis temperature on biochar characteristics (Glimmix procedure; SAS 9.4, SAS Institute Inc.). A one-way mixed model ANOVA was used to determine the effect of feedstock type on feedstock composition. Data were logarithmically transformed to achieve normality when necessary. The univariate procedure was used for checking normal distribution of residuals. Normality was determined by the Shapiro–Wilk’s test. Equal variance was determined by Levene’s test. The post hoc least-squares means for

treatments were compared when there were interactions among the factors. Least-squares means were compared by Fisher’s least significant difference. Significance was set at $p \leq .05$. Results are reported as arithmetic mean $\pm$ standard error.

We also conducted a meta-analysis to summarize the quantitative outcomes from the different studies. The meta-analysis was conducted with RStudio (2022.07.0-548.dmg; Boston). We used a random-effects model for standardized mean difference (SMD). The bias-corrected SMD were calculated with the Hedges’ g method. The DerSimonian–Laird estimator was used to estimate τ^2 to evaluate heterogeneity, and the Knapp–Hartung adjustment was applied. The Jackson method was used for confidence interval (CI) of τ^2 . Input data, R code and output are archived on GitHub (<https://github.com/lilidong1111/meta-analysis>).

3 | RESULTS

Biochar carbon content differed with the interaction effect of pyrolysis temperature and feedstock ($p = .0223$, Figure 1). Only in the case of wood biochar, high pyrolysis temperature was associated with increased biochar carbon content compared with low pyrolysis temperature. It did not significantly affect carbon content for corn stover biochar or switchgrass biochar. Wood biochar had higher carbon content than corn stover biochar and switchgrass biochar ($74.99 \pm 1.05\%$, $62.93 \pm 1.22\%$ and $60.98 \pm 1.89\%$, respectively) regardless of pyrolysis temperature.

The biochar H/C ratio was only affected by the main effect of pyrolysis temperature ($p < .0001$), with low pyrolysis temperatures resulting in higher H/C ratio. Biochar nitrogen content varied with feedstock type ($p < .0001$). Biochar nitrogen content was ranked as wood $<$ switchgrass $<$ corn stover ($0.57 \pm 0.05\%$, $0.79 \pm 0.09\%$ and $1.13 \pm 0.06\%$). Biochar pH was affected by the main effects of both feedstock and pyrolysis temperature ($p < .0001$), but the interaction effect was not significant ($p = .5615$). Wood and switchgrass biochar had lower pH (8.83 ± 0.19 and 9.00 ± 0.52) than corn stover biochar (10.13 ± 0.22), and the pH was lower when biochar was produced at low pyrolysis temperature compared with high temperature (8.25 ± 0.14 and 9.32 ± 0.20).

The specific surface area of biochar also differed with the main effects of feedstock and pyrolysis temperature ($p = .0001$ and $p < .0001$), but the interaction effect was not significant ($p = .0909$). Specific surface area was higher for wood biochar than corn stover biochar and switchgrass biochar and higher at high pyrolysis temperature than low temperature. Biochar ash content varied with the main effects of feedstock and pyrolysis temperature ($p < .0001$ and

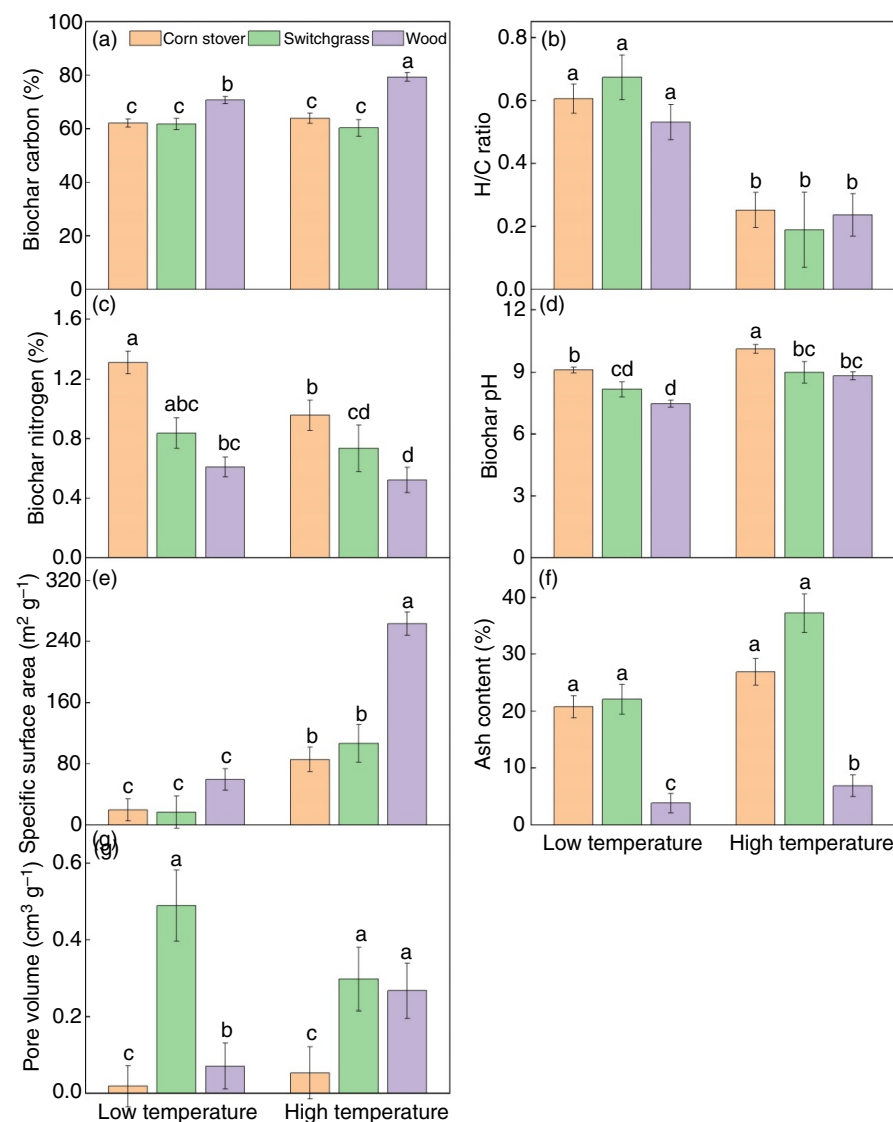


FIGURE 1 Effects of pyrolysis temperature and feedstock on biochar characteristics. Low pyrolysis temperature: $\leq 500^{\circ}\text{C}$; high pyrolysis temperature: $> 500^{\circ}\text{C}$. Results are reported as means $\pm$ standard errors. Same letters indicate no significant difference at $p > .05$. See Tables S2–S4 for data sources and references.

$p = .0002$), but the interaction effect was not significant ($p = .3351$). Wood biochar had lower ash content than switchgrass biochar and corn stover biochar, and low pyrolysis temperature had lower ash content than high temperature. Biochar pore volume changed with feedstock ($p < .0001$), ranked as corn stover < wood < switchgrass.

Our meta-analysis showed that the overall effect size of high pyrolysis temperature on biochar characteristics was 0.22, with the 95% CI ranging from -0.16 to 0.60 (Figure 2). The test of heterogeneity ($\tau^2 = 0.45$; $\chi^2 = 179$, $df = 20$, $p < 0.0001$; $I^2 = 89\%$) indicated that the effect of pyrolysis temperature differed with biochar characteristics and feedstock types, with effect size varying from -1.77 to 1.64 . Specifically, the effect sizes of high pyrolysis temperature on biochar carbon content were ordered as wood > corn stover > switchgrass (0.72, 0.13 and -0.09 , respectively). High pyrolysis temperature had negative effects on biochar H/C ratio and nitrogen content for all the three types of feedstocks. The effect

size of high pyrolysis temperature on biochar pH was larger for wood (1.06) than corn stover and switchgrass (0.70 and 0.53). High pyrolysis temperature had positive effects on specific surface area and ash content regardless of feedstock type. The largest effect size of 1.64 occurred on specific surface area of wood biochar, with the 95% CI of 1.19–2.09. The effect sizes indicated positive effects on pore volume for wood biochar and corn stover biochar (0.70 and 0.95) but a negative effect for switchgrass biochar (-0.44).

4 | DISCUSSION

4.1 | Carbon, H/C ratio and nitrogen

Previous studies have associated higher pyrolysis temperatures with higher biochar carbon content and stability but lower biochar yields (Crombie et al., 2013; Wei

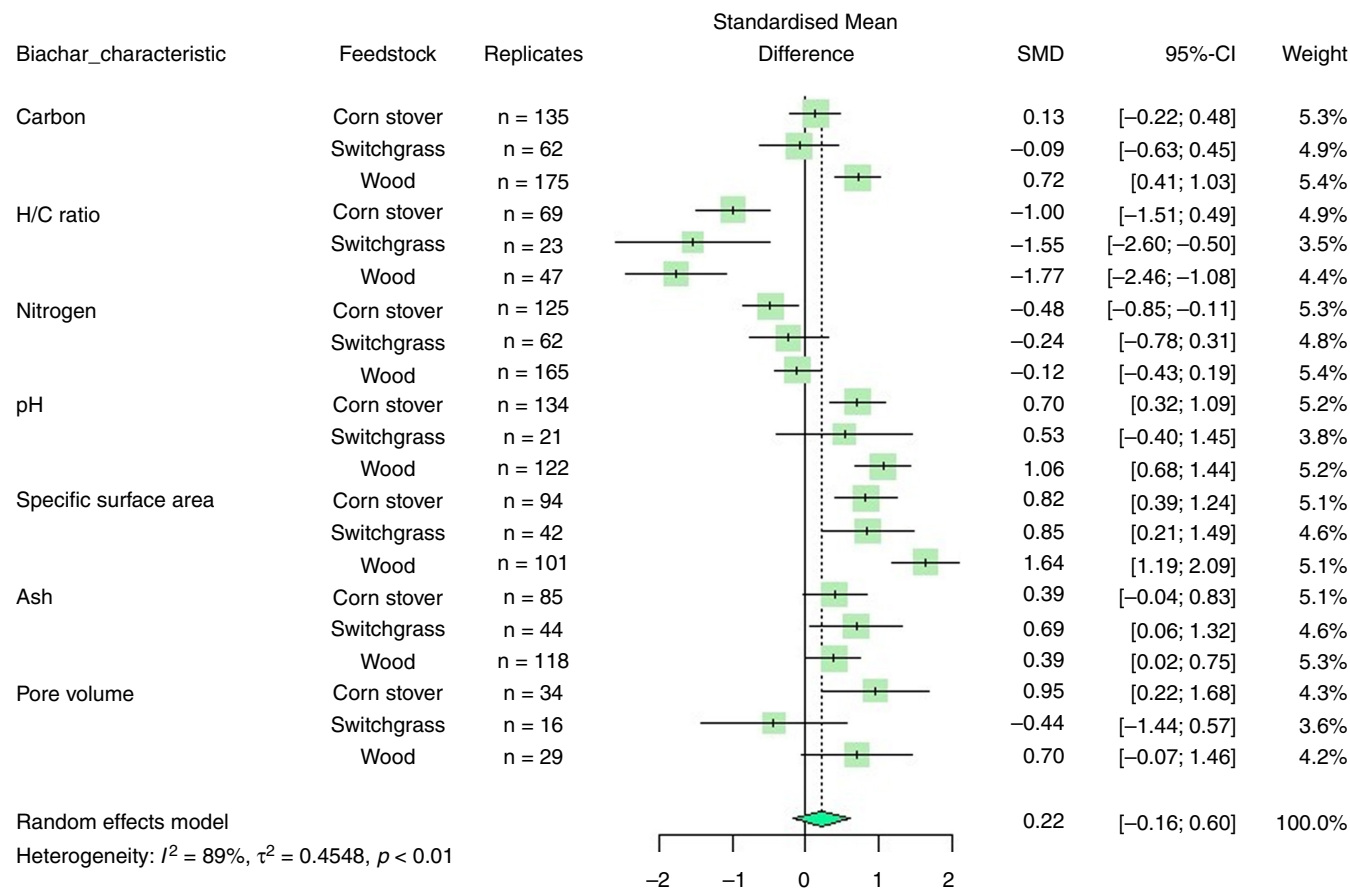


FIGURE 2 Effects of high pyrolysis temperature ($>500^\circ\text{C}$) on biochar properties compared with low pyrolysis temperature ($\leq 500^\circ\text{C}$). The points in the centre of squares indicate effects sizes on the x-axis, that is standardized mean difference (SMD). The lines across squares denote confidence intervals (CIs) calculated for the observed effect size. The area of a square indicates the weight of each effect size. The diamond shape represents the observed overall effect, and the length of the diamond symbolizes its CI. See Tables S2–S4 for data sources and references.

TABLE 1 Feedstock composition

Feedstock type	Lignin (%)	Cellulose (%)	Hemicellulose (%)
Corn stover	15.45 $\pm$ 2.45b	43.29 $\pm$ 4.50b	26.85 $\pm$ 3.63a
Switchgrass	13.01 $\pm$ 0.69b	38.97 $\pm$ 0.96b	31.23 $\pm$ 0.74a
Wood	27.17 $\pm$ 1.27a	55.13 $\pm$ 1.87a	19.12 $\pm$ 1.49b

Note: Results are reported as means $\pm$ standard errors. Same letters indicate no significant difference at $p > .05$. See Table S6 for data sources and references.

et al., 2019). In our study, high pyrolysis temperature ($>500^\circ\text{C}$) increased carbon content compared with low temperature ($\leq 500^\circ\text{C}$) for wood biochar ($79.32 \pm 1.60\%$ vs. $70.65 \pm 1.36\%$, Figure 1a). The increase could result from higher degree of carbonization and more condensed carbon structure at higher pyrolysis temperature (Chatterjee et al., 2020; Domingues et al., 2017). The greater carbonization suggests a more aromatic structure (Chatterjee et al., 2020; Pariyar et al., 2020), as this increases aromaticity proportionally with biochar carbon content (Hassan et al., 2020; Wiedemeier et al., 2015). Biochar carbon is mostly aromatic and formed in condensed polyaromatic clusters at high

pyrolysis temperature (Chia et al., 2015; Hue, 2020; Kleber et al., 2015; Weber & Quicker, 2018).

High pyrolysis temperature had a larger effect on the carbon content of wood biochar than switchgrass biochar and corn stover biochar (Figure 2). This suggests that using wood as the feedstock for biochar production will yield higher carbon content than corn stover and switchgrass for the same energy expense. This difference is likely because of the variations of lignin, cellulose and hemicellulose contents among raw wood, corn stover and switchgrass. Woody species often contains more lignin and cellulose than the herbaceous or grass species (Tomczyk et al., 2020; Wang et al., 2015). The wood feedstock had

76%–109% more lignin and 27%–47% more cellulose than switchgrass and corn stover (Table 1). The decomposition of lignocellulosic structure and the development of aromatic structure during pyrolysis can promote carbonization (Chatterjee et al., 2020).

The degree of carbonization and aromaticity can be evaluated by the biochar H/C ratio, with lower H/C ratios usually indicating increased aromatic structure in biochar (Krull et al., 2012). Because increased aromatic structure is associated with increased biochar resistance to microbial decomposition in soil, the H/C ratio is usually often used as a proxy of biochar stability (Burgeon et al., 2021; Crombie et al., 2013; Leng et al., 2019). The H/C ratios smaller than 0.7 are assumed to signify aromatic ring structures and distinguish biochar from raw feedstock (IBI, 2015). The H/C ratios smaller than 0.4 indicate high biochar stability and high carbon sequestration potential (Cantrell et al., 2012; Hassan et al., 2020; Leng et al., 2019), with decreased biochar decomposition rates (Crombie et al., 2013; Han et al., 2020; Singh et al., 2012; Zimmerman, 2010; Zimmerman & Gao, 2013).

The low H/C ratios at higher pyrolysis temperatures shown in Figure 1b suggest high-temperature pyrolysis is a means of attaining biochar with stability against microbial decomposition (Hassan et al., 2020; Leng et al., 2019). One of the underlying reasons might be found in highly hydrophobic surfaces of biochar produced at high pyrolysis temperatures (Fang et al., 2014), which can protect organic matter from microbial decomposition because of soil water repellency (Goebel et al., 2005). After mixing biochar into mineral soil, the lower H/C ratio may also lead to higher surface functionality because of hydrophobic interactions (Han et al., 2014; Keiluweit & Kleber, 2009; Xiao et al., 2016). The hydrophobic surfaces of biochar can thereby interact with hydrophobic or amphiphilic organic matter and with hydrophobic mineral particles. Both can promote the formation of organo-mineral complexes and aggregates, which are known to contribute to the long-term stabilization of biochar against microbial decomposition in soil (Burgeon et al., 2021; Joseph et al., 2021).

Besides the H/C ratio, the estimated mean residence time using isotope approaches coupled with decomposition experiments is an alternative way to evaluate long-term stability of biochar. One study showed that the mean residence time of biochar in soil was estimated to be up to 891 years, with an average of 107 years among studies (Wang et al., 2016). Biochar produced from wood usually has longer mean residence time in soil than that from crop and grass (Bird et al., 1999; Wang et al., 2016) probably because of more condensed carbon structure.

Biochar nitrogen content decreased at high pyrolysis temperature compared with low temperature (0.74% vs. 0.92%, Figure 1c). Reduction in nitrogen content can

be attributed to volatilizations of nitrogen-containing groups at high temperature (Chatterjee et al., 2020). The nitrogen-containing groups decompose and then volatilize at pyrolysis temperatures greater than ~200°C (DeLuca et al., 2015). However, pyrolysis temperature had a smaller effect on nitrogen content for wood biochar than switchgrass biochar and corn stover biochar (Figure 2) probably because of the lower nitrogen content of wood biochar (0.57%) than switchgrass biochar (0.79%) and corn stover biochar (1.13%) (Figure 1c). The difference in biochar nitrogen content is likely the result of different amino acid and protein contents in the raw feedstock (Ippolito et al., 2020; Tsai et al., 2012).

4.2 | pH, specific surface area, ash content and pore volume

High pyrolysis temperature produced biochar with higher pH values than low temperature (Figure 1d). The increase in biochar pH is mainly because of the destruction of acidic functional groups and the formation of basic functional groups (Hue, 2020; Tomczyk et al., 2020). With temperature increasing during pyrolysis, the C≡C, C=C and C=O bonds break down and aromatic rings form; these aromatic rings contain more hydroxyl groups, and thus increase biochar pH (Hassan et al., 2020). The separation of alkali salts from organic materials at high pyrolysis temperature also increases biochar pH (Pariyar et al., 2020). Corn stover biochar had higher pH than wood biochar and switchgrass biochar (Figure 1d) because of higher alkali salt content in corn stover biomass.

Biochar-specific surface area increased by 3.8 times at high pyrolysis temperature compared with low temperature (Figure 1e). This increase probably resulted from the decomposition of lignin and cellulose and thus the formation of channel structures during pyrolysis (Ahmed et al., 2016). These channel structures promote the specific surface area and pore volume. High pyrolysis temperature had a larger effect on biochar-specific surface area for wood than corn stover and switchgrass (Figure 2) because of the higher lignin and cellulose contents of wood. The decomposition of lignin-rich biomass usually occurs at high temperature (Leng et al., 2021). The lower content of the non-decomposable component of woody feedstock can also contribute to the larger specific surface area (Tomczyk et al., 2020; Wang et al., 2015). Indeed, wood biochar had 4 and 5 times less ash content than corn stover biochar and switchgrass biochar, respectively (Figure 1f).

Similarly, the increase in biochar pore volume at high pyrolysis temperature for wood biochar is mainly because of the increase in micro-pore volume caused by the release

of volatile compounds (Ahmed et al., 2016; Hue, 2020). Additionally, switchgrass biochar had larger pore volume than corn stover biochar and wood biochar regardless of pyrolysis temperature (Figure 1g). Much of the original biomass structure can be maintained in the biochar after pyrolysis and therefore influence the biochar structure (Brewer et al., 2014; Sun et al., 2012). Switchgrass biochar can retain the pore structure characterized by thinner cell walls and channels, contributing more pore volume. However, high pyrolysis temperature can further destroy these structures and thus had a negative effect on pore volume of switchgrass biochar (Figure 2).

4.3 | Biochar application to soil

Given the effects of pyrolysis temperature and feedstock type on biochar characteristics, production conditions and feedstock selection should be purpose-specific for more effective and efficient biochar application to soil (He et al., 2021). If biochar application is intended to improve soil organic carbon storage, wood-based biochar produced at high pyrolysis temperature would be more suitable because of its higher carbon content and stability. Biochar contains appreciable amount of carbon and acts as a carbon sink for climate change mitigation. It has been reported that only 3% of biochar carbon is bioavailable, and the other 97% contributes directly to long-term carbon sequestration in soil (Wang et al., 2016). Rendering great stability, however, biochar is not a substantial source of soluble carbon or nitrogen. Plant-based biochar usually contains less than 1% and 0.03% of dissolvable organic carbon and dissolvable total nitrogen, respectively (Mukherjee & Zimmerman, 2013; Sun et al., 2021). The 0.03% of dissolvable total nitrogen is negligible compared with nitrogen fertilizer application rates in croplands (Ippolito et al., 2020). It will not be realistic to apply biochar alone for a nitrogen fertilization purpose. For acidic soil remediation, biochar produced using corn stover at high pyrolysis temperature would be preferred because of its higher pH value. To relieve soil compaction, switchgrass biochar can be used to promote air and water movement since it has larger pore volume. As a sorbent for soil contaminant management, wood biochar may be a good choice because of its larger specific surface area, providing abundant reactive adsorption sites (Luo et al., 2022). Adsorption capacity also relates to biochar surface functionality. Biochar produced at low pyrolysis temperature may be more suitable for adsorption of cation contaminants because of the predominance of cation exchange reactions, electrostatic interaction and complexation on biochar surface; high pyrolysed biochar may be more

suitable for the sorption of organic contaminants because of higher aromaticity (Hassan et al., 2020).

Associated with improved soil properties, increased crop yields can be achieved through biochar application to soil, as demonstrated in previously published meta-analyses (Biederman & Harpole, 2013; Dai et al., 2020; Jeffery et al., 2011). Biochar application to soil can increase plant productivity, nitrogen uptake, nutrient use efficiency, symbiotic nitrogen fixation, as well as reduce soil N₂O emissions and nitrate leaching (Biederman & Harpole, 2013; Borchard et al., 2019; Dai et al., 2020; He et al., 2017; Liu et al., 2018).

Biochar was reported to increase soil porosity by 8%, aggregate stability by 8%, water holding capacity by 15%, saturated hydraulic conductivity by 25%, and to reduce soil bulk density by 8% (Omondi et al., 2016), with these changes being beneficial for crop production. Considering the importance of biochar characteristics in the effectiveness of biochar applications for improved soil ecosystem functioning, such as plant production and mitigating climate change, more targeted production of biochar is needed.

4.4 | Sustainable biochar production

Our study reviewed and summarized the available data in current publications, providing a sound understanding of the relationships between desired biochar characteristics and production conditions. Untapped economic potential is hidden behind these relationships. Despite substantial benefits, the use of biochar in commercial agriculture is yet to bloom (Maroušek et al., 2019). A production cost of ~500 USD t⁻¹ hinders the expansion of biochar production into a commercial scale (Maroušek, 2014; Maroušek et al., 2019; Vochozka et al., 2016). Biochar's cost is critical to its commercial sustainability and consists of a variety of cost components including capital investment, operating cost and electricity consumption (Ahmed et al., 2016; Vochozka et al., 2016). Our results can help to develop more cost-effective biochar from common biomass sources such as corn stover, switchgrass and wood waste and by using efficient pyrolysis temperatures, making it both economically and environmentally sounder.

5 | CONCLUSIONS

Our review has helped clarify the effects of pyrolysis temperature and feedstock type on biochar characteristics. We found that high pyrolysis temperature can promote certain biochar characteristics and that biochar produced from wood had advantages over those produced

from corn stover and switchgrass in terms of biochar carbon content and specific surface area because of its biochemical composition. For application to soils, biochar produced by high-temperature pyrolysis of wood may be beneficial to soil organic carbon sequestration and nutrient retention. However, corn stover biochar, especially when pyrolysed at high temperature, could be more efficient for acidic soil remediation because of its higher pH. Switchgrass biochar can be used to relieve soil compaction and promote air and water movement since it has a large pore volume. The targeted production of biochar according to specific needs or desired outcomes by selecting pyrolysis temperature and/or feedstock will be helpful for developing more efficient biochar application strategies and increase the chances of adoption.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the [Supplementary Material](#) of this article.

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REFERENCES

- Ahmed, M. B., Zhou, J. L., Ngo, H. H., & Guo, W. (2016). Insight into biochar properties and its cost analysis. *Biomass and Bioenergy*, 84, 76–86.
- Biederman, L. A., & Harpole, W. S. (2013). Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis. *GCB Bioenergy*, 5, 202–214.
- Bird, M., Moyo, C., Veenendaal, E., Lloyd, J., & Frost, P. (1999). Stability of elemental carbon in a savanna soil. *Global Biogeochemical Cycles*, 13, 923–932.
- Borchard, N., Schirrmann, M., Cayuela, M. L., Kammann, C., Wragemann, N., Estavillo, J. M., Fuertes-Mendizábal, T., Sigua, G., Spokas, K., & Ippolito, J. A. (2019). Biochar, soil and land-use interactions that reduce nitrate leaching and N₂O emissions: A meta-analysis. *Science of the Total Environment*, 651, 2354–2364.
- Brewer, C. E., Chuang, V. J., Masiello, C. A., Gonnermann, H., Gao, X., Dugan, B., Driver, L. E., Panzacchi, P., Zygourakis, K., & Davies, C. A. (2014). New approaches to measuring biochar density and porosity. *Biomass and Bioenergy*, 66, 176–185.
- Burgeon, V., Fouché, J., Leifeld, J., Chenu, C., & Cornelis, J.-T. (2021). Organo-mineral associations largely contribute to the stabilization of century-old pyrogenic organic matter in cropland soils. *Geoderma*, 388, 114841.
- Cantrell, K. B., Hunt, P. G., Uchimiya, M., Novak, J. M., & Ro, K. S. (2012). Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. *Biorescience Technology*, 107, 419–428.
- Chatterjee, R., Sajjadi, B., Chen, W.-Y., Mattern, D. L., Hammer, N., Raman, V., & Dorris, A. (2020). Effect of pyrolysis temperature on physicochemical properties and acoustic-based amination of biochar for efficient CO₂ adsorption. *Frontiers in Energy Research*, 8, 85.
- Chia, C. H., Downie, A., & Munroe, P. (2015). Characteristics of biochar: Physical and structural properties. In J. Lehmann, & S. Joseph (Eds.), *Biochar for environmental management* (pp. 121–142). Routledge.
- Crombie, K., Mašek, O., Sohi, S. P., Brownsort, P., & Cross, A. (2013). The effect of pyrolysis conditions on biochar stability as determined by three methods. *GCB Bioenergy*, 5, 122–131.
- Dai, Y., Zheng, H., Jiang, Z., & Xing, B. (2020). Combined effects of biochar properties and soil conditions on plant growth: A meta-analysis. *Science of the Total Environment*, 713, 136635.
- DeLuca, T. H., Gundale, M. J., MacKenzie, M. D., & Jones, D. L. (2015). Biochar effects on soil nutrient transformations. In J. Lehmann, & S. Joseph (Eds.), *Biochar for environmental management* (pp. 453–486). Routledge.
- Domingues, R. R., Trugilho, P. F., Silva, C. A., Melo, I. C. N. D., Melo, L. C., Magriotis, Z. M., & Sanchez-Monedero, M. A. (2017). Properties of biochar derived from wood and high-nutrient biomasses with the aim of agronomic and environmental benefits. *PLoS One*, 12, e0176884.
- Fang, Q., Chen, B., Lin, Y., & Guan, Y. (2014). Aromatic and hydrophobic surfaces of wood-derived biochar enhance perchlorate adsorption via hydrogen bonding to oxygen-containing organic groups. *Environmental Science & Technology*, 48, 279–288.
- Goebel, M.-O., Bachmann, J., Woche, S. K., & Fischer, W. R. (2005). Soil wettability, aggregate stability, and the decomposition of soil organic matter. *Geoderma*, 128, 80–93.
- Gujre, N., Soni, A., Rangan, L., Tsang, D. C., & Mitra, S. (2021). Sustainable improvement of soil health utilizing biochar and arbuscular mycorrhizal fungi: A review. *Environmental Pollution*, 268, 115549.
- Han, L., Sun, K., Jin, J., Wei, X., Xia, X., Wu, F., Gao, B., & Xing, B. (2014). Role of structure and microporosity in phenanthrene sorption by natural and engineered organic matter. *Environmental Science & Technology*, 48, 11227–11234.
- Han, L., Sun, K., Yang, Y., Xia, X., Li, F., Yang, Z., & Xing, B. (2020). Biochar's stability and effect on the content, composition and turnover of soil organic carbon. *Geoderma*, 364, 114184.
- Hassan, M., Liu, Y., Naidu, R., Parikh, S. J., Du, J., Qi, F., & Willett, I. R. (2020). Influences of feedstock sources and pyrolysis temperature on the properties of biochar and functionality as adsorbents: A meta-analysis. *Science of the Total Environment*, 744, 140714.
- He, M., Xu, Z., Sun, Y., Chan, P., Lui, I., & Tsang, D. C. (2021). Critical impacts of pyrolysis conditions and activation methods on application-oriented production of wood waste-derived biochar. *Biorescience Technology*, 341, 125811.
- He, Y., Zhou, X., Jiang, L., Li, M., Du, Z., Zhou, G., Shao, J., Wang, X., Xu, Z., & Hosseini Bai, S. (2017). Effects of biochar application on soil greenhouse gas fluxes: A meta-analysis. *GCB Bioenergy*, 9, 743–755.
- Hue, N. (2020). Biochar for maintaining soil health. In B. Giri, & A. Varma (Eds.), *Soil health* (pp. 21–46). Springer.
- Hussain, M., Farooq, M., Nawaz, A., Al-Sadi, A. M., Solaiman, Z. M., Alghamdi, S. S., Ammara, U., Ok, Y. S., & Siddique, K. H.

- (2017). Biochar for crop production: Potential benefits and risks. *Journal of Soils and Sediments*, 17, 685–716.
- IBI. (2015). *Standardized product definition and product testing guidelines for biochar that is used in soil*. International Biochar Initiative.
- Ippolito, J. A., Cui, L., Kammann, C., Wrage-Mönnig, N., Estavillo, J. M., Fuertes-Mendizabal, T., Cayuela, M. L., Sigua, G., Novak, J., & Spokas, K. (2020). Feedstock choice, pyrolysis temperature and type influence biochar characteristics: A comprehensive meta-data analysis review. *Biochar*, 2, 421–438.
- Jeffery, S., Verheijen, F. G., van der Velde, M., & Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment*, 144, 175–187.
- Joseph, S., Cowie, A. L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., Cayuela, M. L., Graber, E. R., Ippolito, J. A., & Kuzyakov, Y. (2021). How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy*, 13, 1731–1764.
- Joseph, S., Kammann, C. I., Shepherd, J. G., Conte, P., Schmidt, H.-P., Hagemann, N., Rich, A. M., Marjo, C. E., Allen, J., & Munroe, P. (2018). Microstructural and associated chemical changes during the composting of a high temperature biochar: Mechanisms for nitrate, phosphate and other nutrient retention and release. *Science of the Total Environment*, 618, 1210–1223.
- Kannan, P., Paramasivan, M., Marimuthu, S., Swaminathan, C., & Bose, J. (2021). Applying both biochar and phosphobacteria enhances *Vigna mungo* L. growth and yield in acid soils by increasing soil pH, moisture content, microbial growth and P availability. *Agriculture, Ecosystems & Environment*, 308, 107258.
- Keiluweit, M., & Kleber, M. (2009). Molecular-level interactions in soils and sediments: The role of aromatic π -systems. *Environmental Science & Technology*, 43, 3421–3429.
- Kleber, M., Hockaday, W., & Nico, P. S. (2015). Characteristics of biochar: Macro-molecular properties. In J. Lehmann, & S. Joseph (Eds.), *Biochar for environmental management* (pp. 143–170). Routledge.
- Kroeger, J. E., Pourhashem, G., Medlock, K. B., & Masiello, C. A. (2021). Water cost savings from soil biochar amendment: A spatial analysis. *GCB Bioenergy*, 13, 133–142.
- Krull, E. S., Baldock, J. A., Skjemstad, J. O., & Smernik, R. J. (2012). Characteristics of biochar: Organo-chemical properties. In J. Lehmann, & S. Joseph (Eds.), *Biochar for environmental management* (pp. 85–98). Routledge.
- Lehmann, J., Cowie, A., Masiello, C. A., Kammann, C., Woolf, D., Amonette, J. E., Cayuela, M. L., Camps-Arbestain, M., & Whitman, T. (2021). Biochar in climate change mitigation. *Nature Geoscience*, 14, 883–892.
- Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota – A review. *Soil Biology and Biochemistry*, 43, 1812–1836.
- Leng, L., Huang, H., Li, H., Li, J., & Zhou, W. (2019). Biochar stability assessment methods: A review. *Science of the Total Environment*, 647, 210–222.
- Leng, L., Xiong, Q., Yang, L., Li, H., Zhou, Y., Zhang, W., Jiang, S., Li, H., & Huang, H. (2021). An overview on engineering the surface area and porosity of biochar. *Science of the Total Environment*, 763, 144204.
- Liu, Q., Liu, B., Zhang, Y., Hu, T., Lin, Z., Liu, G., Wang, X., Ma, J., Wang, H., & Jin, H. (2019). Biochar application as a tool to decrease soil nitrogen losses (NH_3 volatilization, N_2O emissions, and N leaching) from croplands: Options and mitigation strength in a global perspective. *Global Change Biology*, 25, 2077–2093.
- Liu, Q., Zhang, Y., Liu, B., Amonette, J. E., Lin, Z., Liu, G., Ambus, P., & Xie, Z. (2018). How does biochar influence soil N cycle? A meta-analysis. *Plant and Soil*, 426, 211–225.
- Luo, Z., Yao, B., Yang, X., Wang, L., Xu, Z., Yan, X., Tian, L., Zhou, H., & Zhou, Y. (2022). Novel insights into the adsorption of organic contaminants by biochar: A review. *Chemosphere*, 287, 132113.
- Maroušek, J. (2014). Significant breakthrough in biochar cost reduction. *Clean Technologies and Environmental Policy*, 16, 1821–1825.
- Maroušek, J., Strunecký, O., & Stehel, V. (2019). Biochar farming: Defining economically perspective applications. *Clean Technologies and Environmental Policy*, 21, 1389–1395.
- Mukherjee, A., & Zimmerman, A. R. (2013). Organic carbon and nutrient release from a range of laboratory-produced biochars and biochar–soil mixtures. *Geoderma*, 193, 122–130.
- Omondi, M. O., Xia, X., Nahayo, A., Liu, X., Korai, P. K., & Pan, G. (2016). Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. *Geoderma*, 274, 28–34.
- Pariyar, P., Kumari, K., Jain, M. K., & Jadhao, P. S. (2020). Evaluation of change in biochar properties derived from different feedstock and pyrolysis temperature for environmental and agricultural application. *Science of the Total Environment*, 713, 136433.
- Ruan, X., Sun, Y., Du, W., Tang, Y., Liu, Q., Zhang, Z., Doherty, W., Frost, R. L., Qian, G., & Tsang, D. C. (2019). Formation, characteristics, and applications of environmentally persistent free radicals in biochars: A review. *Bioresource Technology*, 281, 457–468.
- Schimmelpfennig, S., & Glaser, B. (2012). One step forward toward characterization: Some important material properties to distinguish biochars. *Journal of Environmental Quality*, 41, 1001–1013.
- Singh, B. P., Cowie, A. L., & Smernik, R. J. (2012). Biochar carbon stability in a clayey soil as a function of feedstock and pyrolysis temperature. *Environmental Science & Technology*, 46, 11770–11778.
- Sun, H., Hockaday, W. C., Masiello, C. A., & Zygourakis, K. (2012). Multiple controls on the chemical and physical structure of biochars. *Industrial & Engineering Chemistry Research*, 51, 3587–3597.
- Sun, Y., Xiong, X., He, M., Xu, Z., Hou, D., Zhang, W., Ok, Y. S., Rinklebe, J., Wang, L., & Tsang, D. C. (2021). Roles of biochar-derived dissolved organic matter in soil amendment and environmental remediation: A critical review. *Chemical Engineering Journal*, 424, 130387.
- Tomczyk, A., Sokołowska, Z., & Boguta, P. (2020). Biochar physico-chemical properties: Pyrolysis temperature and feedstock kind effects. *Reviews in Environmental Science and Bio/Technology*, 19, 191–215.
- Tsai, W.-T., Liu, S.-C., Chen, H.-R., Chang, Y.-M., & Tsai, Y.-L. (2012). Textural and chemical properties of swine-manure-derived biochar pertinent to its potential use as a soil amendment. *Chemosphere*, 89, 198–203.

- Vochozka, M., Maroušková, A., Váchal, J., & Straková, J. (2016). Biochar pricing hampers biochar farming. *Clean Technologies and Environmental Policy*, 18, 1225–1231.
- Wang, J., Xiong, Z., & Kuzyakov, Y. (2016). Biochar stability in soil: Meta-analysis of decomposition and priming effects. *GCB Bioenergy*, 8, 512–523.
- Wang, S., Gao, B., Zimmerman, A. R., Li, Y., Ma, L., Harris, W. G., & Migliaccio, K. W. (2015). Physicochemical and sorptive properties of biochars derived from woody and herbaceous biomass. *Chemosphere*, 134, 257–262.
- Weber, K., & Quicker, P. (2018). Properties of biochar. *Fuel*, 217, 240–261.
- Wei, S., Zhu, M., Fan, X., Song, J., Li, K., Jia, W., & Song, H. (2019). Influence of pyrolysis temperature and feedstock on carbon fractions of biochar produced from pyrolysis of rice straw, pine wood, pig manure and sewage sludge. *Chemosphere*, 218, 624–631.
- Wiedemeier, D. B., Abiven, S., Hockaday, W. C., Keiluweit, M., Kleber, M., Masiello, C. A., McBeath, A. V., Nico, P. S., Pyle, L. A., & Schneider, M. P. (2015). Aromaticity and degree of aromatic condensation of char. *Organic Geochemistry*, 78, 135–143.
- Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, 1, 1–9.
- Xiao, X., Chen, Z., & Chen, B. (2016). H/C atomic ratio as a smart linkage between pyrolytic temperatures, aromatic clusters and sorption properties of biochars derived from diverse precursory materials. *Scientific Reports*, 6, 1–13.
- Yang, H., Yan, R., Chen, H., Lee, D. H., & Zheng, C. (2007). Characteristics of hemicellulose, cellulose and lignin pyrolysis. *Fuel*, 86, 1781–1788.
- Zeeshan, M., Ahmad, W., Hussain, F., Ahamd, W., Numan, M., Shah, M., & Ahmad, I. (2020). Phytostabilization of the heavy metals in the soil with biochar applications, the impact on chlorophyll, carotene, soil fertility and tomato crop yield. *Journal of Cleaner Production*, 255, 120318.
- Zimmerman, A. R. (2010). Abiotic and microbial oxidation of laboratory-produced black carbon (biochar). *Environmental Science & Technology*, 44, 1295–1301.
- Zimmerman, A. R., & Gao, B. (2013). The stability of biochar in the environment. *Biochar and Soil Biota*, 1, 240.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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